Natural Circulation Level Optimization and the Effect during ULOF Accident in the SPINNOR Reactor

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Abstract. Natural circulation level optimization and the effect during loss of flow accident in the 250 MWt MOX fuelled small Pb-Bi Cooled non-refuelling nuclear reactors (SPINNOR) have been performed. The simulation begin with steady state calculation of neutron flux, power distribution and temperature distribution accros the core, hot and cool pool, and also steam generator. Then the accident started by the loss of pumping power. The sequence is then the transient flow calculation across the core, the core temperature distribution, hot pool and cool pool fluid dynamic calculation and temperature change simulation, and the transient flow and temperature calculation across the steam generator. Then the reactivity feedback calculation is conducted, followed by kinetic calculation, and then the sequence repeated. The results show that the SPINNOR reactor has inherent safety capability against this accident.

Keywords: natural circulation, ULOF accident, SPINNOR reactor
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INTRODUCTION

Safety aspect is the most important part of designing a nuclear reactor. After the Chernobyl Accident and Tree Mile Island II, there was a change of paradigm in the design and reactor safety. Fourth-generation nuclear reactors must have inherent safety criteria.

The SPINNOR (Small Power Reactor, Indonesia, No On-Site Refuelling) are concepts of small lead-bismuth cooled nuclear power reactors with fast neutron spectrum that could be operated for more than 15 years without on-site refuelling. They are based on the concept of a long-life core reactor developed in Indonesia since early 1990 in collaboration with the Research Laboratory for Nuclear Reactors of The Tokyo Institute of Technology [2]. The reactor has been used in relatively isolated areas, small island and operated to the end of its life without refueling or fuel shuffling. Some important characteristics required are easy operation, easy maintenance, transportability, inherent/passive safety and nuclear proliferation resistance [2].

During ULOF accident, natural circulation level, coolant-fuel temperature difference, and reactivity feedback play important role to reach inherent safety capabilities. The paper discuss the optimization natural circulation and the effect during ULOF accident in the SPINNOR reactor.

COMPUTATIONAL METHOD

The model and computational aspect of accident analysis performed in this research are mainly based on the method described in [8].The general calculations are neutronic, thermal hydraulic, and feedback calculations.

Calculation of distribution fluxs neutron

If the reactor is evaluated in a steady state and the material core region is assumed homogen, the diffusion equation can is writen as [6] :

$$-\nabla, D_g \nabla \varphi_g(r) + \Sigma_{rg}\, \varphi_g(r) = \frac{x_g}{k_{eff}} \sum_{g^1=1}^{G} \nu \Sigma_{fg^1}\, \varphi_{g^1}(r) + \sum_{g^1=1}^{G} \Sigma_{sg^1\to g}\, \varphi_{g^1}(r) \qquad (1)$$

The neutronic calculation yields neutron flux distribution and multiplication factor (K_{eff}). In adiabatic model, the amplitude function *p(t)* is satisfied by the following equations [8]:

$$\frac{dp(t)}{dt} = \left[\frac{\rho(t)-\beta}{\Lambda}\right] p(t) + \sum_{i=1}^{6} \lambda_i C_i \qquad (2)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} p(t) - \lambda_i C_i(t) \qquad (3)$$

Thermal Hydraulic Calculation

Calculation of thermal hydraulic covers calculation on distribution of temperature in all parts of reactor reactor core and steam generator (SG) that is fuel temperature, coolant temperature and temperature cladding and gap, so pressure in reactor and all coolant circulation aspects in the reactor.

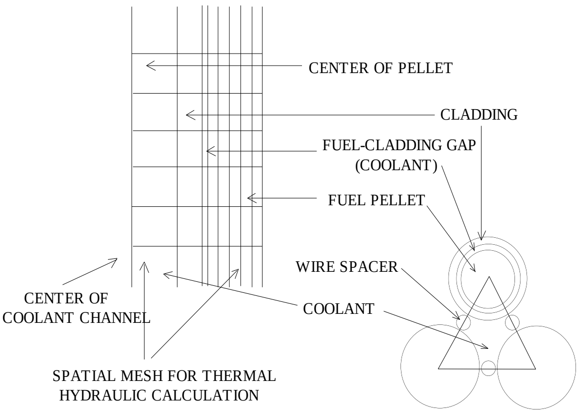

FIGURE 1. The model for thermo-hydraulic calculation

Figure 1. shows thermal hydraulic model in this calculations. Reactor is divided into concentric ring, where the cross-flow between two adjacent rings is assumed zero. For coolant, calculation uses mass and energy conservation equation:

$$\rho c_p \frac{\partial T}{\partial t} - w c_p \frac{\partial T}{\partial z} = Q''' \qquad (4)$$

