

## **CALCULATION-BASED DEMONSTRATION OF THE DETERMINISTIC SAFETY ANALYSIS OF A FLOATING POWER UNIT BASED ON A DESIGN-BASIS ACCIDENT SEQUENCE**

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### **Abstract:**

The paper presents a deterministic safety analysis of a floating power unit (FPU) using a design-basis accident sequence involving a complete station blackout and loss of core cooling following an earthquake and tsunami. An empirical decay-heat relationship and the heat-conduction equation for a fuel rod are used, with the latter solved by the Laplace integral-transform method, to estimate the time-dependent fuel centerline temperature. For the input assumptions adopted in the calculation, the fuel temperature reaches the assumed limiting value of 600 °C after approximately 1495 s (about 25 min) without cooling. This result provides an estimate of the time window available for restoring power or initiating alternative residual-heat-removal measures. The paper also discusses key safety measures for protecting floating power units against external hazards and complete loss of electrical power.

**Keywords:** Floating Power Unit, Deterministic Safety Analysis, Design-Basis Accident, Decay Heat, Fuel Thermal Conductivity, Station Blackout, Passive Safety Systems

### **Introduction**

A floating power unit (FPU) belongs to a specific class of nuclear power installations whose safety is determined not only by the characteristics of the reactor system, but also by the marine environment, the floating platform, electrical power systems, and residual heat removal systems [1]. For such facilities, external natural hazards, including earthquakes, tsunamis, storm loads, and associated flooding, must be taken into account [2]. International nuclear safety requirements provide for systematic identification of external hazards and assessment of their impact on safety functions [3]. The Fukushima Daiichi accident demonstrated that the combination of a strong earthquake, tsunami, and subsequent loss of electrical power can result in the simultaneous loss of several safety functions. On 11 March 2011, following the earthquake, the reactors at the affected units automatically shut down, however, the subsequent tsunami flooded equipment and resulted in the loss of emergency power supply and cooling. According to the IAEA, the water level at the Fukushima Daiichi site reached approximately 14–15 m, after which Units 1–5 lost alternating current power, while at several units part of the direct-current power supply was also lost shortly thereafter [4]. This experience demonstrates

the need to consider a complete loss of electrical power as one of the key scenarios in the deterministic safety analysis of an FPU.

## Materials and Method

Based on the accident sequence considered, an assessment was made of the time available for restoring electrical power or implementing alternative heat removal following a complete station blackout. The main calculation criterion is the fuel reaching the temperature value specified as a limiting value in the calculation model. The decay-heat load after reactor shutdown is determined using an empirical relationship [5]. This approach is consistent with the general principle that decay heat following reactor shutdown must be taken into account in the analysis of accident conditions and in the design of residual heat removal systems [6].

$$\frac{Q_{\text{ock}}(\tau)}{Q_0} = 7.5 \cdot 10^{-2} \cdot [\tau^{-0.2} - (T_0 + \tau)^{-0.2}], \quad (1)$$

where  $T_0$  — is the reactor operating time before shutdown,  $\tau$  — is the time after shutdown, and  $Q_0$  — is the reactor power before shutdown at which the reactor operated for the time  $T_0$ . The formula is applicable over the time interval from 10 to 100,000 s  $\pm 25\%$ .

The thermal state of the fuel pellet is described using the heat-conduction equation for a cylindrical fuel element [7]. The calculation model accounts for the thermophysical properties of the fuel, fuel-rod geometry, coolant temperature, volumetric heat generation, and heat-transfer coefficient [8]. The calculation uses an average value of the specific heat capacity of the fuel, which is a simplification and should be refined in further analysis by accounting for the temperature dependence of the material properties.

$$\left\{ (c_p \cdot \rho) \frac{\partial T(r, \tau)}{\partial \tau} = \lambda_{\text{top}} \cdot \frac{1}{r} \cdot \frac{\partial}{\partial r} \left( r \frac{\partial T(r, \tau)}{\partial r} \right) + Q_{\text{ock}}(\tau), \quad 0 < r < r_1 \right.$$

$$T(r, 0) = T_{\text{ж}} + \frac{q_{v0} r_1}{2 \cdot k_1} + \frac{q_{v0} r_1^2}{4 \cdot \lambda_{\text{top}}} \left( 1 - \frac{r^2}{r_1^2} \right), \quad 0 \leq r \leq r_1 \quad (2)$$

where  $c_p$  — is the specific heat capacity of the fuel,  $\rho$  — is the fuel density,  $\lambda_{\text{т}}$  — is the thermal conductivity,  $r_1$  — is the fuel-pellet radius,  $T_{\text{ж}}$  — is the coolant temperature,  $q_{v0}$  — is the average volumetric heat generation in the core, and  $k_1$  — is the heat-transfer coefficient.

