Thermal Analysis of CANDU Spent Fuel Bay Cooling System

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1. Introduction

Spent fuel bundles are stored under water to allow the residual energy in the spent fuel to dissipate safely and to protect personnel from radiation exposure. A spent fuel bay cooling and purification system is provided to dissipate the decay heat of stored fuel and to remove dirt, radioactive particles and dissolved solids from the spent fuel bay and two auxiliary bays of the reception bay and the discharge bay as shown in Fig. 1. The spent fuel bay cooling and purification system for Wolsong Nuclear Power Plant (NPP) Units 2, 3 and 4 was designed to remove heat from the spent fuel bay generated by 10 years accumulation of spent fuel at an 80% capacity factor refueling rate plus an emergency discharge of one-half the core fuel inventory over a 20-day period for 25.5°C of the cooling sea water temperature [1].

The heat load in the spent fuel bay depends on the capacity factor refueling rate and the amount of spent fuel accumulated at the spent fuel bay. An 80% capacity factor refueling rate was considered as a design condition, but the highest capacity factor refueling rate of 93.75% for Wolsong NPPs was calculated based on nine (9) years of operating experience from 2000 to 2008.

The heat exchangers were designed to be cooled by Raw Service Water (RSW) at a temperature of 25.5°C. The maximum RSW temperature during the summer months for four-unit operation was expected to be 26.7°C but RSW temperature has been increased due to the global warming or the effects of neighboring plants. The increment in RSW temperature affects the capability of the spent fuel bay cooling system.

The objective of this study is to identify the heat loads in spent fuel bay at various capacity factor refueling rates and to evaluate the capability of the spent fuel bay cooling system for the conditions of heat loads and RSW temperatures.

2. Analysis Method

2.1 System Description

The spent fuel bundles are removed from the reactor core by the fuelling machines and transferred from the fuelling machines through the spent fuel ports onto a fuel transfer mechanism which transports the fuel into the discharge bay. The spent fuel is then transferred through the canal on a conveyor to the reception bay and from there to the main storage bay. All movements of spent fuel from the discharge bay to the main storage bay are carried out underwater.

Three pumps are provided to draw water from the appropriate transfer pit and recirculate it through the heat exchangers to remove decay heat. Two pumps are required for the spent fuel bay cooling and purification circuit and one pump is required for the auxiliary bay cooling and purification circuit. However, all three pumps are identical and are connected such that any pump may be used for any circuit. Three heat exchangers are provided. Two heat exchangers are used to cool the storage bay water and one heat exchanger is used to cool the auxiliary bays.

The heat exchangers are designed to be cooled by RSW at a temperature of 25.5°C. The maximum RSW temperature during the summer months for four-unit operation would be 26.7°C. Two heat exchangers in the storage bay at 26.7°C RSW inlet temperature remove 1.7 MW(th) heat from the spent fuel bay generated by ten years accumulation of spent fuel at an 80% capacity factor refueling rate, while maintaining an operating temperature within the bay not exceeding 38°C, and 2.9 MW(th) heat from the spent fuel bay generated by ten years accumulation of spent fuel at an 80% capacity factor refueling rate plus one-half charge of reactor fuel discharged from the reactor within 20 days after shutdown, while maintaining an operating temperature within the bay not exceeding 49°C. One heat exchanger removes 0.2 MW(th) heat from the auxiliary bays generated by spent fuel in transit through the discharge bay and the reception bay, while maintaining an operating temperature within the bays not exceeding 38°C. The maximum accumulation of fuel in the auxiliary bays is equal to five days discharge of fuel, which generates about 0.2 MW(th) heat.

