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Three-dimensional core analysis on a super fast reactor with negative local void reactivity

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ABSTRACT

Keeping negative void reactivity throughout the cycle life is one of the most important requirements for the design of a supercritical water-cooled fast reactor (super fast reactor). Previous conceptual design has negative overall void reactivity. But the local void reactivity, which is defined as the reactivity change when the coolant of one fuel assembly disappears, also needs to be kept negative throughout the cycle life because the super fast reactor is designed with closed fuel assemblies. The mechanism of the local void reactivity is theoretically analyzed from the neutrons balance point of view. Three-dimensional neutronics/thermal-hydraulic coupling calculation is employed to analyze the characteristics of the super fast reactor including the local void reactivity. Some configurations of the core are optimized to decrease the local void reactivity. A reference core is successfully designed with keeping both overall and local void reactivity negative. The maximum local void reactivity is less than −30 pcm.

1. Introduction

The concept of supercritical water-cooled reactor (SCWR) has been well developed world-widely. It includes many options, for example, thermal neutron spectrum, fast neutron spectrum, thermal/fast hybrid neutron spectrum, pressure tube type, pressure vessel type, and so on. Among those options, a pressure vessel type fast neutron spectrum reactor called super fast reactor has some special merits from the fuel cycle point of view. It has potential of converting fertile fuel and transmutation of high level wastes (HLW).

A 700 MWe super fast reactor was designed with MOX fuel and stainless steel cladding by the University of Tokyo (Cao et al., 2008) using a 3D neutronics/thermal-hydraulics coupling method under a research program, named “research and development of the super fast reactor”, entrusted by MEXT of Japan. Zirconium–Hydride ($ZrH_{1.7}$, hereafter called ZrH) layers were arranged in blanket assemblies to reduce the void reactivity. The designed core has a high power density of 158.8 W/cm^3 with the maximum linear heat generation rate (MLHGR) less than 39 kW/m, 500 °C of the average coolant outlet temperature is achieved with the maximum cladding surface temperature (MCST), estimated by subchannel analyses, less than 650 °C, the overall void reactivity coefficients are negative throughout the cycle life.

As loss-of-coolant-accident (LOCA) is regarded as a design base accident (DBA) of the super fast reactor, it is important to keep the void reactivity negative throughout the whole fuel cycle. Nevertheless, as the super fast reactor was designed with closed fuel assemblies, which means there is no cross flow between the assemblies, the local void reactivity, which is defined as the reactivity change when the coolant of one assembly disappears, also needs to be kept negative throughout the cycle.

Previous study showed that the void reactivity is mainly affected by the neutron spectrum and neutron leakage rate (Waltar and Reynolds, 1980). Many efforts have been done to mitigate the neutron spectrum hardening and increase the neutron leakage. But those efforts may not work well for the super fast reactor. Oka and Jevremovic (1996) devised an innovative concept by inserting a ZrH layer between the seed region and blanket region. But the core analyses for this concept were mostly based on two-dimensional R–Z models. The local void reactivity was not studied in detail because of the limitation of the model. Only the partial void reactivity was calculated by dividing the core into several rings (Jevremovic et al., 1992). Three-dimensional neutronics/thermal-hydraulics coupling calculation is needed to analyze the local void reactivity and make sure all of seed assemblies have negative local void reactivity.

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Table 1
Main characteristics of the reference core.

Parameter	
Core thermal power (MWt)	1650
Core height (cm)	300
Fuel rod diameter (cm)	7.0
Pitch to diameter ratio	1.16
Number of seed assemblies	126
Number of blanket assemblies	73
Fissile Pu enrichment (wt%)	24.87
Coolant inlet/outlet temperature (°C)	280/503.7
Cycle length (EFPD)	380
Refueling scheme	3 batches

The mechanism of the local void reactivity is more complex than the overall void reactivity. Some core configurations, including the geometrical structure and core arrangement, influence the distribution of the local void reactivity. The effect of those configurations on the local void reactivity of the super fast reactor needs to be quantitatively studied by using three-dimensional neutronics/thermal-hydraulics coupling calculation to enhance the safety property of the super fast reactor concept.

The purpose of this study is to perform three-dimensional analyses on the core characteristics of the super fast reactor including the local void reactivity, find out the mechanism of the local void reactivity and design a core with negative local void reactivity coefficients for all seed assemblies throughout the cycle.

The remainder of this paper is as follows. Section 2 analyzes the principle of reducing the local void reactivity theoretically. Section 3 performs some sensitivity analyses according to the analysis of Section 2. A final core design with negative local void reactivity is given in Section 4. Section 5 ends this paper with some conclusions.

2. Principle of reducing the local void reactivity

Main concern arising from coolant voiding is the hardening of the neutron spectrum, which increases fast fission in both seed and blanket fuel regions, and also increases neutron leakage at the same time. Then, coolant void reactivity is determined by neutron balance change coming from those opposite effects.

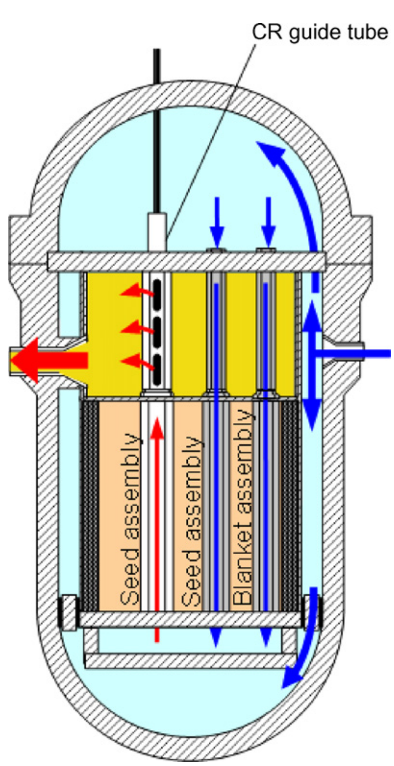


Fig. 1. In-vessel layout and flow pattern.

We can quantitatively analyze the void reactivity by considering the neutron balance. The general equation for neutron balance is diffusion equation

$$\frac{dn}{dt} = -D\nabla^2\phi - \Sigma_a\phi + S \tag{1}$$

where D is the diffusion coefficient, ∇^2 is the Laplacian operator, Σ_a is the absorption cross section, and S is neutron production.

