Thermal Safety Analysis of Spent Fuel Pool in Marine Nuclear Power Platform

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Abstract. Based on design criteria of fuel handling equipment and storage installation in land-based nuclear power plants and ship conditions for nuclear-powered vessels, a state classification is developed for the SFP(spent fuel pool) in marine nuclear power platform, including normal condition, accident condition, heel & trim operation condition and relevant acceptance criteria. A calculation model, accuracy verified by steady state calculation before developing limiting accidental analysis, is established to analyse the thermal safety of the SFP, including geometry structure and heat transfer models. Simulation of loss of cooling system and water inventory scenario shows that reject water into the SFP within the first 14 hours after the accident is good enough to bring spent fuels into a safer state. Meanwhile, parameters sensitivity study show that the timing of refilling and coolant flow rate is much more important than the coolant temperature.

1. Introduction
Considering potential user needs and the economic cost, the frequency of return voyage and refueling of a marine nuclear power platform should be controlled as low as reasonably achievable, in a condition that the nuclear safety is ensured. Because of the convenience and accessibility of water source, which are key elements of nuclear safety, a SFP can be designed and constructed to store fuels retired from the reactor. With respect to mechanic system design, a typical SFP consists of spent fuel storage pool (racks included), packing pool and washing pool, just like the land-based NPP(nuclear power plant). With respect to thermal safety analysis, since the operating region switches from land to the sea, complicated sea conditions will cause obvious impact to the system design. Thus, thermal safety study of the SFP in marine nuclear power platform is conducted through the simulation of operating SFP under both normal and abnormal conditions.

2. Summary
The SFP is typically 12 meters or more deep, with the bottom 4.3 meters equipped with storage racks design to hold fuel assemblies removed from the reactor. The water cools the fuel and provides shielding from radiation.[1]

Cooling system is needed for the SFP to bring the decay heat of spent fuel to ultimate heat sinks. Since the heat power is relatively low and the ship space is limited, pumps are used to drive the coolant from the SFP to heat exchanger instead of using passive ways, which usually need giant water tanks. After the heat exchanger cools the coolant, the natural circulation will be established consequently.
In order to guarantee the safety of the SFP, the cooling system should be equipped duplicated, while one set is capable of 100% heat removal.

3. Operation conditions
In normal conditions, the water level and temperature should be maintained in certain range. When any error develops, key thermal parameters should be monitored, including PCT (peak fuel-cladding temperature) and minimum response time from accident initiation to SFP racks exposed to air. Similar to nuclear reactor thermal safety analysis, different operation condition results in different acceptance criteria for a SFP. Referring to design criteria of traditional nuclear power plants and nuclear ships, operation conditions and relevant thermal acceptance criteria of the SFP are drawn as follows:

3.1 Normal conditions
Normal conditions include normal storage condition and normal refueling condition, and relevant acceptance criteria are as follows:
1) water level is higher than minimum limiting value,
2) water temperature is lower than 60°C, even if only one set cooling system is operational.

3.2 Accident conditions
Accident conditions can be divided as two categories: a) simply loss of cooling system, b) loss of both cooling system and water inventory. [2]
As for the former, the water level and water average temperature should be monitored, and relevant criteria are as follows:
1) SFP racks should not be exposed to air,
2) water average temperature is lower than 80°C,
3) minimum response time is longer than 72 hours.
As for the latter, the PCT should be analyzed to avoid severe oxidation of zirconium (PCT > 1088K) or failure of fuel rod (PCT > 1477K), besides the water level and water average temperature. Relevant acceptance criteria are as follows:
1) SFP racks should not be exposed to air,
2) water average temperature is lower than 95°C,
3) minimum response time is longer than 72 hours,
4) PCT value is lower than 1477 K[2].
Loss of both cooling system and SFP water storage is chosen as the limiting accident scenario.

3.3 Sea environmental conditions
Different from land-based NPP, the marine nuclear power platform is barge-mounted. Thus, the ship has far-reaching impact on the SFP. The major characteristics of a ship include buoyance, stability, damaged stability, sea-keeping performance and etc. For the SFP, the initial stability & stability at large angle, and roll & pitch will impact the natural circulation process and the accuracy of water level monitoring.

![Fig. 1 Simplified Model of Heel & Trim Operation Condition](image-url)
A simplified model of heel & trim operation condition is established as shown in figure 1. The distance from top of racks to top of pool is defined as the maximum water layer thickness. Suppose any side of the SFP run off the straight, as angle $\phi$, the maximum water layer thickness then changed to:

$$L_{\text{max}} = (L_{\text{max}} - (a + b) \cdot \tan \phi) \cdot \cos \phi \quad (1)$$

Maximum water volume changed to:

$$V_{\text{max}} = (A \cdot L_{\text{max}} = (A \cdot \cos \phi) \cdot [L - (a + b) \cdot \tan \phi] \cdot \cos \phi \quad (2)$$

$$= V_{\text{max}} \cdot \frac{L - (a + b) \cdot \tan \phi}{\cos^2 \phi}$$

Where, $a$ is rack width in side view; $b$ is the distance from rack wall to pool wall.

