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Analysis of accidents and abnormal transients of a high breeding fast reactor cooled by supercritical-pressure light water

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HIGHLIGHTS

- The safety analysis of Super FBR at supercritical pressure is carried out.
- The control rod ejection is the most important accident for Super FBR.
- All the safety criteria are satisfied for the selected events.

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ABSTRACT

A high breeding core of supercritical water cooled fast reactor (Super FBR) is designed with the tightly packed fuel assembly for obtaining a high breeding ratio with negative void reactivity. The coolant volume fraction is substantially smaller than that of the tight lattice fuel assembly in Super FRs. The present study conducted the safety analysis of this reactor for the abnormal transients and accidents at supercritical pressure. The safety system and safety criteria are similar to those of Super FRs. The accident "control rod ejection" gives the highest fuel cladding temperature and the highest peak pressure, although which are still within the limit of safety criteria. The overall results show that all the safety criteria are satisfied at the selected events.

1. Introduction

Supercritical pressure light water cooled fast breeder reactor (Super FBR) is proposed by Oka et al. (2013), which is a type of supercritical pressure water cooled reactor (SCWR) with once-through coolant cycle. The newly developed tightly packed fuel assembly is adopted for high breeding. The cross-section of this assembly is shown in Fig. 1. It is characterized by the configuration of fuel rods and coolant channel: the fuel rods are closely packed without gap and the coolant channel is tangent to the surrounding fuel rods, the space among them being filled with the metal fitting that is the same material as cladding. The coolant to fuel volume fraction is dramatically reduced to 0.085 compared with 0.82 of the conventional BWR and 0.17 of reduced moderation water reactor (RMWR, Hibi et al., 2001). This fuel assembly enables designing of a high breeding water cooled reactor with hard neutron energy spectrum. As reported by Yoshida and Oka (2013), the compound system doubling time (CSDT) is decreased to 43 years, and the fissile plutonium serving ratio (FPSR) is increased to 1.026. By contrast, the BWR-type RMWR with axially double heterogeneous core achieved CSDT of 245 years and FPSR of 1.006 (Hibi et al., 2001).

Super FBR adopts the once-through direct cycle just as Super LWRs and Super FRs, and the plant system is almost the same. However, the volume fraction of the coolant is smaller than the Super FR. It makes the pressure be more sensitive to the core heat up. The coolant channels are physically independent from each other, the cross flow cannot be formed. The special layout of coolant channels and fuel rods gives rise to different cladding temperature distribution from that of conventional fuel assembly. The above mentioned characteristics would influence the safety performance, especially for Super FBR on account of its small flow rate and once through

Abbreviations: ADS, automatic depressurization system; AFS, auxiliary feedwater system; ATWS, anticipated transient without scram; BOC, beginning of the cycle; CR, control rod; CSDT, compound system doubling time; DU, depleted uranium; EOC, end of the cycle; FPSR, fissile plutonium serving ratio; LOCA, loss of coolant accident; LPCI, low pressure core injection system; MCT, maximal cladding temperature; MOX, uranium mixed oxides; MSIV, main steam isolation valve; RCP, reactor coolant pump; RMWR, reduced moderation water reactor; RPV, reactor pressure vessel; SCWR, supercritical pressure water cooled reactor; SLCS, standby liquid control system; SRV, safety relief valve; Super FBR, supercritical pressure light water cooled fast breeder reactor; TBV, turbine bypass valve; TCV, turbine control valve; USC, ultra super-critical.

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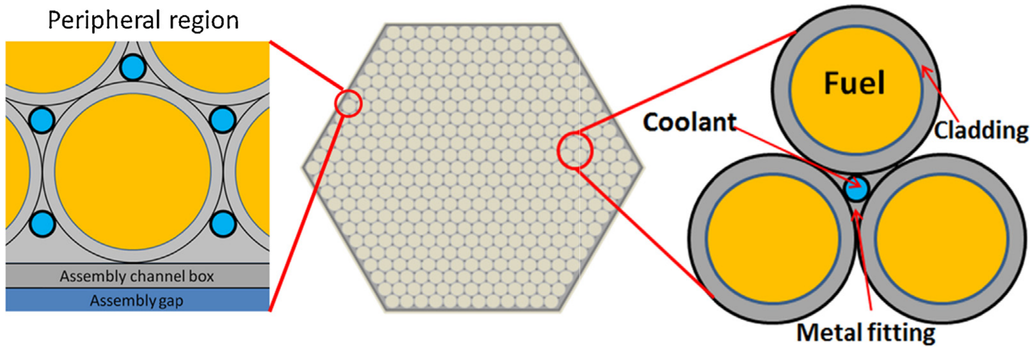

Fig. 1. Cross-section of the tightly packed fuel assembly.

direct cycle (Yoshida and Oka, 2013). Therefore, it is necessary to clarify the safety characteristics of Super FBR at accidents and abnormal transients.