2.2 Heat Load in Spent Fuel Bay

The total fission power in the reactor core of Wolsong NPP unit 2, 3 or 4 is 2158.5 MW(th). Since the reactor has 380 fuel channels and each channel has 12 bundles per channel, the average bundle power is 0.473 MW(th). The mass of uranium per bundle is 19.1 kg so that the average power per kilogram of uranium is 0.473/19.1=0.0248 MW(th)/kg. Since the average discharge burnup is expected to be 171.7 MW·h/kgU the average irradiation time of the bundle will be 171.7 /0.0248 = 6928 hours, which corresponds to a discharge rate of about 16 bundles per day[2]. After 10 years irradiation at an 80% capacity factor, the number of bundles in the spent fuel bay will be 16 x 365 x 10 x 0.8

= 46,720 bundles. The heat load from the 46,720 irradiated fuel bundles in the spent fuel bay is 1.525 MW(th), calculated using the equation (1).

For the abnormal operating condition, the heat load in the spent fuel bay from the half-core discharge of 2280 bundles within 20 days after reactor shutdown is 1.373 MW(th), calculated using the equation (1).

The maximum accumulation of fuel in the auxiliary bays (i.e., discharge and reception bays) is equal to five days of fuel discharge. The heat from accumulation of fuel is expected to be about 0.2 MW(th) on the fifth day.

$$\mathrm{Q} = \mathrm{P}D_r \sum_{n=1}^{n=t} \left[\sum_{i=1}^{23} \frac{\alpha_i}{\lambda_i} e^{-\lambda_i (n-0.95)\Delta t} \left(1 - e^{-\lambda_i T}\right) \right] \quad (1)$$

Where,

P : average power of the bundles, fissions/s
D_r : rate of bundles discharged, bundles/s
Δt : interval of decay time at t, s
t : accumulation time of the bundle, day
T : average irradiation time of the bundle, bundles/day
α_i, λ_i : constants for thermal fission of U-235[3]

Discharged spent fuel bundles for Wolsong NPP Units 2, 3 and 4 are 5304, 5411 and 5353 respectively for nine (9) years from 2000 to 2009. Maximum spent fuel bundles of 5411 correspond to a discharge rate of about 15 bundles per day and capacity factor refueling rate of 93.75%. The calculation results of heat load are summarized in Table I and plotted in the Fig. 2.

Table I: Heat load in spent fuel bay

Conditions		Design Condition	Plant Condition
Fuel Bay Capacity(bundle)		49,000	44,688
Normal operation	Duration(day)	3,650	2,827
	Discharge rate(bundle/day)	12.8	15.0
	Capacity factor (%)	80.0	93.75
	Max. stored bundles	46,720	42,405
	Heat load (MW)	1.525	1.735
Half-core discharge	Fuel bundles	2,280	2,280
	Heat load (MW)	1.373	1.373
Abnormal operation heat load (MW)		2.898	3.108

2.3 Analysis Model and Assumptions

The Flowmaster V7 computer code has been widely used to evaluate fluid effects within a complex system by calculating the internal flow and thermal effects through the use of empirical and mathematical relationships of pressure, flow rate and temperature.

Fig. 3 shows the model of the CANDU spent fuel bay cooling and purification system for a thermal analysis. The model includes cooling and purification systems with components for a thermal analysis, including spent fuel and auxiliary bays, three (3) identical pumps, three (3) heat exchangers, two (2) ion exchangers, piping and valves. 1 MW heat exchangers of HX1 and HX2 are used for the spent fuel bay and 0.2 MW heat exchanger of HX3 is used for the auxiliary bays.

Since the purpose of this thermal analysis is to evaluate the capability of spent fuel cooling system, the spent fuel and auxiliary bays are modelled as components of heat exchanger in the Flowmaster model. The inlet temperatures in these models represent the bulk temperatures of the spent fuel and auxiliary bays.

There are ten (10) different combinations used for cooling purposes, achieved by means of closing and opening valves and matching pumps with corresponding heat exchangers. Possibilities of pump and heat exchanger operation are shown in Table II.