When a neutron chain reaction is in equilibrium state, the above equation becomes

$$S = D\nabla^2\phi + \Sigma_a\phi \tag{2}$$

which means

$$\text{Production} = \text{leakage} + \text{absorption} \tag{3}$$

The effective multiplication factor is the ratio of the number of neutrons of a given generation to the number of neutrons of the immediately preceding generation. It can be expressed as

$$k_{\text{eff}} = \frac{\text{production}}{\text{absorption} + \text{leakage}} \tag{4}$$

The void reactivity is defined as

$$\Delta\rho = \rho_{\text{void}} - \rho_{\text{normal}} = \frac{k_{\text{eff}}^{\text{void}} - 1}{k_{\text{eff}}^{\text{void}}} - \frac{k_{\text{eff}}^{\text{normal}} - 1}{k_{\text{eff}}^{\text{normal}}} = \frac{k_{\text{eff}}^{\text{void}} - k_{\text{eff}}^{\text{normal}}}{k_{\text{eff}}^{\text{void}}\,k_{\text{eff}}^{\text{normal}}} \tag{5}$$

So, the negative void reactivity requires:

$$\frac{P_v}{P_n} < \frac{A_v}{A_n + L_n} + \frac{L_v}{A_n + L_n} \tag{6}$$

where P_v = neutron production at void condition; P_n = neutron production at normal condition; A_v = neutron absorption at void condition; A_n = neutron absorption at normal condition; L_v = neutron leakage at void condition; and L_n = neutron leakage at normal condition.

For convenience, we define

$$f_p = \frac{P_v}{P_n}, \quad f_a = \frac{A_v}{A_n + L_n}, \quad f_l = \frac{L_v}{A_n + L_n} \tag{7}$$

Eq. (6) can be written as

$$f_p < f_a + f_l \tag{8}$$

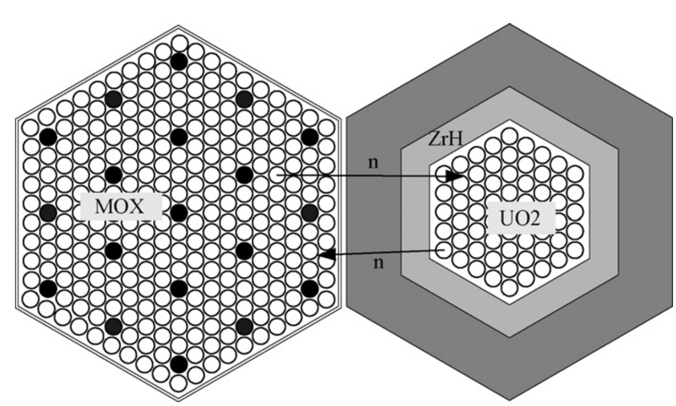
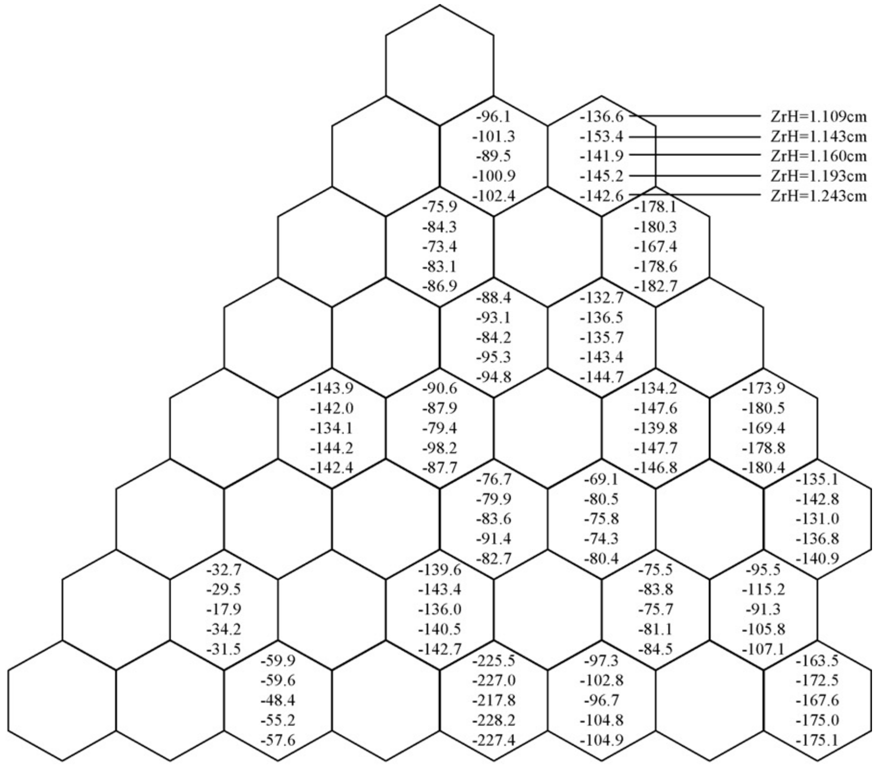
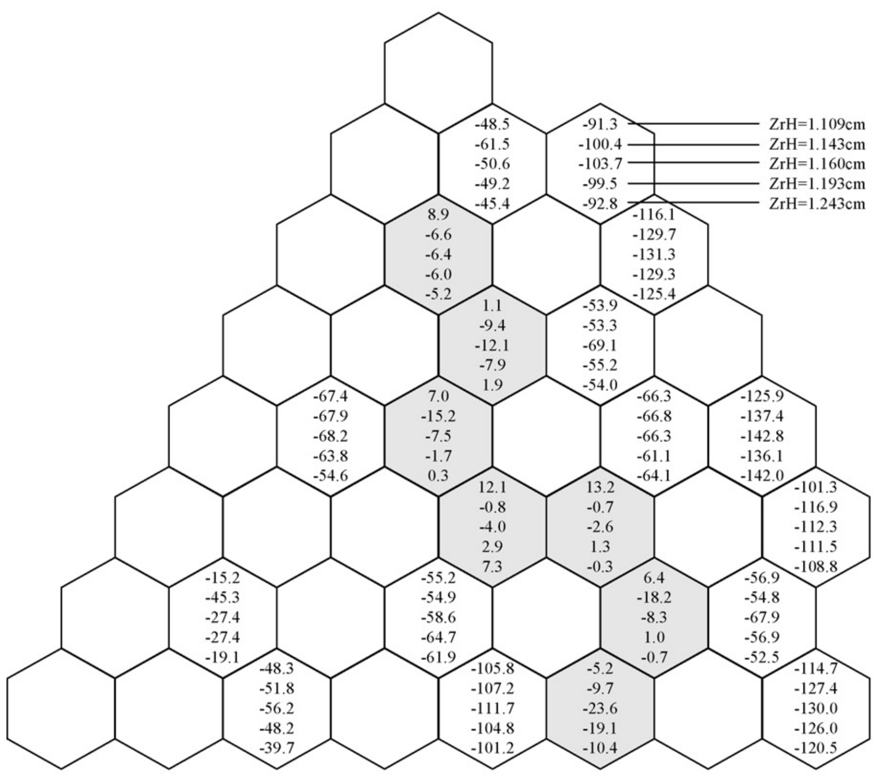