$$k_1 = \frac{1}{R_{\text{т}} + \frac{\delta_{\text{ог}}}{\lambda_{\text{ог}}} + \frac{1}{\alpha_1}}, \quad (3)$$

where  $R_{\text{т}}$  — is the thermal resistance of the fuel pellet,  $\delta_{\text{ог}}$  — is the fuel-cladding thickness,  $\lambda_{\text{ог}}$  — is the thermal conductivity of the fuel cladding, and  $\alpha_1$  — is the heat-transfer coefficient. In the calculations, the dependence of the fuel specific heat capacity  $c_p$  on temperature should be taken into account, for simplicity, its average value is used in this work.

At the heat-transfer boundary between the fuel rod and the coolant, a boundary condition is specified that relates the heat flux to the heat-transfer coefficient. When normal cooling is disrupted, the heat-transfer coefficient changes with time, therefore, this variation is represented in the model by a separate relationship.

$$\lambda_{\text{top}} \frac{\partial T(r_1, \tau)}{\partial r} = k_2 \cdot [T(r_1, \tau) - T_{\text{ж}}], \quad \tau > 0 \quad (4)$$

where  $k_2$  — is the heat-transfer coefficient (6.1.4) under the specified condition and  $\alpha_2$  — is the heat-transfer coefficient when the intensity of heat removal from the fuel-rod surface changes.

The Laplace integral-transform method is used to obtain an analytical solution to the heat-conduction problem. Similar heat-conduction problems in cylindrical coordinates are considered in classical works

on the mathematical theory of heat conduction [9]. The resulting solution makes it possible to estimate the time-dependent temperature at the centerline of the fuel pellet.

$$\theta(R, F_0) = \sum_{n=1}^{\infty} \left[ \frac{1}{2} \cdot \left( \frac{1}{Bi_0} - \frac{1}{Bi} \right) + \frac{1}{\mu_n^2} + \int_0^{F_0} \frac{q_v(F_0)}{q_{v0}} \cdot \exp \exp (\mu_n^2 F_0) dF_0 \right] \cdot A_n \cdot J_0(\mu_n R) \cdot \exp \exp (-\mu_n^2 F_0), \quad (5)$$

where  $\theta(R, F_0) = \frac{t(r, \tau) - t_{ж}}{\frac{q_{v0} r_1^2}{\lambda_T}}$  — is the dimensionless temperature,

$R = \frac{r}{r_1}$  — is the dimensionless radius,  $Bi_0 = \frac{k_1 r_1}{\lambda_T}$ ,  $Bi = \frac{k_2 r_1}{\lambda_T}$  — is the Biot number, and  $F_0 = \frac{\alpha_T \tau}{r_1^2}$  is

the heat-transfer surface.  $A_n = 2 \cdot \frac{J_1(\mu_n)}{\mu_n [J_0^2(\mu_n) + J_1^2(\mu_n)]}$ ,

$\mu_n$  — are the roots of the characteristic equation,  $\frac{J_0(\mu)}{J_1(\mu)} = \frac{\mu}{Bi}$ ,  $\alpha_T$  — is the thermal diffusivity of the fuel.

When the feedwater pumps are shut down, the amount of liquid coolants gradually decreases and the heat-transfer conditions at the fuel-rod surface change. Within the adopted model, the heat-transfer coefficient is approximated by an exponential dependence. The characteristic time for the change in the heat-transfer coefficient is determined from the energy balance for coolant evaporation.

$$\alpha(\tau) = \alpha_0 \exp \exp \left( -\frac{\tau}{T} \right), \quad (6)$$

where  $T$  — is the characteristic time for the change in the heat-transfer coefficient, it is the time over which the amount of coolant decreases by a factor of  $e$  due to evaporation. The value of  $T$  is as follows:

$$c_p^{T/H} \cdot m_{T/H} \cdot (t_{кип} - t) + r \cdot m_{T/H} \cdot \left( 1 - \frac{1}{e} \right) = V_{a3} \int_0^T q_v dt, \quad (7)$$

where  $r$  — is the specific latent heat of vaporization, and  $c_p^{T/H}$ ,  $m_{T/H}$  — are the specific heat capacity and mass of the coolant, respectively,  $t_{кип}$  — is the coolant boiling temperature,  $V_{a3}$  — is the core volume, and  $q_v$  — is the average volumetric decay-heat generation.