Pressure drop calculation is solved by applying momentum conservation equation.

$$\frac{\partial G}{\partial t} = -\frac{\partial P}{\partial z} - \frac{\partial}{\partial z}\frac{G^2}{\rho} - \frac{fG^2}{2D_e\rho} - \rho g \qquad (5)$$

Hot pool and Cool Pool

During this analysis, average temperature in both hot pool and cool pool are used. For hot pool, the following equation used :

$$\begin{aligned} T_{hp} &= [(h_{hp}A_{hp}\rho_{hp} - G_{psg}\Delta t)C_{php}T_{hp}^{old} \\ &+G_{core}\Delta t C_{pcore}T_{core}]/[(h_{hp}A_{hp}\rho_{hp} - \\ &G_{psg}\Delta t + G_{core}\Delta t)C_{php}] \end{aligned} \qquad (6)$$

$$\begin{aligned} h_{hp}^{i+1} &= (h_{hp}^{j}A_{hp}\rho_{hp} + (G_{psg} - G_{core}) \\ &\Delta t)/(\rho_{hp}A_{hp}) \end{aligned} \qquad (7)$$

T_{hp} = Temperature of hot pool
h_{hp} = Height of hot pool
A_{hp} = Area of hot pool
ρ_{hp} = Mass density of hot pool
G_{psg} = Total mass flow rate in primary SG
C_{php} = Specific heat of hot pool
G_{core} = Total mass flow rate of core
C_{pcore} = Specific heat of core

Similarly the temperature cool pool is solved using the following equations:

$$\begin{aligned} T_{cp} &= [(h_{cp}A_{cp}\rho_{cp} - G_{psg}\Delta t)C_{pcp}T_{cp}^{old} \\ &+G_{core}\Delta t C_{pcore}T_{core}]/[(h_{cp}A_{cp}\rho_{cp} - \\ &G_{psg}\Delta t + G_{core}\Delta t)C_{pcp}] \end{aligned} \qquad (8)$$

$$\begin{aligned} h_{cp}^{i+1} &= (h_{cp}^{j}A_{cp}\rho_{cp} + (G_{psg} - G_{core}) \\ &\Delta t)/(\rho_{cp}A_{cp}) \end{aligned} \qquad (9)$$

T_{cp} = Temperature of cool pool
h_{cp} = Height of cool pool
A_{cp} = Area of cool pool
ρ_{cp} = Mass density of cool pool

Feedback Calculations

ρ(t) in Eq. (3) is the summation of external reactivity and feedback reactivity. Feedback reactivity included Doppler, axial expansion, radial expansion, and void reactivity.

Feedback reactivity is the effect of the core temperature *T* [6]. Can be express as follow the temperature coefficient of reactivity:

$$\alpha \equiv \frac{\partial \rho}{\partial T} \qquad (11)$$

Where α is a negative value that is inserted in calculation since increasing temperature will cause decreasing ρ. T is average temperature in side the core (fuel and coolant).

General Calculation Algorithm

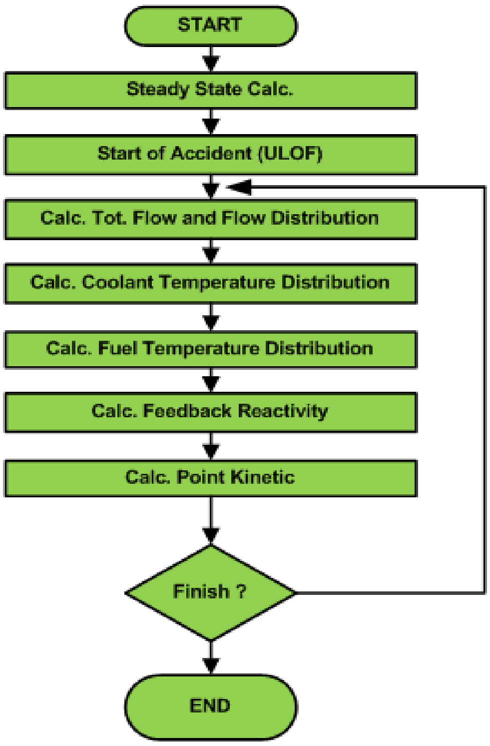

FIGURE 2. Calculational flow diagram

For the first step, the steady state neutronic and the thermal-hydraulic calculation are performed, then the accident condition are taken.The ULOF accident is started by failure of the primary pumping system. Temperature in the core will be changed depend on how much flow rate has been inserted. The change core temperature will change average hot pool temperature and steam generator temperature. In this research, reactivity external of reactor is assumed constant, then heat will be transferred to water circulation in steam generator.

