Study on Improvement of Capacity Expansion of Spent Fuel Pit Cooling System in PWR Nuclear Power Plants

Yupei Piyue

Abstract Based on the analysis of domestic second-generation modified million-kilowatt-class nuclear power-generating mature technology, by means of Flowmaster software calculation and design optimization, cooling capacity of spent fuel pit cooling system is evaluated, improved scheme is put forward to increase cooling capacity of spent fuel pit cooling system, and the design scheme that meets the third-generation nuclear power technology is put forward.

Keywords Cooling capacity · Spent fuel pit cooling system · Spent fuel pit cooling pump · Heat calculation

1 Introduction

It is necessary for nuclear power plants to keep replacing the new nuclear fuel and removing the spent fuel throughout the life cycle. The spent fuel is radioactive and continues to emit decay heat; in particular cases, it is possible to return to critical. Therefore, for the spent fuel, the storage, cooling and other issues need to be resolved. In recent twenty years, with the rapid development of Chinese nuclear energy industry [1], the continuous improvement of nuclear power installed capacity, and the increasing of production and accumulation of spent fuel, the pressure on spent fuel in plant storage occurs directly. On the one hand, many nuclear power plants have taken the spent fuel intensive storage. On the other hand, the time limit for the storage of spent fuel in the plant has been raised from 7–10 to 20 years, which means that the maximum number storage of spent fuel elements in a power plant can reach thousand. Also with the improvement of fuel handling machine, at present nuclear power plant refueling method and refueling period have great changes relative to the original design basis. It changes from original design basis that is one-third of the refueling method to full core refueling method;

Y. Piyue (✉)
China Nuclear Power Engineering CO. LTD, Shenzhen 100840, China
e-mail: yupei@cnpe.cc

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moreover, refueling time shortens from 14 days to 6–8 days, this may cause the cooling capacity of the spent fuel pool cooling system insufficient. At the Fukushima nuclear accident, due to lack of pool cooling water, a plurality of component faces meltdown risk [2]. Fukushima nuclear accident highlights the importance of fuel storage safety and cooling, Chinese nuclear safety agency is also pay attention to this issue during the dialogue. Based on the analysis of the mature technology of the second-generation nuclear power plant, the cooling capacity of the spent fuel cooling system is calculated in operated and building power plant, and the improvement scheme of the cooling capacity of the spent fuel cooling system is put forward in this paper by calculation and analysis. It satisfied the third-generation NPP technology.

2 Calculation of Heat Load of Spent Fuel

For the operated and constructing nuclear power plant, fuel management scheme is usually in accordance with the 12 months period. The heat load of the spent fuel includes the whole reactor core and the heat load of the spent fuel discharged into the pool more than one cycle.

The decay heat of the whole reactor core discharged into the pool after shutdown is shown in Fig. 1.

Assuming that the spent fuel pool is full at 20 years, a year refueling period is 305 days. The 19 batches spent fuel assemblies discharged into the spent fuel pool over a cycle. Considering about the envelope of the calculation results, the spent fuel assemblies in transition cycle are overlooked. The heat load of 19 batches of spent fuel assemblies removed into the spent fuel pool is 1.115 MW. Due to the

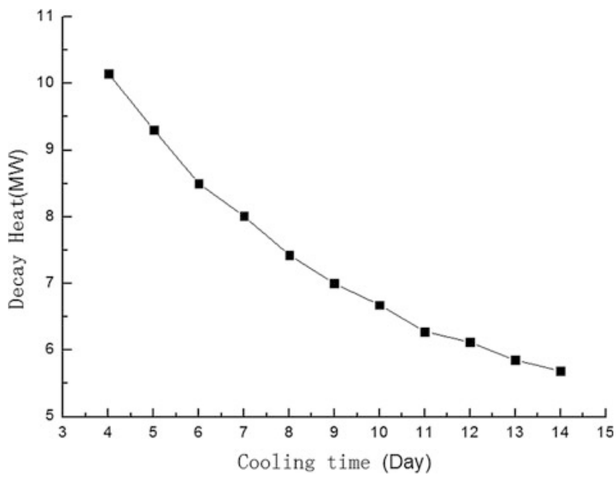

Fig. 1 Core decay heat curve

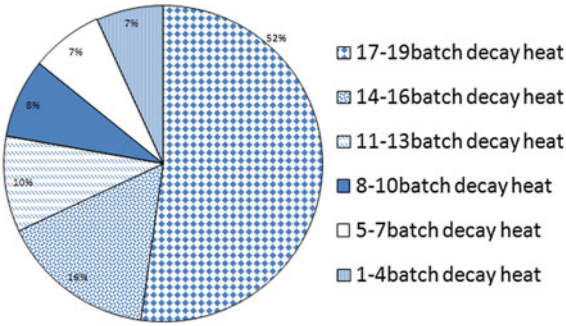

Fig. 2 The proportion of decay heat with different refueling time

Table 1 The decay heat of spent fuel assemblies with different refueling completion time