Fig. 2. The role of ZrH Layer in reducing the void reactivity.



(a) BOEC



(b) EOEC

Fig. 3. Local void reactivity distribution with different ZrH layer thicknesses (pcm).

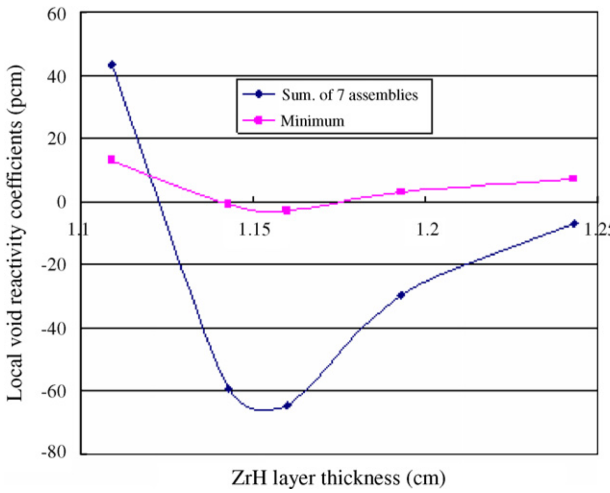


Fig. 4. Local void reactivity with respect to thickness of ZrH layer.

Then, the void reactivity can be approximately expressed as

$$\Delta\rho \approx f_p - f_a - f_l \tag{9}$$

The local void reactivity is defined as the reactivity change caused by the loss of the coolant inside one assembly. Similarly, it can be written as

$$\Delta\rho_i \approx f_{p,i} - f_{a,i} - f_{l,i} \tag{10}$$

where i is the index of the assembly.

Eq. (10) shows that, in order to reduce the local void reactivity of a seed assembly, we have three options, decreasing the fission rate, increasing the neutron leakage rate, or increasing the neutron absorption at void condition. Two of them are realized by inserting thin ZrH layers between seed assemblies and blanket assemblies. The ZrH layer slows down the fast neutrons leaked from seed assemblies at void condition and decreases the fast fission at blanket assemblies. More neutrons moderated by ZrH layer will be absorbed in blanket assemblies, which increases the neutron absorption at void condition. Therefore, some core configurations, including the thickness of ZrH layer, the layout of the seed assembly, will affect both overall and local void reactivity.

Increasing the neutron leakage from the core can be realized by flattening the core geometry, *i.e.* increasing the ratio of the core surface area to the core volume. Those methods were widely used in the LMFBRs (Hummel and Okrent, 1970) and the Reduced Moderator Water-cooled Reactors (RMWR) (Uchikawa et al., 2007). At void condition, the absent of moderator will increase neutron leakage from the core surface. But those methods are not suitable for reducing the overall void reactivity of pressurized water reactors because a flat core requires larger core diameter and a thicker pressure vessel, which will increase the capital cost significantly. However, we can employ this idea to reduce the local void reactivity. If we focus on one seed assembly which is surrounded by several blanket assemblies, those neutrons generated in this seed assembly and absorbed in its neighboring blanket assemblies can be seen as the neutron leakage of this seed assembly. Increasing the number of interfaces between seed and blanket assemblies can decrease the local void reactivity of this seed assembly. Therefore, the core arrangement and the loading pattern will affect the distribution of the local void reactivity.

3. Sensitivity analysis

In order to quantitatively evaluate the effect of those core design parameters, *i.e.* the thickness of the ZrH layer in the blanket assembly, the fuel layout of the seed assembly, the core arrangement and the loading pattern, on the local void reactivity, sensitivity of those configurations are analyzed in this chapter.

Strictly speaking, this is a multi-variable multi-constrain nonlinear optimization problem. It is difficult to optimize those