RESULT AND DISCUSSION

A schematic view of the system being analyzed is shown in Fig.3. The overall system includes a reactor core, hot pool, cool pool, steam generator and pump. The intermediate heat exchanger (IHX) is eliminated, and heat from primary coolant system is transferred directly to the steam-water loop through the steam generator. The coolant flows trough the core, removes heat generated in the core, and then flows up to the hot pool. From the hot pool, coolant flows into the steam generator, transferring the heat into the steam-water loop, and then goes down to the cool pool. From the cool pool the coolant is pumped back to the core.

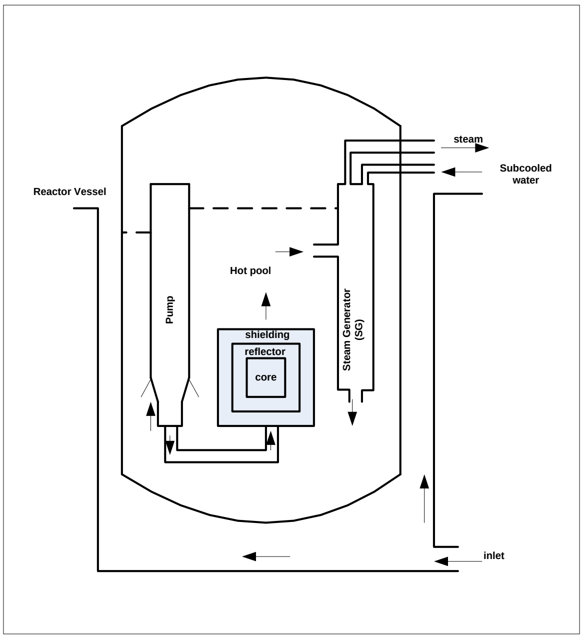

FIGURE 3. Overview of the SPINNOR reactor

TABLE 1. Main reactor design parameter

No	Parameter	Value
1	Reactor Power	250 MWth
2	Fuel	UO_2- PUO_2
3	Shielding Material	B4C
4	Coolant	Pb-Bi
5	Pin/Pitch diameter	1.2 cm
6	Pin diameter	1.0 cm
7	Cladding Thickness	0.8 cm
8	Total Flowrate	8000 kg/s

Table 1. shows the main reactor design parameter. In this section, calculation results including power reactor, reactivity feedback, max of fuel and coolant temperature and total flowrate, will be discussed.

Fig.4 shows the core flow and steam generator primary side flow pattern change during ULOF accident. As reactors loose pumping power at t=0, the core flow rate decreases significantly and goes to the natural circulation level.

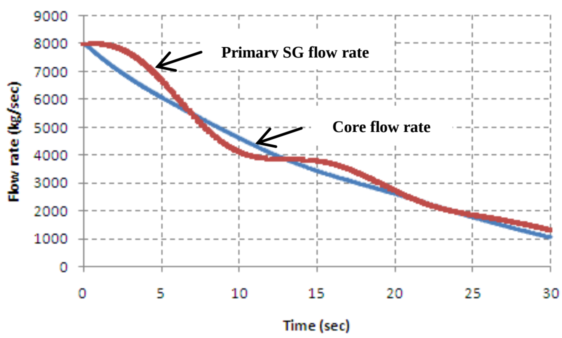

FIGURE 4. Flow change during ULOF accident

Natural circulation can drive the coolant circulation, and the flow rate remain about 20-30% of normal value at the latter part of the accident. There is a small oscillation of the total coolant flow rate in the primary side of the steam generator. which are mainly caused by the fact that flow rate in the core and primary side SG in the absence of primary pumping is mainly controlled by level and temperature of coolant in the hot and cool pool which in turn depend on the flowrate of the core and primary SG.