Time (day)	Heat (MW)	Time (day)	Heat (MW)	Time (day)	Heat (MW)
4	11.265	8	8.545	12	7.235
5	10.4245	9	8.1157	13	6.9685
6	9.615	10	7.795	14	6.805
7	9.1249	11	7.3969		

different batches assemblies suffered different cooling time, the proportion of decay heat with different refueling time is shown in Fig. 2.

From Fig. 2, we can see that the earlier the fuel assemblies are discharged into the pool, the effect of the fuel assemblies on the heat load is lower. Therefore, for the simplified calculation, the thermal load of the spent fuel assemblies has been discharged into the pool is 1.115 MW.

Because the refueling time shortens from 14 days to 6–8 days, it is necessary to analyze heat load with different refueling time, the load including the decay heat of the total core and the spent fuel stored in the pool; the calculation results are shown in Table 1.

3 Cooling Capacity Evaluation of Generation Two Cooling System

The second-generation improved pressurized water reactor spent fuel pool cooling system design condition is that: using 1/3 core reloading method, when the temperature of the component cooling water system is 35 °C, spent fuel pool cooling system with one train operation, component cooling water side with series operation ensure spent fuel pool temperature below 50 °C. The flow diagram is shown in Fig. 3.

However, with refueling technology improvement, the heat load is enhanced caused by the whole core reloading and it is necessary to reevaluate the cooling capacity of the system. The calculation method of heat efficiency of heat exchanger

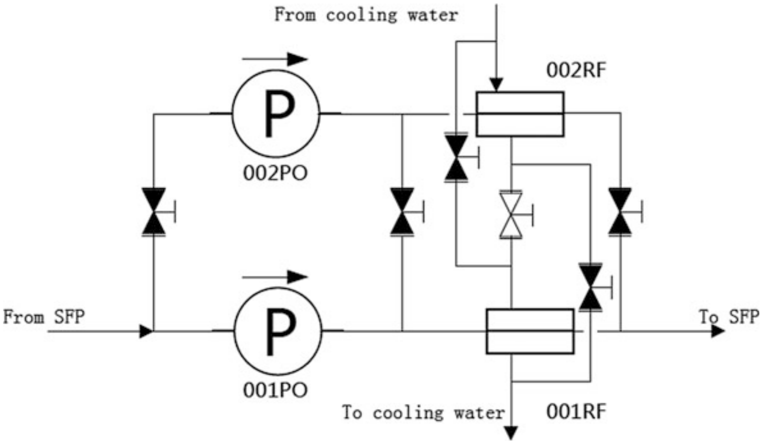

Fig. 3 Concept flow diagram of generation two reactor spent fuel pit cooling system

has 4 kinds; commonly, ε-NTU method and logarithmic mean temperature difference (LMTD) method are used. The heat exchanger of Flowmaster software calculation unit is used ε-NTU method, and specific methods are as follows

$$q = \varepsilon C_{\min}(t_{hi} - t_{ci})* \quad (1)$$

*h-hotside; c-coolside; i-inlet; o-outlet;

$C_{\min}$ Min capacity between two sides;
ε Efficiency of heat transfer;

When the heat loss of the heat exchanger to environment is overlooked, the heat generated by the hot fluid is equal to the heat absorbed by the cold fluid [3]. That is:

$$q = C_c(t_{co} - t_{ci}) \quad (2)$$

$$q = C_h(t_{hi} - t_{ho}) \quad (3)$$

In this paper, the Flowmaster software is used to build the system model, as shown in Fig. 4.

Per heat exchanger spent pool side flow is 542.25 m^3/h, equipment cooling water side flow is 361.5 m^3/h. Ensuring the spent fuel pool temperature is lower than 50 °C, different refueling time corresponds to the equipment cooling water temperature is calculated as shown in Table 2.