2. Description of the core and safety system

2.1. Core characteristics

Although the neutron energy spectrum is hardened by adopting the tightly packed fuel assembly, the negative coolant void reactivity is ensured by applying ZrH rods in part of the blanket assemblies and elaborately arranging the core layout. The major parameters of the assembly and the core design are summarized in Tables 1 and 2 respectively. In seed assemblies, fuel composition is plutonium and uranium mixed oxides (MOX) with fissile Pu enrichment of 16.8 wt%. In blanket assemblies, including blanket assemblies with ZrH rods, depleted uranium (DU, ^{238}U 99.8 wt%) is used for fuel rods (Yoshida and Oka, 2013). Compared to previous Super FRs (Yoo et al., 2006; Liu and Oka, 2013), the current design mainly serves the purpose of high breeding and some parameters are very different such as the inlet and outlet temperatures, the proportion of seed and blanket assemblies and the core pressure. While the coolant flow scheme is similar to other one pass Super LWRs (Wu and Oka, 2014) and Super FRs (Liu and Oka, 2013), as shown in Fig. 2: the coolant flows through the downcomer and fills the bottom dome, then flows upward via the fuel channels. Then, the coolant is mixed in the upper plenum, and finally comes out from the hot-leg. It is noted that the top dome is connected with core and cooled by a small fraction of inlet coolant flow as in PWR, but the leakage flow is small and can be ignored. Compared with Super FRs (Ikejiri et al., 2010; Liu and Oka, 2013), although the coolant channels of tightly packed fuel assembly are designed with smaller cross-section and smaller hydraulic diameter, the core cooling is still efficient by increasing the rated coolant flow rate. For instance, the flow rate averaged on thermal power of “all-upward two-pass flow Super FR” (Liu and Oka, 2013) is 0.5 kg/s/MW, while that of the current study is 1.3 kg/s/MW.

Table 1
Design specification of the tightly packed fuel assembly (Yoshida and Oka, 2013).

Channel box thickness [cm]	0.2
Gap between fuel assemblies [cm]	0.1
Fuel assembly pitch [cm]	24.66
Outer diameter of fuel rods [cm]	1.2
Cladding thickness [cm]	0.0873
Pellet diameter [cm]	1.0124
Gap between clad and pellet [cm]	0.0065
Fuel rod pitch [cm]	1.2
Gap between fuel rods [cm]	0
Diameter of coolant channel [cm]	0.1856

Table 2
Core characteristics (Yoshida and Oka, 2013).

Reactor thermal power [MW]	1156
Core height [m]	2.0
Core equivalent diameter [m]	4.12
Number of seed/blanket assemblies	97/162
Fuel batch (seed/blanket)	4/1
Operating cycle length [d]	550
Core operating pressure [MPa]	30
Core pressure drop [MPa]	1.6
Inlet temperature [°C]	385
Average outlet temperature [°C]	440
Average coolant density [kg/m^3]	248
Maximal cladding temperature (MCT) [°C]	654
Discharge burnup (seed) [GWd/t]	48.7
Void reactivity (BOC/EOC) [%Δk/k]	−0.70/−0.37
FPSR	1.026
CSDT [y]	43

2.2. Safety system and actuations

The present plant and safety system are almost the same as Super LWRs and Super FRs (Ishiwatari et al., 2003a,b, 2005a) due to the similar characteristics in thermal-hydraulics, as shown in Fig. 3. However, it is very different from BWRs mainly because of no separations of water and steam (single phase flow) and no coolant recirculation. As it is single phase flow, the water level does not

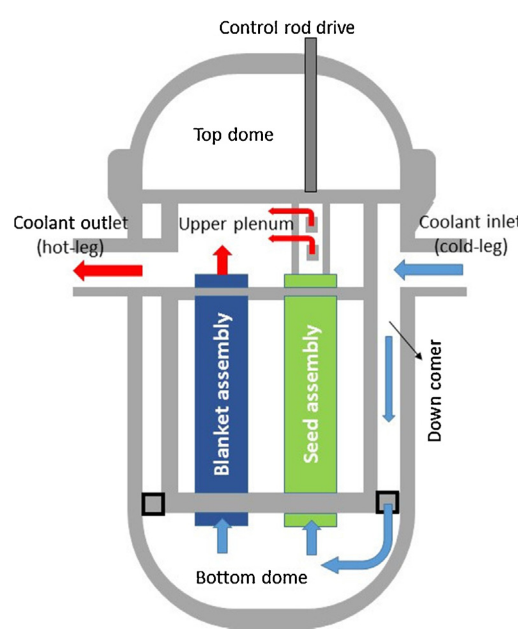

Fig. 2. Coolant flow scheme.