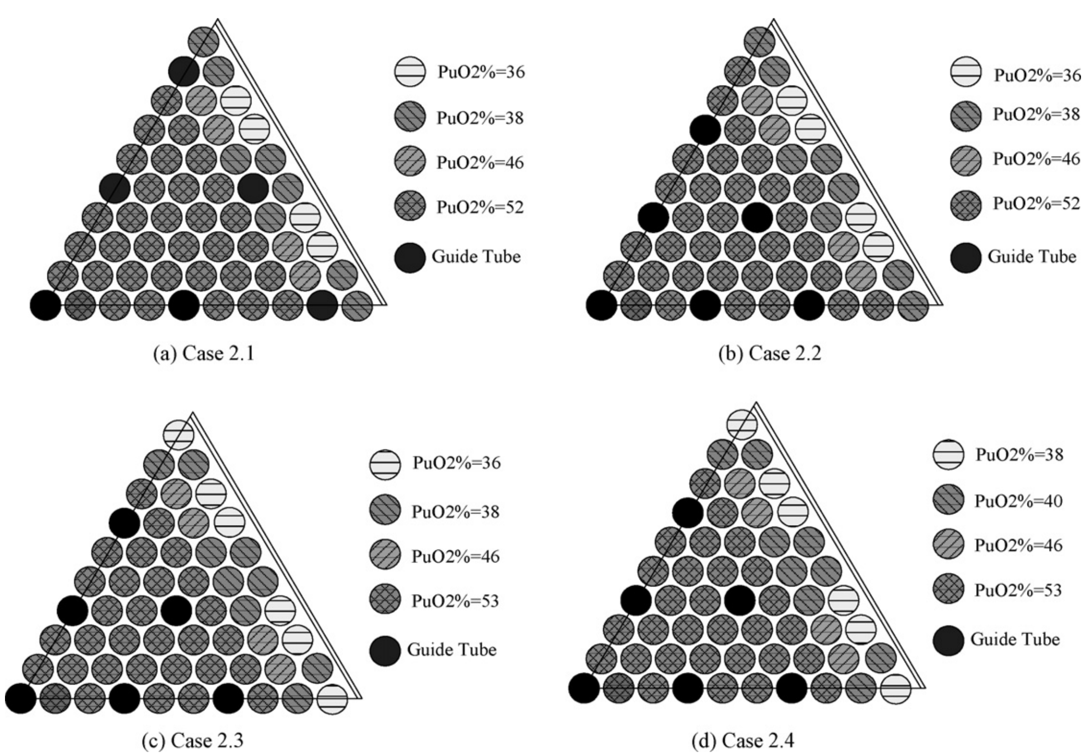
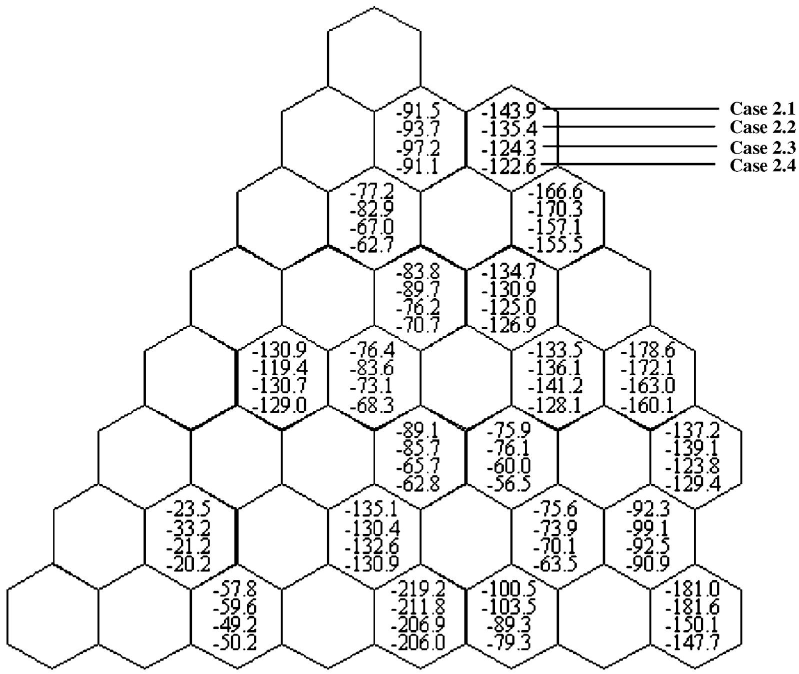
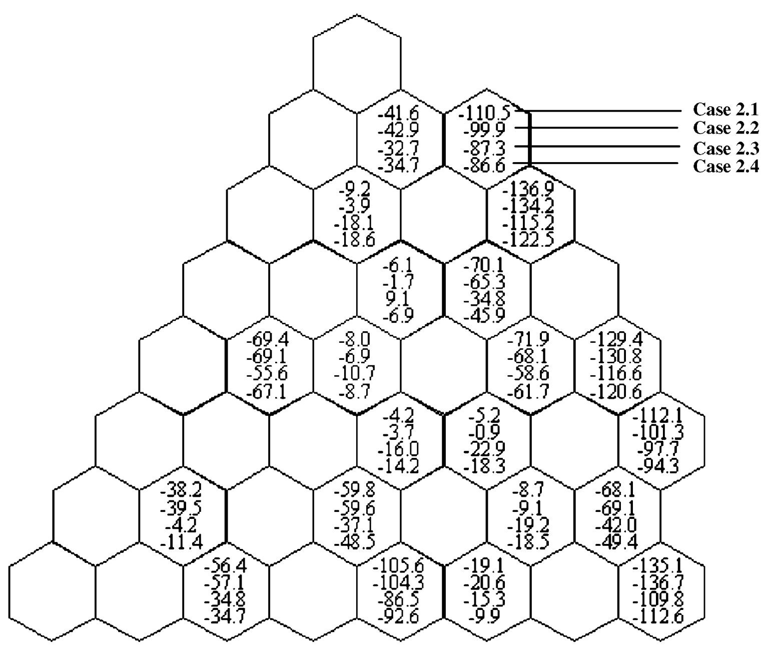


Fig. 5. Assembly layout candidates.



(a) BOEC



(b) EOEC

Fig. 6. Local void reactivity of different assembly layouts (pcm).

variables simultaneously. We decouple them and analyze their sensitivity on the local void reactivity one by one, assembly configurations (ZrH layer thickness for blanket assembly and fuel layout for seed assembly) firstly, and core configurations (core arrangement and loading pattern) afterwards.

3.1. Calculation model and method

All of the core configurations used in the sensitivity analyses are based on the reference core designed by Cao et al. (2008). Main characteristics are given in Table 1. The in-vessel layout and flow pattern are kept the same as the previous study, which is shown in Fig. 1.

The 3D neutronics/thermal-hydraulics coupling calculation method is the same as that of the reference core design. The neutronics calculation is based on three-dimensional fine-mesh multi-group neutron diffusion solution (Okumura et al., 2002). Single channel analysis is employed to perform the thermal hydraulic analysis to calculate the average outlet temperature and coolant density in the phase of core design. To consider the cross flow between subchannels inside one fuel assembly, subchannel analysis based on a control volume approach (Tanabe et al., 2004) is used to calculate the MCST.

