SPENT FUEL STORAGE BAY COOLING SYSTEM MODELLING, ANALYSIS AND RECOMMENDATIONS

A. Gidi, PhD., P.Eng.
Wardrop Engineering Inc, Energy Division
6835A Century Avenue
Mississauga Ontario, Canada, L5N 2L2
alex.gidi@wardrop.com

Abstract

An engineering study was prepared for New Brunswick Power, Point Lepreau Nuclear Generating Station (PLNGS) to evaluate the capability of the Spent Fuel Storage Bay Cooling (SFSB) System to reject the heat radiation load of a complete reactor core fuel discharge.

The objective of the study was to develop a mathematical model capable of predicting the Spent Fuel Bay water temperature during the period the reactor fuel bundles were being placed in the bay for long term storage. Three periods were contemplated, 35, 38, and 40 days. The final water temperature predicted in each case was compared to the design limit temperature.

1. Introduction

Operators had plans to perform a rehabilitation outage of the PLNGS starting in April of 2008 and for a period of 18 months. At the commencement of the outage, and for a period of 40 days, all fuel bundles in the reactor core needed to be removed and transferred to the SFSB. After full transfer, the Bay contained the totality of the reactor core fuel plus the spent fuel accumulated during the previous seven years.

According to design requirements, the cooling system is required to maintain the water contained in the Spent Fuel Bay below 49ºC [1], to avoid potential damage to the epoxy lining on the walls of the bay. This requirement must accommodate the case of full core discharge after the plant has been operating for ten years at 80% power capacity, when the transfer is executed in 40 days.

Since this activity fell on the critical path of the planned outage, it was proposed to discharge the core fuel in 35 days, or if not possible, in 38 days. This scenario, however, had not been analyzed in the design of the cooling system. Therefore, it was not known if the cooling system was capable of maintaining the water temperature of the spent fuel bay below 49ºC.

To determine if a 35 day, 38 day or 40 days discharge time was feasible, a heat transfer model of the SFSB cooling system, using actual operating conditions, was required.

2. System description

The main components of the Spent Fuel Storage bay are shown on the schematics of figure 1. The schematics is a simplification of the actual system [2],[3], but it contains the necessary components required for the modelling process.