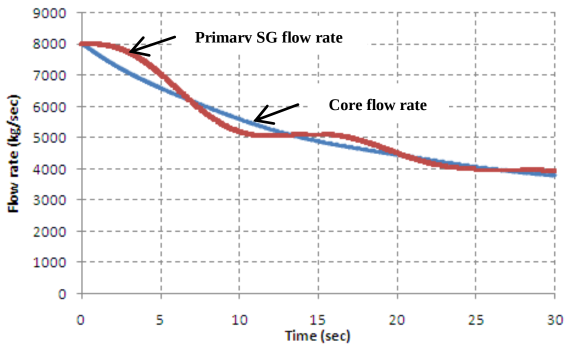

FIGURE 5. Primary SG flow rate change during ULOF accident with up chimney level

Fig.5 shows the pattern of change core flow rate and primary SG flow rate after optimizing the pin pitch, pin diameter and height the chimney. This optimization contributes to increase natural circulation level. After optimization, the natural circulation is about 45% of the initial flow rate.

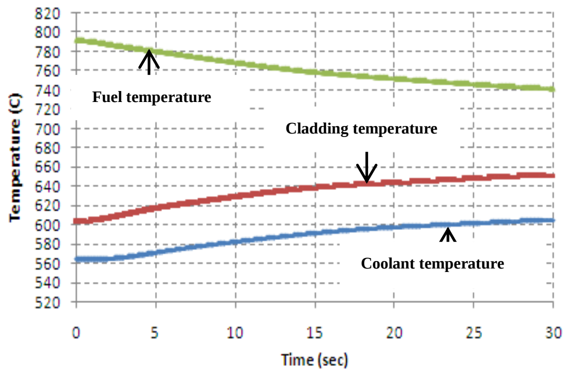

FIGURE 6. Hot spot temperature during ULOF accident

Fig.6 show temperature of fuel, cladding and coolant. The maximum of fuel temperature, cladding temperature and coolant temperature, respectively 791,61 ^{o}C, 603,32 ^{o}C, and 564,22 ^{o}C. Fuel, cladding and coolant temperature are still below the maximum temperature limits.

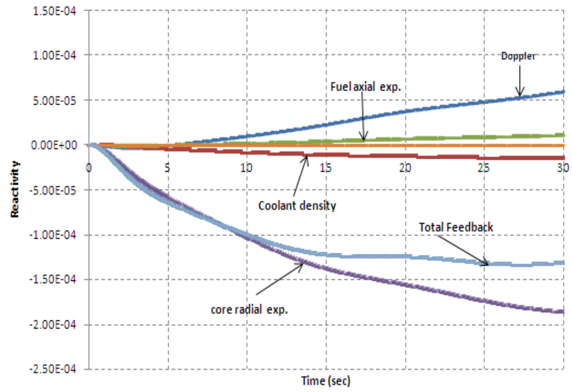

FIGURE 7. Reactivity component change during ULOF accident

Fig. 7 shows the reactivity component change during ULOF accident.The most important feedback in this accident is core radial expansion. At the beginning stage of the accident, the Doppler component is negative but then move to positive value near the asymptotic condition. At the asymptotic condition, a new equilibrium condition occurs at reduced power level (40% of nominal power) balancing the natural circulation level. Doppler reactivity feedback, core radial expansion reactivity feedback, coolant density feedback and axial expansion feedback, all give negative feedback contribution at the beginning of accident sequence to force the power down.

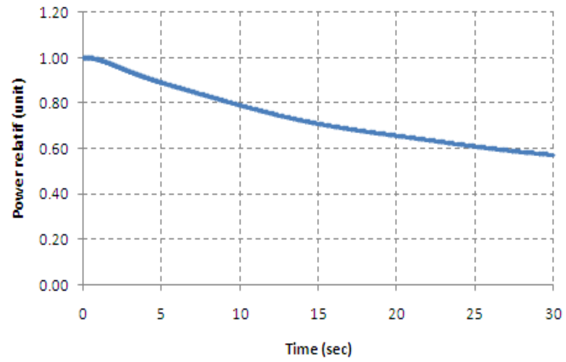

FIGURE 8. Power change during ULOF accident

Fig. 8 shows the reactor power change pattern during accident. The power increase at the beginning of the accident but then decrease and goes towards a new stable condition which is about 45% of initial power.

CONCLUSION

The conclusions are summarized as follows,

1. In general, the reactor can survive the ULOF accident inherently.

2. The relatively high natural circulation component contributes important factor to keep the reactor survive ULOF accident.
3. To exchange from the natural circulation level, optimization can be done by adjusting the ratio between pin pitch and pin diameter and height of the chimney.
4. The result of analysis shows that the maximum temperatures of coolant, fuel and cladding are still below each temperature limit, and margin to coolant and fuel are large.

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