3.2. Thickness of the ZrH layer

The ZrH layer was proposed to reduce the overall void reactivity of the supercritical water-cooled fast reactors (Oka and Jevremovic, 1996). The role of the ZrH layer can be explained as in Fig. 2. When the coolant in the seed assembly disappears, more neutrons would flow from the voided seed assembly through the ZrH layer to the neighboring blanket assemblies. They are slowed down in the ZrH layer and then absorbed by the blanket fuel. Because the depleted UO_2 contains large amount of ^{238}U, which has a large thermal absorption cross-section and a small thermal fission cross-section, thermal neutrons will be absorbed and cause no fission. Because of the role of the ZrH layer, the void reactivity is very sensitive to its thickness. Thicker ZrH layer has higher moderating capability, but too much thickness will prevent thermal neutrons from penetrating the ZrH layer and thus reduce the absorption rate. It is necessary to optimize its thickness to pursue the most negative local void reactivity.

In order to optimize the thickness of the ZrH layer, the local void reactivity is calculated with different thicknesses, 1.109 cm, 1.143 cm, 1.160 cm, 1.193 cm and 1.243 cm labeled cases 1.1–1.5, respectively. The local void reactivity of all the seed assemblies at the beginning of equilibrium cycle (BOEC) and the end of equilibrium cycle (EOEC) are calculated by SRAC code (Okumura et al., 2002) and compared in Fig. 3.

From above results, we can find that the local void reactivity does not decrease monotonously with the increasing of ZrH thickness. There exists a peak value between case 1.2 and case 1.3. It should be also noticed that 7 assemblies with grey background in Fig. 2(b), which are located at the middle region of the core, have very small negative (or large positive) local void reactivity. Since the aim of this study is to ensure negative local void reactivity for all of the seed assemblies, we focus our concentration on those 7 assemblies. The summation of the local void reactivity of those 7 assemblies and the maximum value among them are plotted with respect to the thickness of the ZrH layer in Fig. 4.

From Fig. 4, we can see that there is a concave point in the curve. We can approximately conclude that 1.15 cm of the ZrH layer thickness is the optimized size for the local void reactivity for the current core design. The following analyses will fix the ZrH layer thickness as 1.15 cm.

3.3. Layout of the seed assembly

In order to suppress the power peaking caused by the existence of the ZrH layer, the seed assembly was designed with fuel rods having different Pu enrichments. The distribution of Pu enrichment and the layout of the control rod guide tubes may affect the local void reactivity. Four types of the assemblies are designed to analyze them. The first type (case 2.1) is based on the reference design. In the second type (case 2.2), the guide tubes are moved to the inner region. In the third one (case 2.3), the Pu enrichment of the peripheral fuel rods is changed from the second type. The last type (case 2.4) has the same layout as case 2.3 but with higher Pu enrichment in the peripheral rods. The layouts are given in Fig. 5

Four candidate cores are designed by using those 4 types of assemblies respectively. The detailed local void reactivity distributions of case 2.1 through case 2.4 are given in Fig. 6.

From above comparison, we can see that the results of case 2.1 and case 2.2 do not differ so much. It means the positions of the guide tubes do not affect the void reactivity obviously. From the viewpoint of the mechanical design, case 2.2 is better because larger ligament is possible in the upper core tie-plate that is subject to the smallest distance between the guide tubes of neighboring seed assemblies. Case 2.3 and case 2.4 have slightly larger negative void reactivity compared with case 2.2, especially in the periphery of the core because the fuel rods with higher Pu enrichment in the periphery of the assembly induces higher neutron leakage and thus increase the $f_{l,i}$. But case 2.4 has relatively higher Pu enrichment in the peripheral region, which leads to much higher power peaking in this region. It will be very difficult to flatten the power peaking. Therefore, the assembly layout of case 2.3 is used in the following analyses.

3.4. Core arrangement

From above discussion, we can easily find that the seed assemblies located in the peripheral region of the core have sufficiently negative local void reactivity. This is due to the large neutron leakage. But the seed assemblies located at the inner region have less negative or positive local void reactivity. Reducing the local

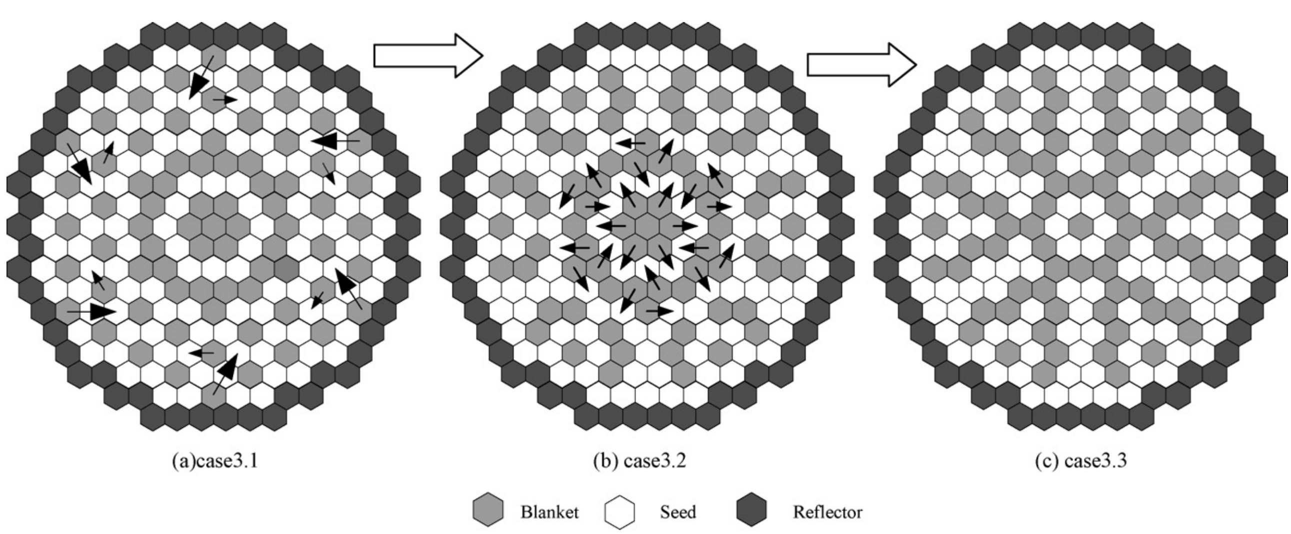


Fig. 7. Core arrangement candidates.

void reactivity of the inner assemblies becomes our main concern.