According to the above table analysis, in the case of considering the dirt coefficient, if refuel is completed in the seventh days after shutdown, according to the spent fuel pool cooling system operation, the temperature of the water in the equipment cooling water system must be lower than 20 °C, for the requirement that the temperature of spent fuel pool is lower than 50 °C. According to the site of the

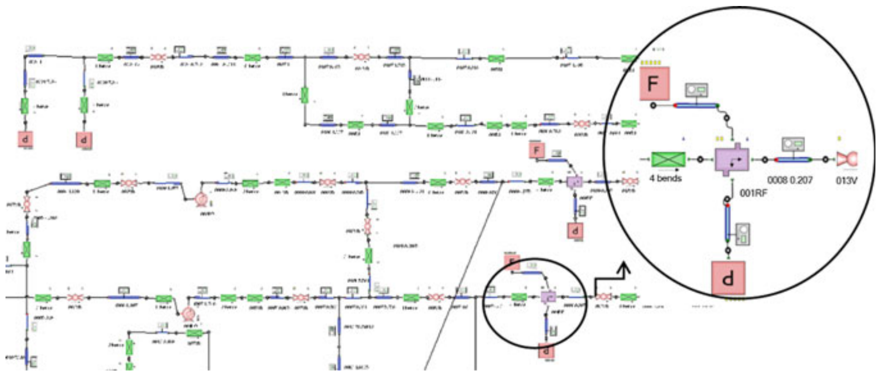

Fig. 4 Spent fuel pit cooling system mode

Table 2 The temperature requirement of component cooling system with different refueling completion time

Day	14	13	12	11	10	9	8	7
Tci (°C)	27	27	26	25	24	23	22	20

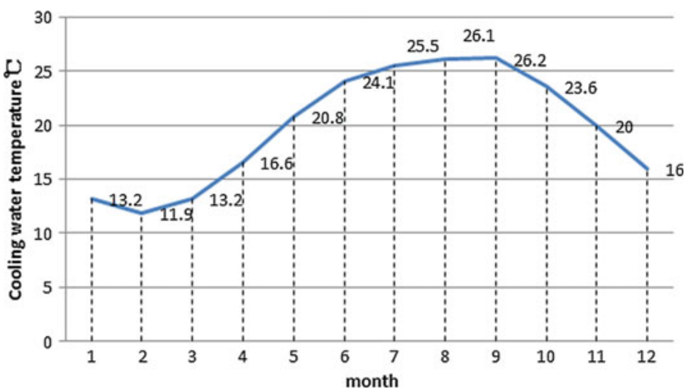

Fig. 5 Sea temperature with different months

nuclear power plant distribution, this requirement in the summer is difficult to meet, as shown in Fig. 5, cooling water temperature for a domestic nuclear power plant.

Therefore, to meet the character that the layout conditions and the progress are fixed in the operated plant and plant in construction, the improved method is supplied to fulfill the requirements of the project schedule and cooling capacity requirements.

4 Analysis of Improved Method in Operation Plant and the Plant Under Construction

4.1 Changing Operation Mode of System in Operated Plant

For operated plant, the main equipment of the spent fuel cooling system includes the spent fuel cooling water pump and the tube shell type heat exchanger: they are arranged in the fuel building, the plant layout is very compact, and increasing the number of equipment and modifying the pipeline will have a great impact on the operation of power plant. Therefore, we propose to modify the operating mode of the spent fuel pool cooling system and the cooling water side to enhance the cooling capacity of the system without modifying the existing lines.

As shown in Fig. 6, as active part of the system such as the pump need to meet the principle of a single failure, only one pump can be put into operation; therefore, only the mode where a pump and two heat exchanger operation are put into operation to improve cooling capacity can be used. Opening the column isolation valve and adjusting the equipment cooling water system pipeline valve from series to parallel both increase the heat exchanger area and reducing the cooling water inlet temperature of each heat exchanger. The per heat exchanger spent pool side flow is 180 m^3/h, equipment cooling water flow is 542.25 m^3/h, and to ensure the spent fuel pool temperature is lower than 50 °C, different refueling time corresponds to the equipment cooling water temperature is calculated, as shown in Table 3.