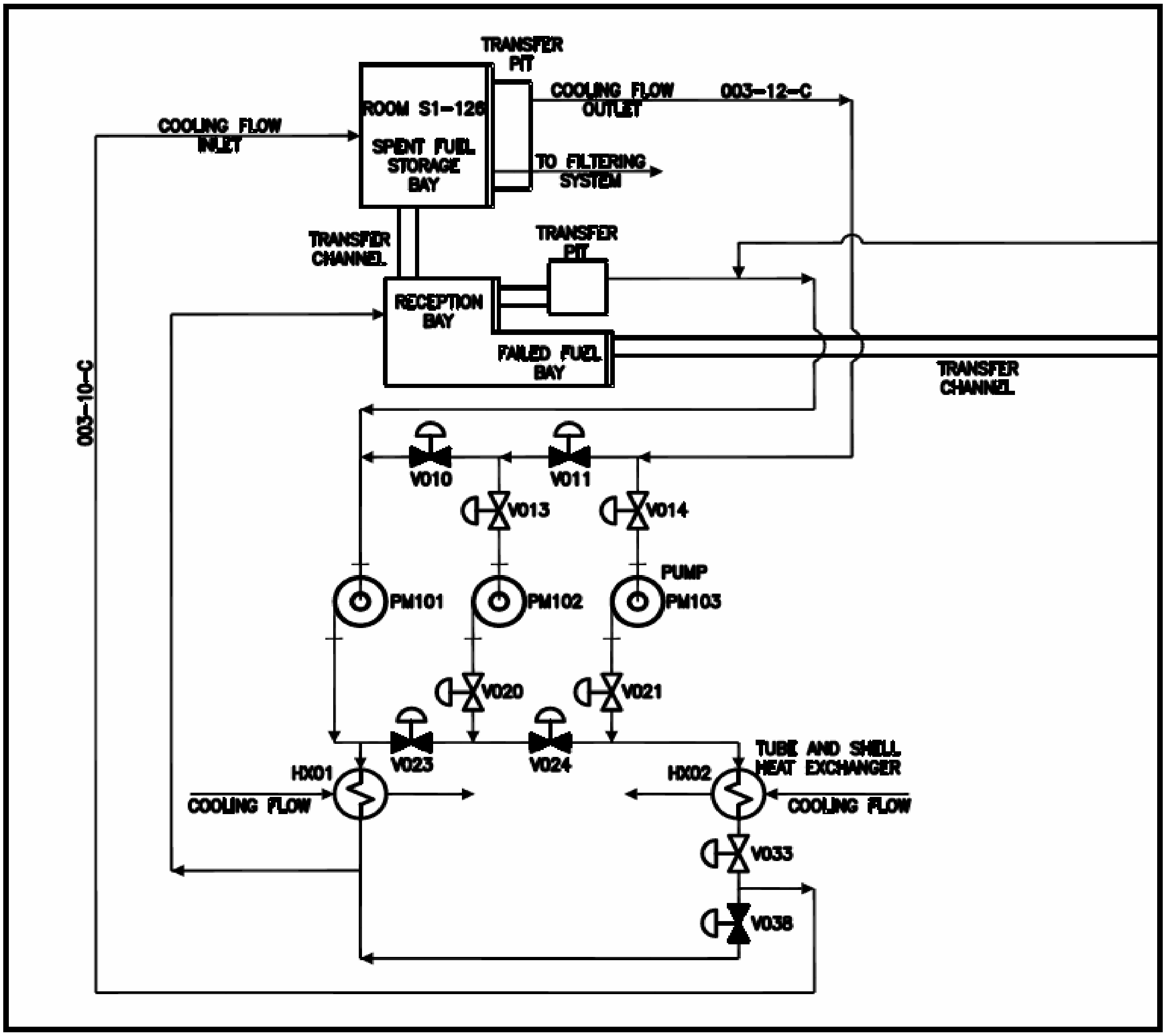

Figure 1 Spent Fuel Storage Bay cooling system flow schematics.

Pumps PM102 and PM103 bring warm water from the storage bay to the heat exchanger HX02 through pipeline 003-12-C and send the cooler water back to the storage bay through line 003-10-C.

3. Modelling process

3.1 Model conceptual approach

The fundamental principle to be used in the construction of the model is the conservation of energy over a control volume and a unit of time. The application of the principle to a control volume (CV) is expressed in the first law of thermodynamics, which for a system with no mechanical power in or out, is described in equation (1) below:

$$E_s(t_2) - E_s(t_1) = \int_{t_1}^{t_2} \left[E'_{in}(t) - E'_{out}(t) + E'_{gen}(t) \right] \cdot dt \qquad (1)$$

That is, the difference in energy $E_s(t)$ of the system between time t_1 and time t_2, is the integral over time of the energy flow in, minus the energy flow out, plus the energy per unit time generated internally. The CV was defined to contain the SFSB, therefore the physical representation of the terms in the equation is as follows:

Energy flow out of the bay, E'_{out} (t) is composed of five terms:

i) Energy flow due to cooling water leaving the bay
ii) Energy flow due to water evaporation
iii) Energy flow due to convection losses
iv) Energy flow due to radiation losses
v) Energy flow due to conduction through the concrete walls and base slab.

Energy flow into the bay, E'_{in} (t) is the Energy flow due to cooling water entering the spent fuel bay. Energy generated within the bay, E'_{gen} (t) is the Energy flow (power) generated due to fuel bundle radiation.

3.2 Model assumptions

The following assumptions were made to simplify the model.

3.2.1 <u>Heat exchangers HX02 and HX01</u>

Only HX02 was credited in the calculation. Heat exchanger HX01 is used for cooling the water in the reception bay and failed fuel bay and as a back up for HX02.

The inlet water temperature to heat exchanger HX02 has been assumed to be the same as that of the outlet flow from the SFSB. Energy added to the flow by the pumps has been neglected, with an estimated additional effect of 0.7% of total power generated by the fuel bundles.