The core arrangement, namely, the location of the seed and blanket assemblies, has essential effect on the distribution of local void reactivity. As suitable thickness of the ZrH layer can reduce the local void reactivity of its neighboring seed assemblies, we can put more blanket assemblies at the inner region of the core in order to reduce the local void reactivity there. Three core arrangements given in Fig. 7 are proposed to analyze the sensitivity of core arrangement on the local void reactivity.

The first core arrangement, labeled case 3.1, is the same as the reference one, full scattering arrangement, but the ZrH layer thickness is changed to 1.15 cm. In the second one, labeled case 3.2, 6 peripheral blanket assemblies are moved to the middle region from case 3.1. In the third one, labeled case 3.3, some inner region blanket assemblies are moved to the middle region from case 3.2. The fraction of blanket assemblies in the middle region of the core increases from case 3.1 to case 3.3. The calculated local void reactivity distributions of those 3 cases are shown in Fig. 8.

As expected, case 3.3 has obviously much more negative local void reactivity than others. The smallest negative local void reactivity at BOEC and EOEC are −43.0 pcm and −23.5 pcm respectively. It can be explained as follows. The larger negative local void reactivity of the peripheral assemblies is due to the larger neutron leakage rate and that of the inner assemblies are due to the larger fraction of the blanket assemblies.

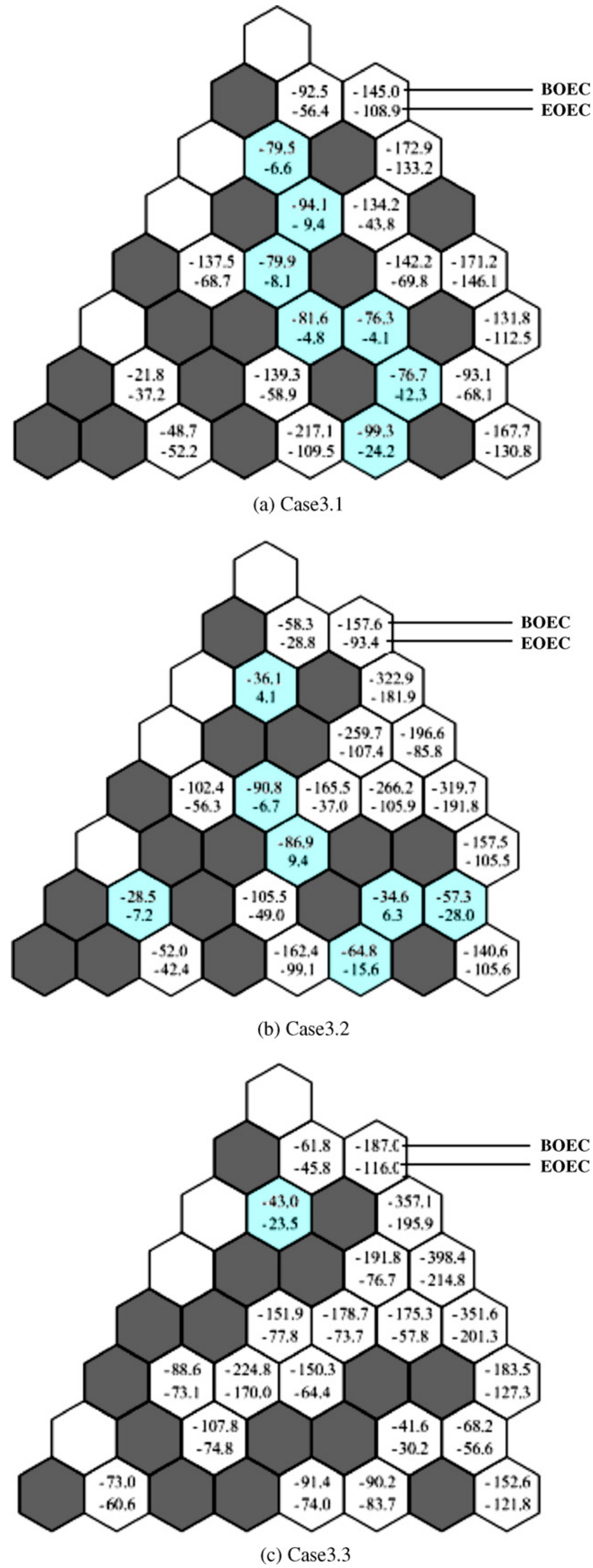


Fig. 8. Local void reactivity of different core arrangements (pcm).

3.5. Loading pattern

Even though the local void reactivity of all the seed assemblies is negative, its distribution is not uniform. Peripheral assemblies have relatively strong negative local void reactivity while some of the inner assemblies have the values very close to zero. It is better to keep all the local void reactivity below −30 pcm in consideration of uncertainties from nuclear data, design methods, etc.

In the previous design, the typical out-in loading pattern for the seed assemblies is employed in order to reduce the power peaking. But in Section 3.4, we move some blanket assemblies to the inner region, which makes the relative power at the inner region lower. So, the power peaking is not a concern any more. On the other hand, compared to the used fuel, the fresh fuel has larger portion of fast fission, which means the $f_{a,i}$ is higher in case of void. It is effective to use the ZrH layer to reduce its local void reactivity. Therefore, we can load some fresh fuels at the middle region of the core and load some used fuels at the periphery of the core.

In order to analyze the sensitivity of the core loading pattern on the distribution of the local void reactivity, we designed 2 candidate cores by using different loading patterns which are shown in Fig. 9. Case 4.1 is the typical out-in loading pattern. In case 4.2, some fresh fuels are moved to the inner region and some used fuels are moved to the peripheral region. The local void reactivity distributions are given in Fig. 10.

From the comparison, we can see the local void reactivity distribution of case 4.2 is much more uniform than that of case 4.1 even though most of the assemblies of case 4.1 have relatively lower void reactivity. The highest value is decreased from −20.8 pcm to −41.6 pcm. This is mainly due to moving some fresh assemblies to the middle region of the core. This loading pattern is also a low-leakage loading pattern, which has lower neutron fluence rate on the pressure vessel.