Table II: Input data with operating combination

RSW Temp (℃)	25.5	Normal Design Condition[1]	
	26.7	Maximum Design Condition[1]	
	29.25	Abnormal Condition	
Heat Load (MW)	1.525	After 10 years irradiation at an 80% capacity factor[1]	
	1.7	After 10 years irradiation at an 80% capacity factor with uncertainty[1]	
	1.74	After 7.75 years irradiation at a 93.75% capacity factor	
	2.9	Abnormal condition with half core[1]	
	3.1	Abnormal condition with 93.75% capacity factor	
Operating Modes	Modes	Pumps	Heat exchanges
	1	P1, P2, P3	HX1, HX2, HX3
	2*	P1, P2	HX1, HX2
	3	P1, P2	HX1, HX3
	4	P1, P3	HX1, HX3
	5	P1, P3	HX2, HX3
	6	P2, P3	HX1, HX3
	7	P1, P3	HX2, HX3
	8	P1, P3	HX1, HX2, HX3
	9	P2, P3	HX1, HX2, HX3
	10*	P1, P3	HX1, HX2

*NOTE: * Cooling is not required for Auxiliary bays*

3. Results and Discussion

The steady state simulation was performed for the combination of ten (10) operating modes, five (5) heat loads and three (3) RSW temperature conditions.

Fig. 4 shows the bulk temperatures in spent fuel bay for operating modes 1, 2 and 10. For the operating modes 2 and 10, it is not required to remove the heat load of auxiliary bays. The calculation results are the same as the temperatures in spent fuel bay for three (3) operating modes because two (2) heat exchangers of HX1 and HX2 are used for removing the heat load of the spent fuel bay. For the normal operating condition without half-core, the operating temperature of spent fuel bay is maintained within acceptance criterion of 38°C for the conditions of the capacity factor refueling rate of 93.75% and RSW temperature below 26.7°C. For the abnormal operating condition with half-core, the operating temperature of spent fuel bay is maintained within acceptance criterion of 49°C for all conditions of given RSW temperature and capacity factor refueling rates. These calculation results indicate that the spent fuel bay cooling and purification system for Wolsong NPP Units 2, 3 and 4 is recommended to increase the capacity of heat exchangers if RSW temperature rises above 26.7°C due to the global warming or the effects of neighboring plants

Fig. 5 shows the bulk temperatures in spent fuel bay for operating modes 3, 4, 5, 6 and 7. In these operating modes, one pump among three pumps works with one heat exchanger of HX1or HX2 to cool spent fuel bay and one pump works with one heat exchanger of HX3 to cool auxiliary bays. For the normal and abnormal operating conditions, the operating temperatures of spent fuel bay do not meet with the acceptance criteria of 26.7°C and 49°C. The application of these operating modes is not recommended with the exception of the beginning of plant life.

Fig. 6 shows the bulk temperatures in spent fuel bay for operating modes 8 and 9. In these operating modes, one pump among three pumps works with two heat exchangers of HX1and HX2 to cool spent fuel bay and one pump works with one heat exchanger of HX3 to cool auxiliary bays. For the normal operating condition, the operating temperature of spent fuel bay is maintained within acceptance criterion of 38°C for the conditions of the heat load below 1.525 MW(th) and RSW temperature below 25.5°C. These calculation results indicate that these operating modes shall be applied in the limited condition of winter season or less than 15,000 spent fuel bundles stored in the spent fuel bay as shown in Fig. 2. For the abnormal operating condition, the operating temperature of spent fuel bay does not meet with the acceptance criterion of 49°C for the conditions of the capacity factor refueling rate of 93.75%. These operating modes are not recommended for the abnormal operating condition.