3.2.2 <u>Ventilation system</u>

Water evaporated from the bay needs to be removed by the air flow provided by the ventilation system. A calculation revealed that before full discharge occurs the ventilation system reaches its vapour removal capacity limit. Therefore, the model was adjusted to allow an energy removal by evaporation below or equal to this limit. It was assumed that the air became saturated and any additional vapour produced in the bay will condense and return to the SFSB [4],[5],[6].

3.2.3 Equal inlet flow distribution pipelines

There are four inlet flow pipes discharging into the bay. To simplify the model they have been lumped and assumed as one, as shown on Figure 1. This condition embodies a further assumption that the flow discharge into the bay does not produce localized temperature gradients that could generate convection flows, affecting the overall heat transfer process.

3.2.4 Filtration flow effects

The SFSB filtration system flow is discontinuous and small (7.6 kg/s) when compared to the total bay cooling flow (76 kg/s), it has been therefore neglected in the model.

3.2.5 Bay water temperature gradient

It was assumed that the average water temperature at the surface will have a similar value to the water bulk temperature and therefore no temperature gradients were assumed to be present.

3.2.6 Water type

Bay water is de-mineralized water. Pure water properties were used and were modeled as function of temperature using empirical numerical correlations.

3.2.7 Other energy terms

Water level in the SF Bay is maintained constant by the control system [7]. This requires the addition of water at a temperature lower than the bay water temperature. The energy associated with this colder water has not been included in the model, as the amount is considered small and also conservative to the model results.

3.3 Data input

Basic parameters used in the model are shown on the table in Table 1. Fuel bundles radiation power curves were developed for each discharge period based on data provided by the operators [8].

Parameter	Value
i) Net volume of water (equivalent) in the bay	1875 m^3
ii) Inlet Volumetric flow of cooling water to the bay	0.076 m^3/s
iii) HX02 U value	658.6 W/ m^2 K
iv) Bay area used for heat conduction (losses)	782.438 m^2
v) HX02 Inlet cooling water temperature	20°C
vi) Horizontal Open area of the storage bay	235.787 m^2
vii) HX02 Inlet cooling water flow	98.2 kg/s
viii) Open vault area above bay (ceiling+walls):	928.84 m^2
ix) Temperature of the air above bay	23°C
x) HX02 tube inlet water flow (warm stream):	76.34 kg/s

Table 1 Main input parameters.

3.3.1 Initial water temperature

Initial steady state bay water temperature at the commencement of fuel discharge was required. This value, however, was not available, because the heat exchanger inlet cooling water flow temperature was not known. To obtain the initial bay water temperature, the model was run for steady state condition, using the expected HX02 inlet cooling water temperature of 20°C [9]. Radiation power level for the existing fuel bundles in the bay was used. From the graph shown on Figure 2 it can be seen that the model shows a clear trend towards a temperature of 32°C, which was the value used in this study.