4. Final design results

Considering the above sensitivity analyses, we finally chose case 4.2 as the design base. In order to satisfy the design criteria and

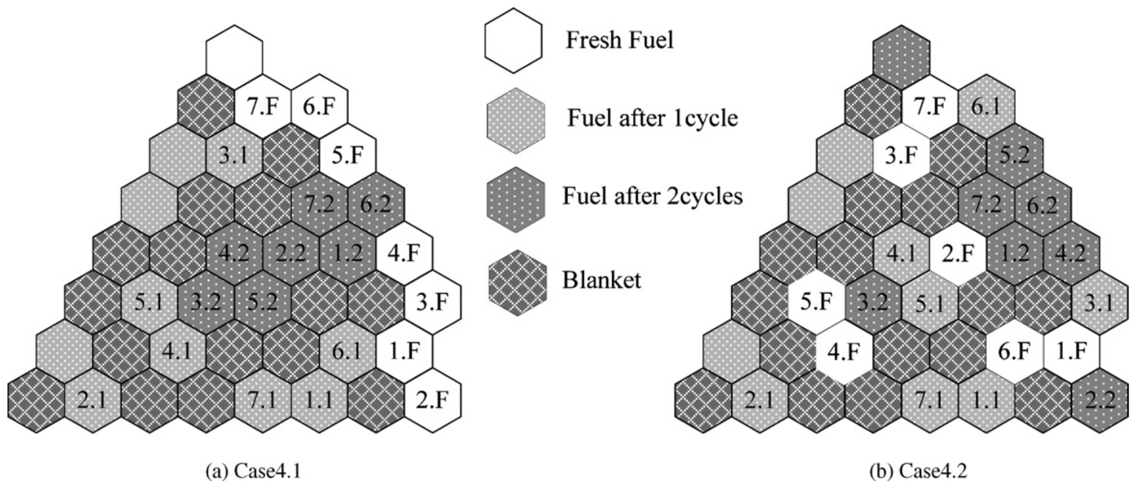


Fig. 9. Loading pattern candidates.

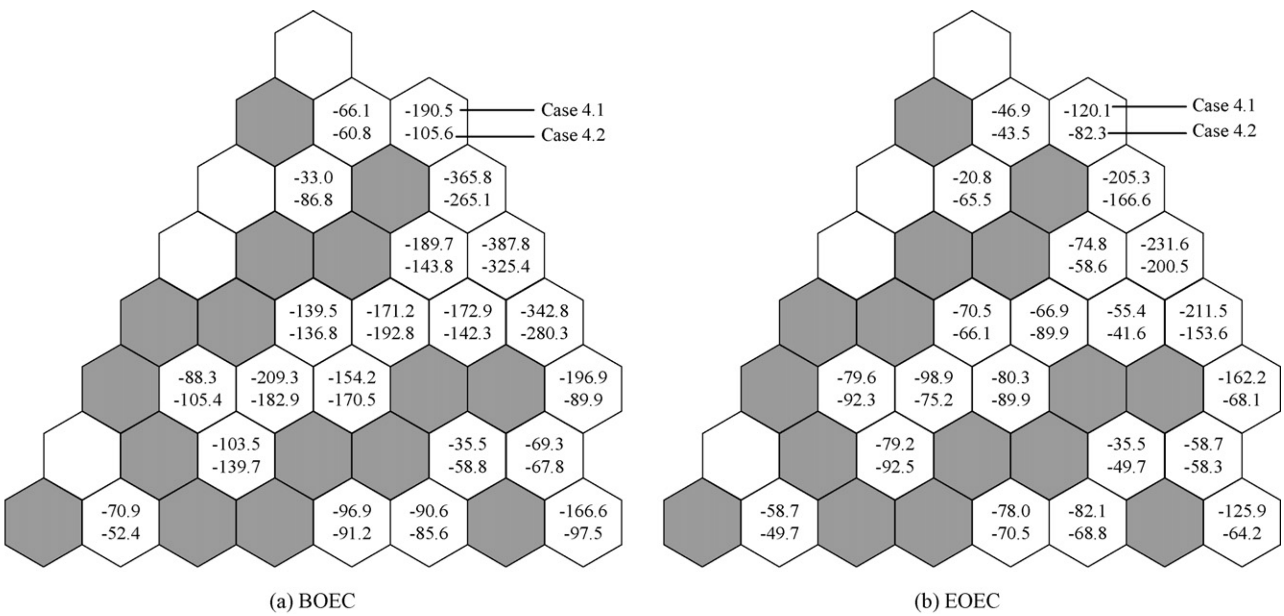


Fig. 10. Local void reactivity of different loading patterns (pcm).

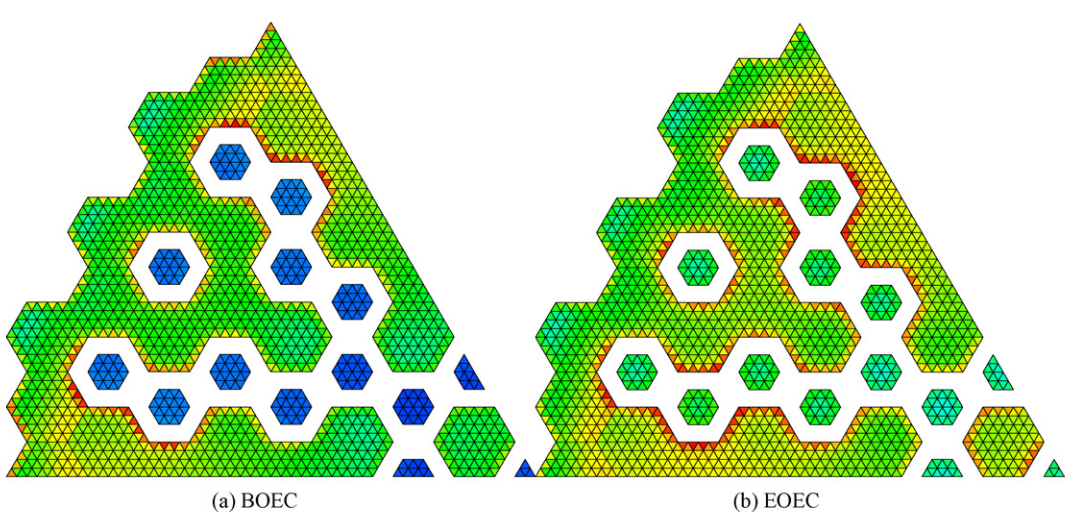


Fig. 11. Radial Power distribution at BOEC and EOEC.