4. Conclusion

The analysis was performed to calculate the heat loads in spent fuel bay at various capacity factor refueling rates and to evaluate the capability of the spent fuel bay cooling system for the conditions of heat loads and RSW temperatures. From the results of this study, it is concluded that:

1) The capacity factor refueling rate for Wolsong NPP Units 2, 3 and 4 is developed as 93.75% based on operating experience which is higher than design condition of 80%.
2) The spent fuel bay cooling and purification system for Wolsong NPP Units 2, 3 and 4 is recommended to increase the capacity of 1 MW heat exchangers if RSW temperature rises above 26.7°C due to the global warming or the effect of neighboring plants.
3) For the economical operation for the CANDU spent fuel bay cooling and purification system, operating modes 8 and 9 given in Table II can be applied in the limited condition of winter season or less than 15,000 spent bundles stored in the spent fuel bay.

Acknowledgments

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REFERENCES

[1] Design Manual, Spent Fuel Bay Cooling and Purification System for Wolsong NPPs 2,3,4, 8600-34410-00-DM-A, Rev.2.
[2] Design Manual, Shielding Design Manual Part 1-Reactor Building, 86-03320-DM-001, Rev.1.
[3] American Nuclear Society, American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS 5.1-1979.

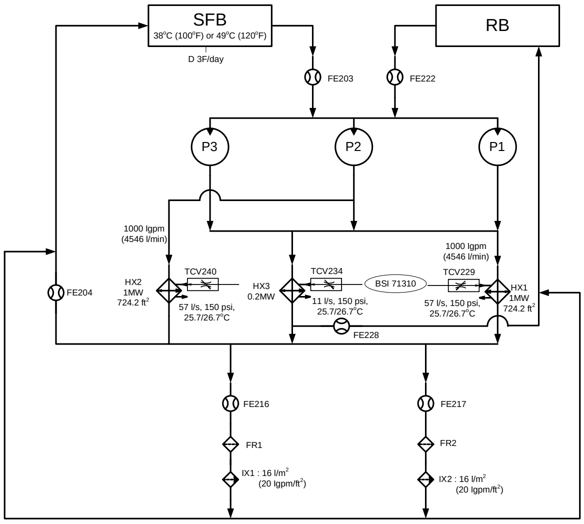

Fig. 1. Schematic diagram of the CANDU spent fuel bay cooling system

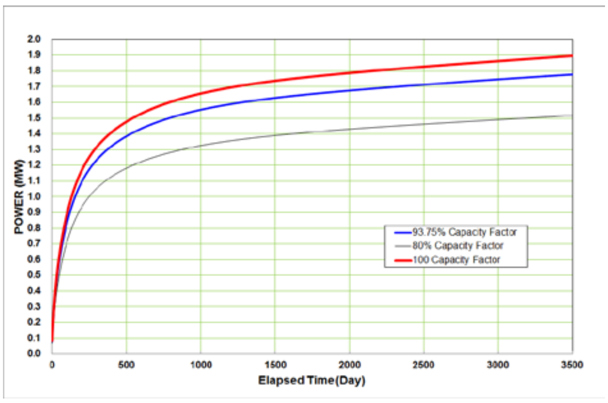

Fig. 2. Heat loads with various capacity factor refueling rates

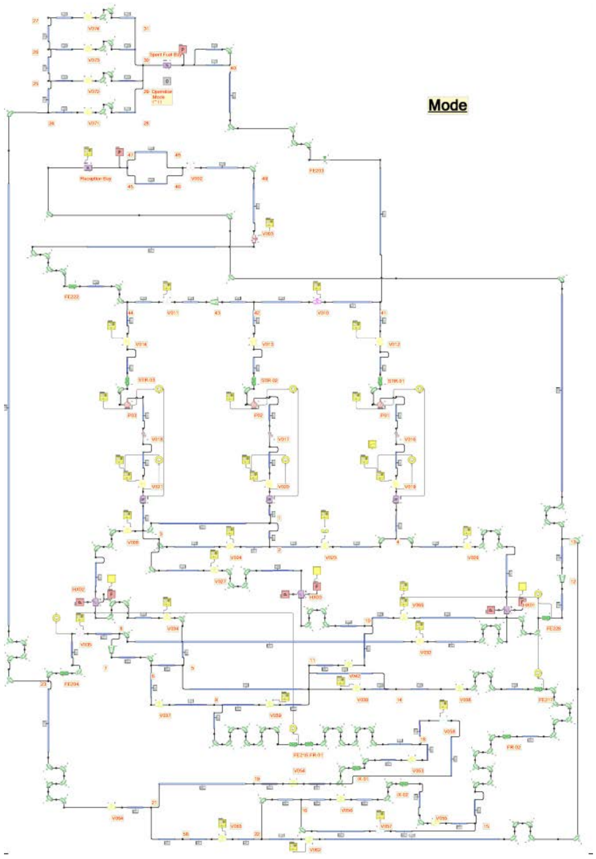

Fig. 3. Flowmaster modeling for spent fuel bay cooling and purification system

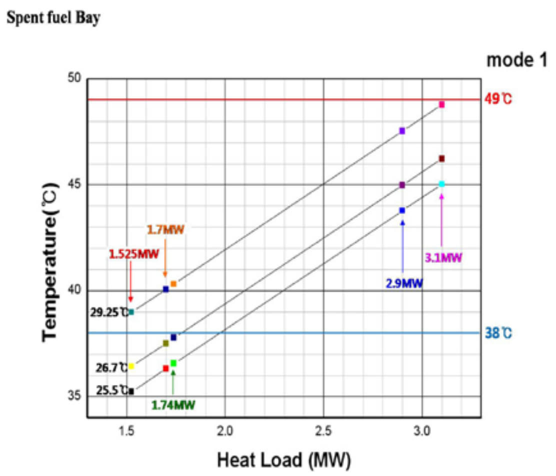

Fig. 4. Bulk temperature in spent fuel bay for operating modes 1, 2 and 10

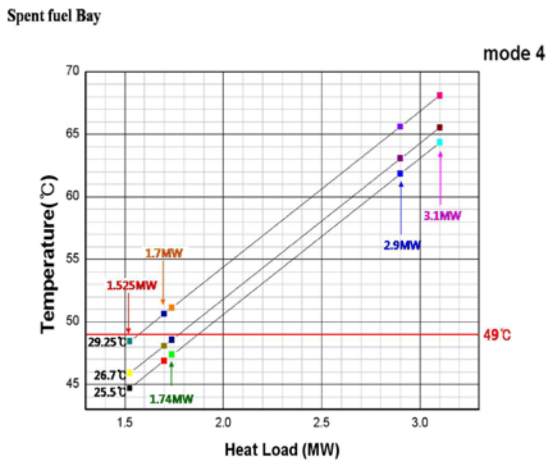

Fig. 5. Bulk temperature in spent fuel bay for operating modes 3, 4, 5, 6 and 7

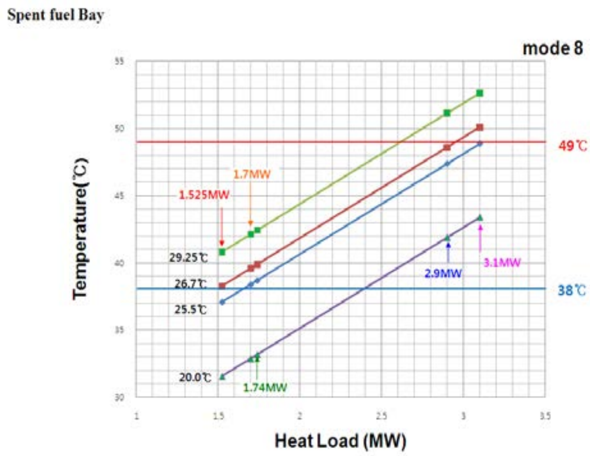

Fig. 6. Bulk temperature in spent fuel bay for operating modes 8 and 9