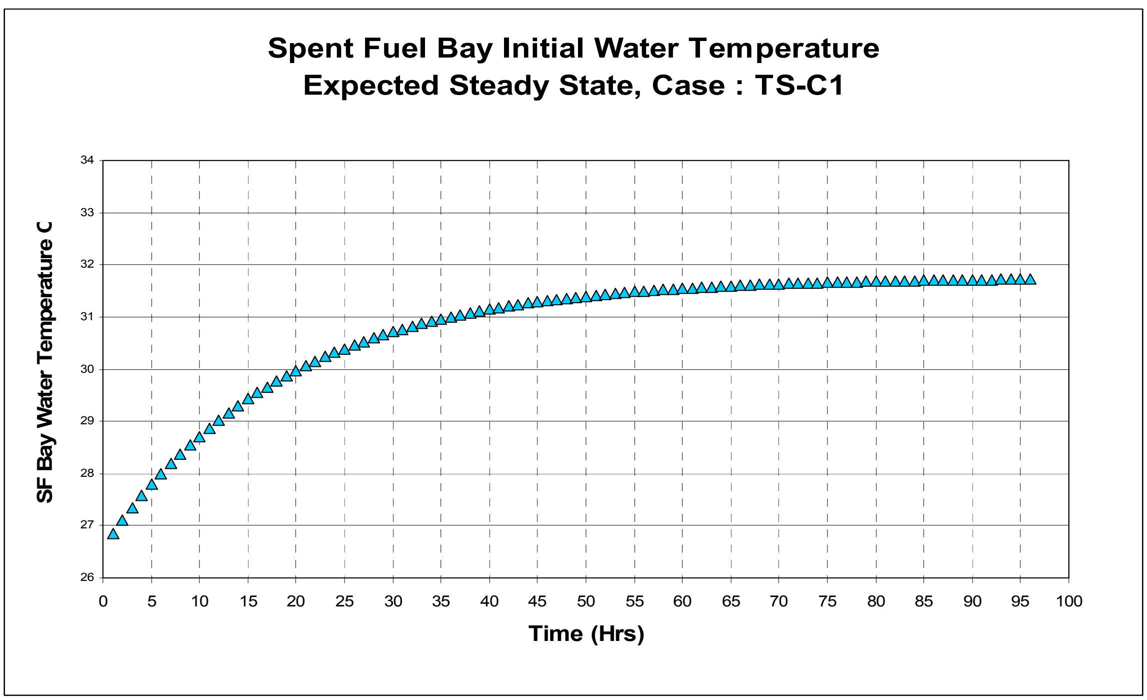

Figure 2. Predicted initial bay water temperature with HX02 cooling water at 20°C.

3.4 Solving technique

Input data was inserted into equation 1 and converted to a numerical equation. The equation was set in an excel spreadsheet and a computer code in Visual Basic was developed for the purpose of finding the temperature of the bay water at the end of each hour given the initial conditions. Time step for integration was one hour.

3.5 Model validation

The model needed to be a faithful physical representation of the SF Bay Cooling System. This means the ability to predict the evolution of the system, based on a set of initial conditions. In order to verify this, two tests were applied to the model. The first one, to verify the ability of the model to predict the steady state bay water temperature. The second one, to predicts the rise in the bay water temperature when the heat exchangers HX02 and HX01 are in a shut down condition. Data for these two cases, were given in [10] and [11] respectively. In both cases, the model predicted the actual system performance with the required fidelity. A brief description of each test follows.

3.5.1 Steady state water temperature

Data given for steady state normal operation of the cooling system [10] and data predicted by using the model are presented on Table 2. The table shows that the predicted water temperatures are within 0.3 °C of the measured values. Also the predicted power transfer for HX02 is within 0.2% of the measured value.

Input Parameters	System Value	Model		Units
HX02 Cooling flow	98.2	98.2		kg/s
HX02 Cooling flow temperature	16.0	16.0		°C
Bay cooling flow (inlet & outlet)	76.34 & 79.4	76.34		kg/s
Output Parameters	**Measured**	**Calculated**	**Difference**	
Bay flow outlet temperature	28.5	28.2	0.3	°C
Bay flow inlet temperature	25.1	24.8	0.3	°C
Power transferred at HX02	1.084	1.082	0.002	MW

Table 2 Bay cooling system operating steady state conditions and model prediction.

The results are shown in Figure 3. The graph shows that the bay water temperature predicted by the model (lower line) trends towards the value of 28.2 °C after 95 hours of operation. This value is very close to the 28.5 °C temperature (horizontal line) given by the plant operators.