## Results and Discussion

The calculation gives a characteristic time for the change in the heat-transfer coefficient of  $T = 178.6$  s. Using Equation (5), the time dependence of the temperature at the centerline of the fuel pellet was calculated. For the adopted input data and assuming that the emergency protection system does not provide any additional reduction in the thermal load, the fuel temperature reaches the limiting value of 600 °C specified in the calculation model after 1495 s, i.e. approximately 25 min. This value should not be interpreted as a universal regulatory temperature limit for nuclear fuel, it is a criterion specific to the present calculation model. For design and licensing analyses, the acceptance criteria established for the specific reactor installation, qualified fuel models, and conservative treatment of uncertainties should be used [10].

It should be noted that the obtained value of 1495 s is a result of a simplified thermal model. The calculation does not replace a full-scale thermal-hydraulic analysis and does not include detailed modelling of two-phase flow, thermo-mechanical behaviour of the fuel and cladding, chemical interaction between the cladding and steam, spatial distribution of heat generation, individual system failures, or uncertainties in the input parameters [11]. Therefore, the result should be used as a preliminary estimate of the available time window for developing a more detailed model.

## Safety Measures

The scenario considered demonstrates the need for a combination of several independent protection measures. First, the design of an FPU should account for seismic and hydrological hazards, including earthquakes [12], tsunamis, storm surges, and associated effects on equipment and safety systems [13].

Second, physical protection and redundancy of power sources should be ensured, together with spatial separation of equipment whose failure could be caused by a common external event [14]. Third, in the event of a complete station blackout, passive or otherwise independent means of residual heat removal capable of operating without external electrical power should be available. For an FPU, structural measures ensuring the stability of the floating platform and preservation of safety functions under wave action, flooding, and other marine hazards are also of particular importance.

In future work, the calculation should be expanded to include analysis of passive-system failures, loss of the ultimate heat sink, loss of direct-current power, combinations of external hazards, and progression to conditions beyond the design basis [15]. Such an approach will make it possible to determine additional time margins and verify the absence of abrupt transitions to unsafe states.

The calculation-based demonstration shows that, under a complete loss of electrical power and cessation of effective heat removal, the fuel temperature increases due to continuing decay heat generation. In the adopted model, the characteristic time for the change in the heat-transfer coefficient was 178.6 s, while the specified limiting temperature of 600 °C was reached after 1495 s, corresponding to approximately 25 min. Thus, for the present calculation model, 25 min may be regarded as an indicative time window during which electrical power must be restored or alternative residual heat removal must be provided.

The result confirms the importance of passive and diversified safety systems for floating power units. Particular attention should be paid to protection against external hazards—earthquakes, tsunamis, and flooding—redundancy and physical separation of power sources, preservation of the ultimate heat sink, and the ability to maintain long-term cooldown in the absence of external electrical power. These areas are consistent with the general principles of deterministic safety analysis and the requirements for maintaining fundamental safety functions.

To move from a preliminary assessment to a calculation suitable for a safety case, the input parameters of the specific reactor and FPU should be refined, qualified thermal-hydraulic and fuel models should be used, uncertainties should be analysed, and failure scenarios involving passive systems should be evaluated. The next stage should include coupled thermal-hydraulic and fuel-behaviour analysis with determination of acceptance criteria and safety margins for a complete station blackout.

## Conclusion

An assessment-based deterministic safety analysis of a floating power unit was performed for a complete station blackout and loss of core cooling caused by earthquake and tsunami effects.

Based on the decay-heat calculation and solution of the heat-conduction equation for the fuel pellet, the characteristic time for the change in heat transfer was determined to be 178.6 s, while the fuel temperature reached the limiting value of 600 °C adopted in the calculation after approximately 1495 s (about 25 min). The result provides an indicative time margin for restoring electrical power or implementing alternative residual heat removal.

The analysis shows that preventing accident progression requires a combination of seismic resistance and tsunami protection, reliable emergency power supply, and passive cooling systems capable of operating during a complete station blackout.

The value of 1495 s is an assessment result obtained from the adopted calculation model. A final safety assessment requires detailed thermal-hydraulic calculations that account for the characteristics of the specific reactor installation and the performance of its safety systems.

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