Table 2
Summary of main parameters of core design.

Parameter	
Core thermal power (MWt)	1650
Core height (cm)	300
Equivalent diameter (cm)	210
Number of seed assemblies	126
Number of Blanket assemblies	73
ZrH layer thickness (cm)	1.15
Seed assembly layout	See Fig. 5(c)
Core arrangement and loading pattern	See Fig. 9(b)
Coolant outlet temperature (°C)	509.7
Maximum cladding surface temperature (°C)	637.8
Cycle length (EFPD)	380
Average power density (W/cm^3)	165.3
Maximum linear heat rate (kW/m)	38.9
Average discharge burnup (GWd/tHM)	69.4
Average fissile Pu enrichment (wt%)	25.62
Coolant flow rate (kg/s)	837.2
Coolant void reactivity (%dk/k) BOEC	−3.029
EOEC	−2.901

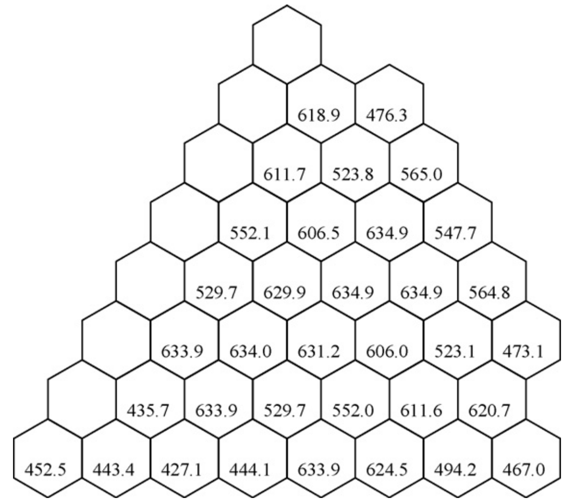


Fig. 13. MCST over cycle (°C).

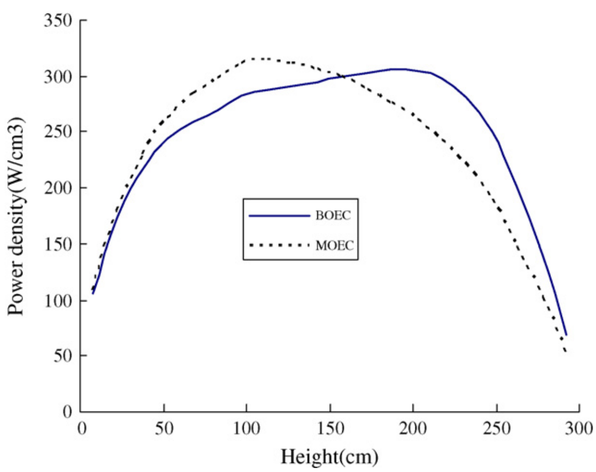
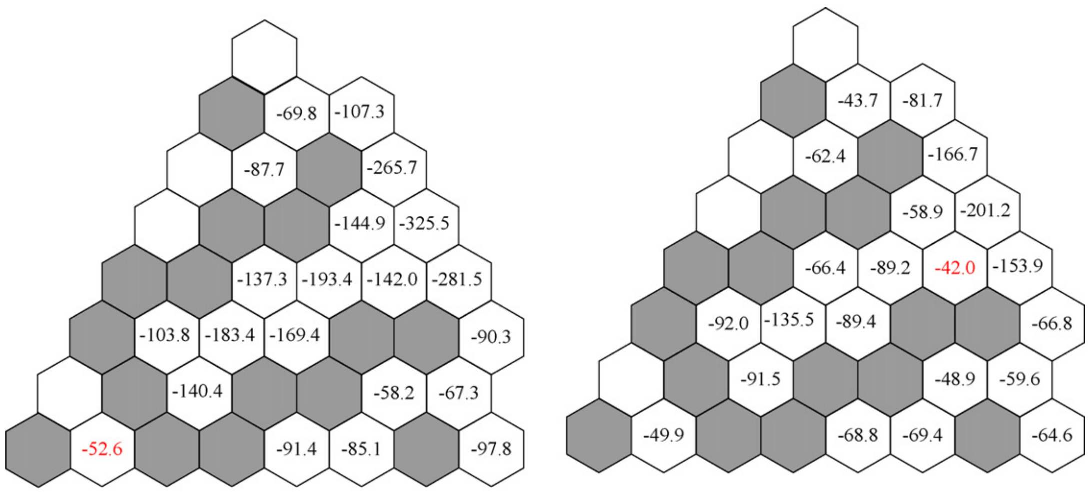


Fig. 12. Average axial power distribution.

design goals, some other parameters are optimized. Table 2 summarizes the main parameters and calculated results of final core design.

The radial and axial power distributions of BOEC and EOEC are given Figs. 11 and 12, respectively. The MCST distribution calculated by subchannel analysis is given in Fig. 13. The final local void reactivity distributions are given in Fig. 14.

We can see that all the design criteria which were determined previously (Cao et al., 2008) are satisfied. The highest local void reactivity coefficients are −52.6 pcm and −42.0 pcm at BOEC and EOEC respectively, which are less than −30 pcm.



(a) BOEC (b) EOEC

Fig. 14. Local void reactivity (pcm).

5. Conclusions

The mechanism of reducing the void reactivity of the super fast reactor is studied theoretically and numerically. The sensitivity of the assembly layout, the thickness of the ZrH layer, the core arrangement and the loading pattern on the void reactivity are analyzed. Fourteen candidate cores are analyzed and compared. The following can be concluded: (1) the local void reactivity does not change monotonously with the increasing of the thickness of the ZrH layer. (2) The assembly layout has no obvious effect on the void reactivity. (3) Loading more blanket assemblies in the inner region of the core is effective for reducing the local void reactivity of the inner assemblies. (4) Low-leakage loading pattern can be employed to make the distribution of the local void reactivity more uniform. (5) A super fast reactor core is successfully designed by satisfying all of the design criteria and design goals as well as keeping the local void reactivity negative for all the seed assemblies.

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