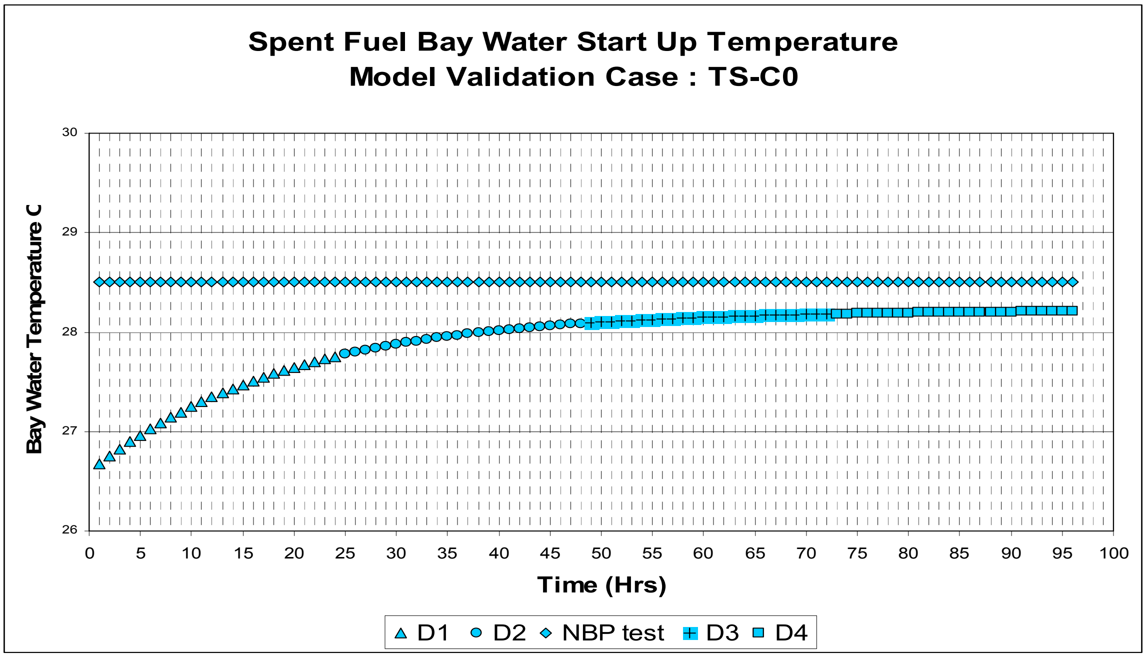

Figure 3. Measured and predicted bay water steady state temperature[1].

3.5.2 System evolution test

This test was intended to confirm that the model can predict the transient evolution of the SF Bay Cooling System. Operators performed a test in which both heat exchangers HX02 and HX01 were shut down by preventing the cooling flow through the shell side [11]. The test lasted for 27 hours. Table 3 shows the main input data used, and also the final results obtained by field measurements and by the model. Figure 4 shows the evolution of the bay water temperature (yellows triangles) and the temperature predicted by the model (blue triangles).

Input Data	Value	Model	Diff	Units
HX02 Cooling flow	98.2	98.2		kg/s
HX02 Cooling flow temperature (inlet)	23.0	23.0		°C
Bay cooling flow	76.3	76.3		kg/s
Bay Cooling flow outlet temperature at time zero	26.6	26.6		°C
Output Data				
Bay Cooling flow outlet temperature at time 27 hr	37.7	38.7	1.0	°C
Bay water temperature rise in 27 hrs	11.1	12.1	1.0	°C

Table 3 Heat Exchangers Shut Down Test results.

Although the model over-predicts the rise in temperature by 1°C (12.1 versus 11.1 degree rise), the difference is small and conservative. This discrepancy can be attributed to the thermal mass of the system. The model uses only the water contained in the system and the concrete that is contained in the Spent Fuel Bay. However, there are numerous other components that will absorb energy during the test (i.e. fuel racks, pipes, valves, pumps, etc).

[1] D1 to D4 represent Day 1 to Day 4 data generated by the model. NBP is New Brunswick Power.

In addition, the full heat transfer capacity of the base slab of the fuel bay has been only partially credited. The conditions of the ground beneath the bay were not known.