According to the above analysis: in the case of considering the dirt coefficient, if refuel is completed in the seventh day after shutdown, according to the spent fuel pool cooling system operation, the temperature of the water in the equipment cooling water system must be lower than 20 °C, for the requirement that the temperature of spent fuel pool is lower than 50 °C. According to seawater

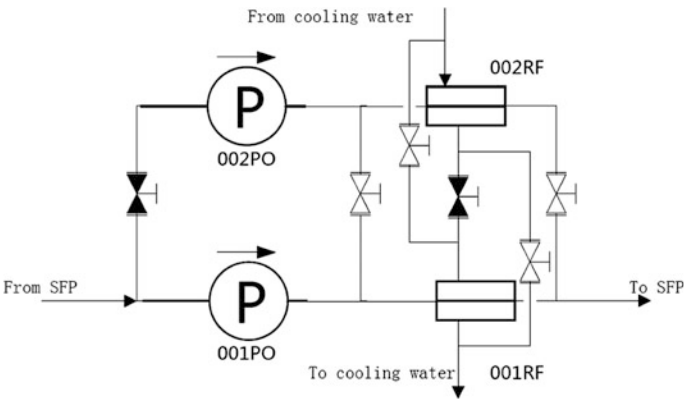

Fig. 6 Concept flow diagram of the amended operation mode

Table 3 The temperature requirement of component cooling system with different refueling completion time after changing the operation mode

Day	14	13	12	11	10	9	8	7
Tci (°C)	29	28	27	26	25	24	23	22

temperature in Fig. 5, when refueling in the summer, it needs to shutdown after 11 days of complete refueling can meet spent pool temperature requirements. The improved scheme can provide a great help to ease the difficulties in the field operation.

4.2 Add a Cooling Pump in Plant Under Construction [4]

As shown in Fig. 7 on the basis of the spent fuel cooling system, a pump (006PO) and the corresponding connecting pipes, instrumentation and valves are added. The new pump type and performance parameters is same as the existing pump (horizontal axial flow pump, the flow is 421.5 m^3/h). During the refueling operation, 006PO-001RF 002PO-002RF are in serve, 001PO is as backup of the two series, cooling water side operated in parallel, same as Sect. 4.1. Per heat exchanger spent pool side flow is 361.5 m^3/h, and equipment cooling water side flow is 542.25 m^3/h. To ensure the spent fuel pool temperature is lower than 50 °C, different refueling time corresponds to the equipment cooling water temperature is calculated and is shown in Table 4.

According to the analysis on the table, spent fuel cooling system through the method adding a pump that three pumps in the two pumps operating in parallel manner, if the refueling is completed in 7 days, equipment cooling water temperature 35 °C will be able to meet the requirement that the spent fuel pool temperature

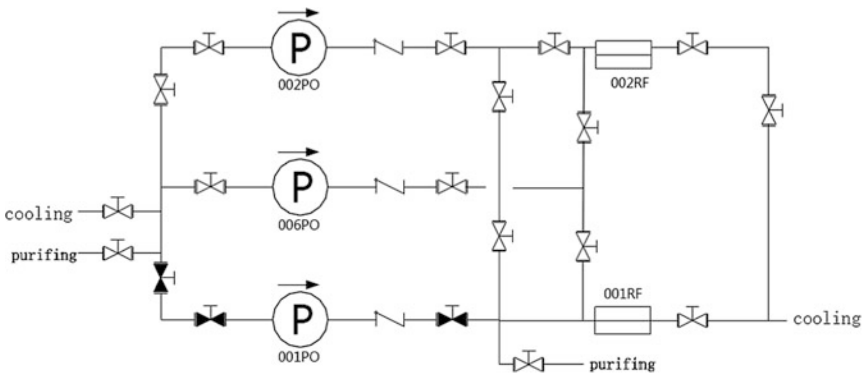

Fig. 7 Concept flow diagram of increasing one pump

Table 4 The temperature requirement of component cooling system with different refueling completion time after increasing one pump

Day	12	11	10	9	8	7	6	5	4
Tci (°C)	35	35	35	35	35	35	34	32	31

is lower than 50 °C. Even the refueling is completed in 4 days, cooling water temperature is lower than 31 °C to meet refueling requirements.

5 Conclusions

(1) In this paper, the heat load of the spent fuel pool is calculated by using Flowmaster, and the cooling water temperature can be used to guide the operation of nuclear power station.
(2) Through evaluation cooling capacity for second-generation improved pressurized water reactor spent fuel pool cooling system, when temperature of cooling water system is below 20 °C, the requirement that refueling after shutdown 7 days can be satisfied.
(3) The mode for operational plant to improve the cooling capacity of the system is by changing the operation mode, and the mode for construction plant is by adding an new cooling pump to improve the cooling capacity of the system and is feasible.

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Author Biography

Yupei (1985–), FM, Engineer, mainly engaged in nuclear power plant system design.