The SFP may lose water inventory under heel & trim conditions if coping strategy is out of plan. Similarly, periodic change will appear under roll & pitch conditions.

Compared with normal operation conditions, the influence under sea conditions focus on heat exchange effect and water level limiting value. Correction factor or penalty factor can be induced to handle the heat exchange effect, while recalculation can be conducted to obtain the normal level and low water level to get a new limiting value under sea conditions.

The design basis angles used in sea conditions are shown in table 1.[3]

| Condition | Machinery and Systems providing operation of | Main and Auxiliary Machinery | Emergence Machinery and Equipment |
|-----------|---------------------------------------------|-----------------------------|----------------------------------|
| Long-term heal | 30° | 15° | 22.5° |
| Roll | 45° | 22.5° | 22.5° |
| Long-term trim | 10° | 5° | 10° |
| Pitch | 15° | 7° | 10° |

4. Calculation models

4.1 Geometry models
From the bottom up, the SFP is composed of rack bottom water space, rack region, rack top mixture space and the cabinet. As typical open-large tank structure, down-comer and up-leg are established to simulate natural circulation phenomenon in the pool. The node diagram is shown in figure 2.
Since number of nodes is limited and most spent fuels are more or less the same in heat power, approximate models are used in rack region, which are shown in figure 3 and 4. Because region E has higher decay heat, exclusive control volume and heat structure are used as hot channel, while the rest are handled as average channels. In hot channel, E1 region, namely hot rod, stands for hottest rack cell, and the rest are lumped.

**4.2 Heat transfer model**
According to the geometry model, the materials used in heat transfer models are processed approximately, which is shown in figure 5. Rack walls facing outside are simulated as rack walls, while rack walls facing inside are lumped into inside materials. Multiple fuel boxes and internal fuel assemblies are lumped into one equivalent fuel box and relevant assembly.
For fuel assembly, the ASB9-2 formula, published by USA Nuclear Regulatory Commission is used to calculate the decay heat:

\[
\frac{P}{P_0}(T_0, T_e) = (1 + K) \frac{P}{P_0}(\infty, T_e) - \frac{P}{P_0}(\infty, T_0 + T_e)
\]

(3)

Where, \(P_0\) is initial decay heat power; \(T_0\) is fuel radiation duration in reactor; \(T_e\) is calculation time after the fuel is removed from reactor; \(K\) is uncertainty factor; the last two items are decay heat power of key nuclides.

4.3 Steady-state calculation

For SFP cooling system, time-dependent flow rate is used as boundary condition instead of simulating circulation pump and heat exchanger to improve the calculation efficiency without reducing the accuracy. Results show that the deviation between calculation values and design values are within 0.5% after steady-state calculation, thus the calculation model is accurate enough to simulate accident process.

5. Typical accident analysis

5.1 Before racks exposed to air

After loss of cooling system, natural circulation is established to remove the decay heat in the SFP. The time of the rack exposed to air is decided by SFP water inventory and fuel decay heat power. Accident process consists of two major phase: a) pool water is heated to boiling; b) heat is removed through evaporation afterwards. Table 2 shows the process, while decay heat power used in accident is five times as normal values to guarantee the conservation of calculation.

\[
\int_{t=0}^{t=\infty} P \, dt = c \cdot \rho V \cdot \Delta T
\]

(4)

\[
\int_{t=0}^{t=\infty} P \, dt = \rho V \cdot r
\]

(5)

Where, \(P\) is decay heat, \(t\) is time, \(c\) is specific heat capacity, \(\rho\) is density, \(V\) is volume, \(T\) is temperature, and \(r\) is latent heat of vaporization.

| Process          | Normal condition | Accident condition |
|------------------|------------------|--------------------|
| ~50°C            | 0 s              | 0 s                |
| 50°C–80°C        | 45.7 hours       | 12.5 hours         |
| 50°C–95°C        | 91.5 hours       | 24.9 hours         |
5.2 After racks exposed to air
Exposed to air, the heat transfer deteriorates in rapid fashion. Figure 6 and 7 show the accident processes.

![Fig. 6 Trend Chart of PCT Value](image)

![Fig. 7 Trend Chart of Rack Water Level](image)

5.3 Parameter sensitivity analysis
Sensitivity analysis is conducted to account for the effect in different injection timing, injection flow rate and injection water temperature.
Referring to figure 8, if water is injected within 14 hours after accident initiated, the PCT will stay within design value, while later injection will cause fuel overheated even if the cooling system can be re-established.

Referring to figure 9, different injection flow rates will lead to different fuel temperature. If flow rate is at half of the design value, the fuel will be overheated.

Referring to figure 10, PCT values after injection at different temperature are more or less the same, and the difference is not obvious overall.
6. Conclusions

1) SFP operating conditions and relevant thermal acceptance criteria are given in this paper. The analysis model in heel & trim condition is relatively simplified, and further study is needed.

2) SFP calculation models, consists of both mechanism formula and computer code model, are established to simulate the steady-state and accident process. It is concluded that water should be injected within 14 hours after loss of both cooling system and water inventory, to avoid the fuel-cladding temperature beyond limiting value.

3) Based on sensitivity study, it is concluded that the injection timing and injection flow have great influence on fuel-cladding temperature.

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