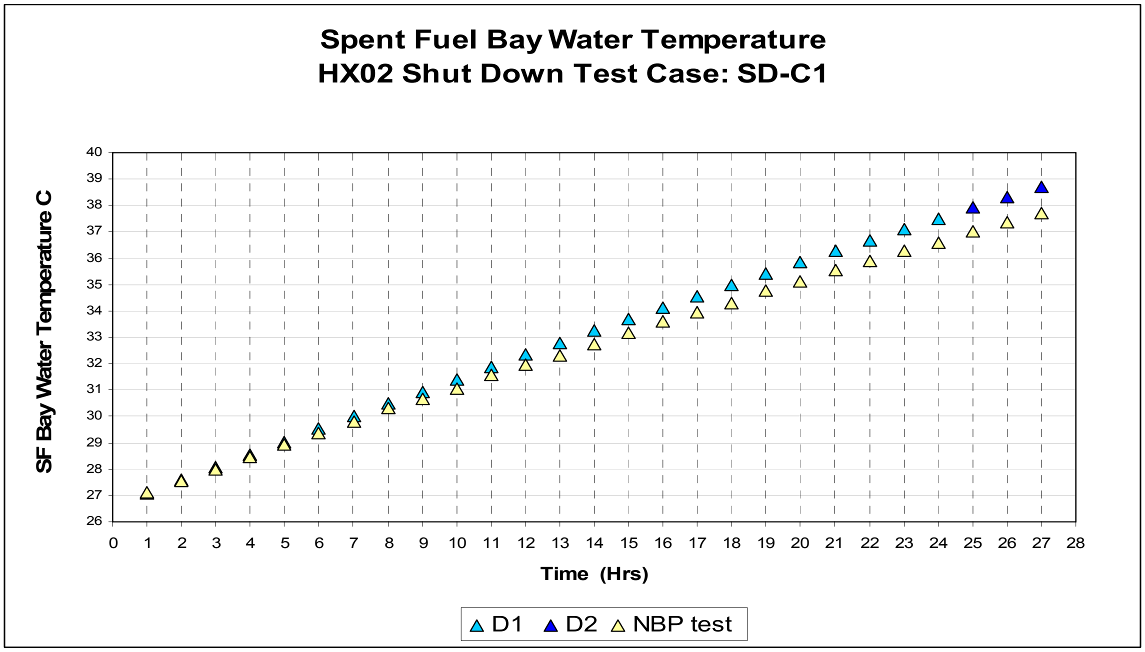

Figure 4 Measured (NBP test) and Predicted (D1 and D2) Bay Water Temperature for Heat Exchanger Shut Down Condition.

4. Results and analysis

Results and analysis for the three basic cases studied are presented.

4.1 Results

The graph in Figure 5 presents the temperature of the spent fuel bay water at the end of each day for each of the three cases considered, 35 days, 38 days and 40 days discharge period. The trend in each case is similar, showing an increase in water temperature (from 32°C) as the days within the discharge period increased. A brief description of each case follows:

<u>Case of 35 days discharge</u>

In this case, the power curve was developed for a discharge of 380 channels in 35 days. The first 34 days had 11 channels discharged each and Day 35 had 6 channels only. The final temperature at the end of Day 35 is 50.2°C.

<u>Case of 38 days discharge</u>

The power curve for this case was developed for a discharge of 380 channels in 38 days, (i.e. 10 channels per day). The final water temperature was 49.0°C on Hour 24, Day 38.

Case of 40 days discharge

The power curve was developed for a discharge of 380 channels in 40 days. The number of channels per day computed is 9.5. The discharge was arranged for alternating ten and nine channels per day discharge, that is, 10 channels on Day 1, 9 channels on Day 2, 10 channels on Day 3 and so on, until Day 40 with 9 channels. The final water temperature was 48.4°C on the last hours of Day 40.

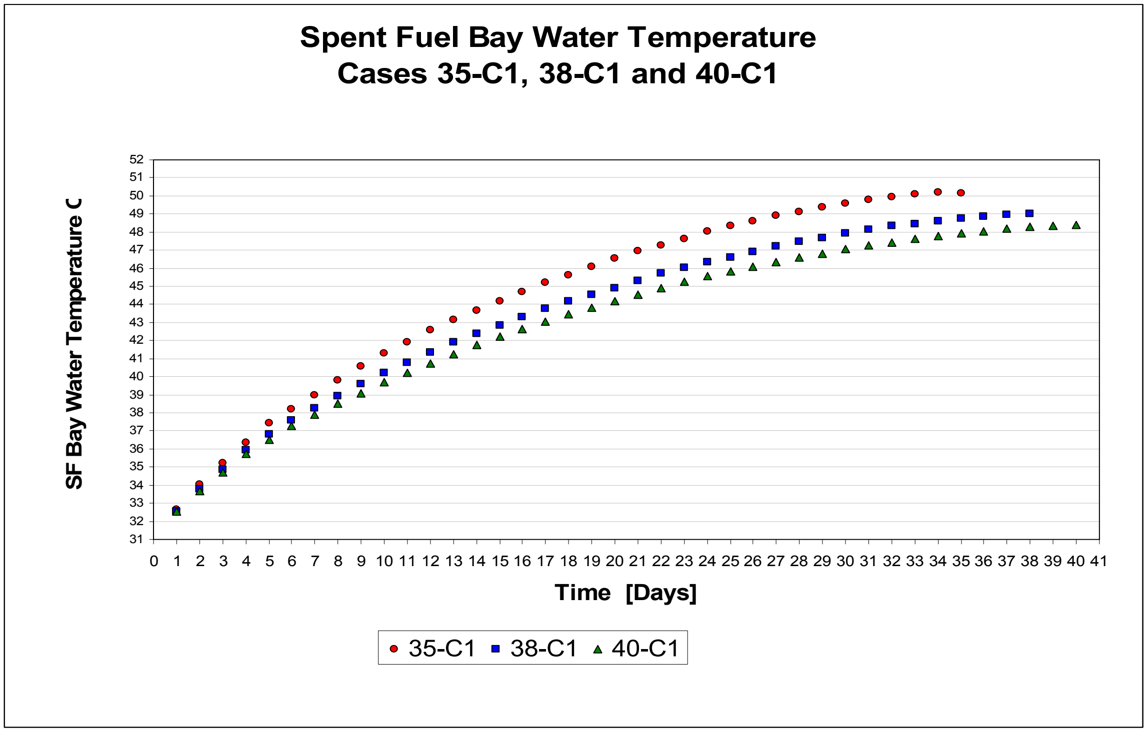

Figure 5 Daily final bay water temperature for 35, 38 and 40 days discharge.

Table 4 contains a summary of the results of the three cases analysed in this section.

Case ID	Initial Power (MW)	Final Power (MW)	Final Water Temperature (°C)	Temperature Difference From Design Limit (°C)
35-C1	1.401	2.955	50.2	1.2
38-C1	1.380	2.860	49.0	0.0
40-C1	1.380	2.802	48.4	-0.6

Table 4 Final bay water temperatures, initial and final fuel power values

It is clear from Figure 5 and Table 4 that, as expected, the final water temperature changes with the discharge period selected. The shorter the period, the higher the final water temperature. For the 35 day discharge period, the final water temperature exceeds the design limit of 49 °C by 1.2 °C. For the discharge period of 38 days the final temperature was equal to the design limit and for the discharge period of 40 days the final water temperature was below the design limit by 0.6°C.

A representation of this relationship is presented in Figure 6, which shows the last day final bay water temperature versus the discharge period in days.

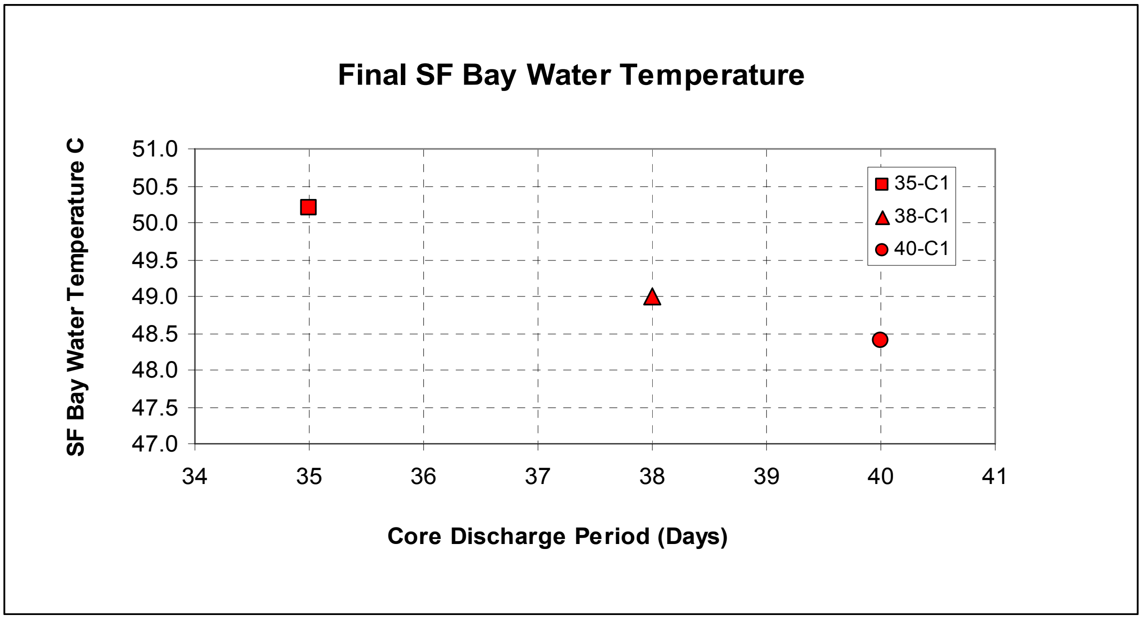

Figure 6 Last day final bay water temperature versus discharge period.

The results and the subsequent analysis, lead to the conclusion that, the discharge of the full core fuel in a period of 35 days was not feasible, as it results in the fuel bay water temperature exceeding the design limit temperature of 49°C. The period of 38 days was marginal and the period of 40 days was within the design limit. Therefore, recommendations were made to improve the system.

Since the differences observed in the final bay water temperature are small relative to the potential variations due to uncertainties in some of the input parameters to the model, a preliminary sensitivity analysis was performed. Results indicate that a variation of 10% in the value of the two most important parameters: HX02 inlet cooling water temperature and the overall heat transfer coefficient U_{hx}, produces an approximate variation of 2°C of the final bay water temperature in each case. This uncertainty should be considered when analyzing the final bay water temperature results.

4.2 Analysis

4.2.1 Heat removal mechanisms

The results reveal that the energy generated by the fuel bundles stored in the bay is removed mainly by heat exchanger HX02 and by water evaporation. The next contributing effect is the sensible energy absorbed by the bay water. Table 5 below shows the percentage of power removed by the different mechanisms in the three cases, including the energy absorbed by the water. The first line in each case is for the last hour of Day 1 and the second line is for the first hour of the last day.

Case	Day & hour	HX02 %	Evapor. %	Convection %	Radiation %	Conduct. %	Absorption %
35-C1	#1, 24	79.8	11.0	0.6	0.9	0.4	8.2
35-C1	#35, 1	90.0	8.2	1.1	1.4	0.5	0.2
38-C1	#1, 24	80.5	11.1	0.6	0.9	0.4	7.4
38-C1	#38, 1	89.7	8.5	1.1	1.4	0.5	0.2
40-C1	#1, 24	80.5	11.1	0.6	1.0	0.4	7.4
40-C1	#40, 1	89.5	8.7	1.1	1.4	0.5	0.2

Table 5 Power removal from bay water (in % contribution) by different mechanisms.

Throughout the discharge period, heat exchanger HX02, evaporation and absorption account for 98.4% to 99% of the power removal.

It can be observed from Table 5 that the contribution of energy absorbed by the water decreases from the range of 7.4 - 8.2% for the first day to 0.2% for the last day. The explanation is that as the discharge period progresses, the higher temperature of the bay water leads to an increased evaporation rate and increased heat transfer rate in the heat exchanger.

5. Conclusions and recommendations

The results obtained for the full core fuel discharge process and the analysis performed lead to the following conclusions:

A) The period of 35 days is not feasible as it exceeds the design limit temperature of 49°C by 1.2°C, reaching a value of 50.2°C.

B) The periods of 38 days and 40 days are tentatively possible as the final bay water temperature is 49°C and 48.4°C respectively.

As discussed in section 4.1 Results, the feasibility of implementing case B will be strongly dependent on the safety margin required by the plant operating procedures and the uncertainty of the solutions. The sensitivity analysis of the results showed an expected variation of 2°C in the final bay water temperature.

Since the heat exchanger is responsible for approximately 90% of the energy removed from the bay, changes in these parameters can have a pronounced effect on the bay water temperature. Therefore, in order to improve the system, the following recommendations were given as options to explore further.

i) Increase water flow from storage bay to the heat exchanger HX02 to the design value.
ii) Increase main heat exchanger cooling flow.
iii) Increase SFSB room ventilation flow.
iv) Evaluate heat exchanger HX01 excess cooling capacity to be utilized.

6. References

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