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A comparison of in-vessel behaviors between SFR and PWR under severe accident

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1. Introduction

The sodium-cooled fast reactor (SFR) has been recognized a promising generation 4 reactor type for its inherent safety features. For its excellent safety characteristics, a possibility of occurrence of severe accident seems almost zero, and consequently a very limited researches have been performed to investigate the behaviors of SFR under a postulated severe accident scenarios. This paper aims to provide an easy guide for experts who know well the severe accident phenomenology of Pressurized Water Reactor (PWR) by comparing both reactor design concepts and in-vessel behaviors under a postulated severe accident condition. This study only provides a preliminary qualitative comparison based on available literature.

2. A comparison of in-vessel of PWR and SFR

The major differences in the in-vessel characteristics between PWR and SFR are the coolant and core design. Each difference is described in the chapter 2.1 and 2.2, respectively.

2.1 A comparison of in-vessel: coolant

In PWR, a coolant is water which acts not only for cooling but also for moderating the neutron. Unlike PWR, SFR needs no moderation of neutron and hence a sodium is acting only for cooling. The main differences of each coolant in the aspect of safety under severe accident conditions are given in the following.

▪ Thermal conductivity: thermal conductivity of water is ca. 0.6 and of sodium is ca. 67 at each operating temperatures (in W/m/℃). In a postulated severe accident condition, sodium would show a by far excellent cooling capability than water.

▪ Boiling point: boiling points of water and sodium are ca. 340℃ and ca. 1000℃, respectively at a system pressure. The core outlet/inlet temperatures of PWR are 325/290℃ and of SFR are 530/385℃. In case of severe accident, water coolant could promptly boil for its relatively small sub-cooling margin to boiling; only 15℃. However, sodium coolant has a very wide margin till boiling; 470℃. For this reason, it would allow operators to conduct a necessary accident management if needed.

▪ System pressure: PWR employs a pressurized water as a coolant, but SFR uses an atmospheric pressure sodium. For a high pressure system of PWR, there would be a chance to bring the loss of coolant accident with a pipe break by a high coolant pressure. On the other hand, there would be a very low potential to trigger a pipe break in a low pressure sodium. In case of a loss of coolant accident in PWR, there exists a flashing and a high pressure water/steam mixture would be dispersed rapidly in a primary circuit and a containment pressure boundary by leading a potential pressure boundary failure. On the contrary, there would be no flashing in case of sodium leak in SFR, but sodium would exothermically react with air by leading a potential sodium fire. However its pressurization impact on a containment pressure boundary is relatively low in comparison to PWR case. In addition, a control rod ejection accident would be occurred in PWR for its high internal pressure that forces the control rod assembly being ejected.

In summary, the sodium coolant shows an excellent inherent safety characteristics than the water coolant due to its high thermal conductivity, large margin to boiling and the low system pressure.

2.2 A comparison of in-vessel: core design

Firstly, a lattice design is different as shown in Fig. 1.

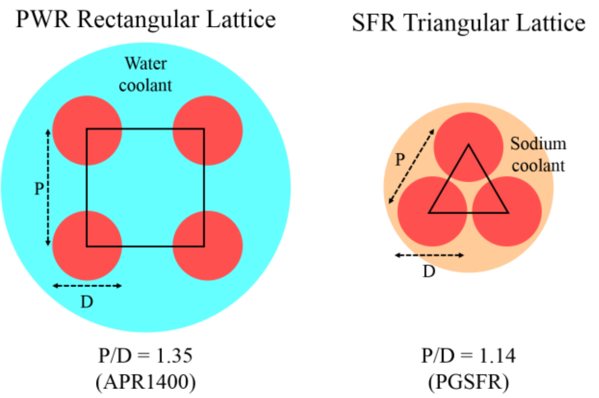

Fig. 1 Lattice design of PWR and SFR

For a PWR, an optimal pitch-to-diameter ratio (P/D) is designed to allow an adequate cooling capability and moderation of neutron by water coolant. However for a SFR, the P/D is smaller than that of PWR (e.g. the P/D of APR1400 is 1.35 and the P/D of PGSFR is 1.14) due to its high heat transfer capability and no necessity of neutron moderation. For this reason, fuel pins in SFR core are packed much closer in a triangular lattice configuration as shown in Fig. 1, and hence the core power density is ca. 5 times higher than that of PWR. [1-2] Under a postulated severe accident condition, the compact packing configuration in SFR core seems to allow more chances to mechanically interact with fuel and coolant that in case of PWR where rather loose packing is. In this view, the fuel should be compatible with sodium coolant to eliminate the risk of fuel coolant mechanical interaction.

Secondly, the core reactivity configuration is different. In PWR, core is in a maximum reactivity configuration, while it is not in a maximum reactivity configuration in SFR. Therefore, the molten core may relocate and get together beyond the critical mass by giving a re-criticality. For this reason, SFR core design must ensure that the re-criticality is excluded in a postulated severe accident scenario.

Lastly, the cladding oxidation by the coolant during a severe accident would be different. In case of PWR, zirconium alloy cladding exothermically reacts with steam by releasing hydrogen and leading to a potential hydrogen explosion. On the contrary, SFR uses a stainless steel cladding and hence there is no risk hydrogen risk during a severe accident.

Even though sodium coolant has many advantages than the water coolant as described in the chapter 2.1, the core design seems to lead an unfavorable accident progression due to its compact lattice configuration, high core power density and the potential of re-criticality. Thus, an appropriate fuel concept should be selected to eliminate the risks that identified above.

In PWR, uranium oxide fuel can be mechanically interacted and would lead to failure of cladding. The failure of cladding deteriorates the coolable geometry and a fission gas release to the primary circuit. In SFR, there are mainly two types of fuel concept. One is an oxide fuel SFR and the other is a metal fuel SFR. In case of oxide fuel SFR, it also leads to fuel-cladding mechanical interaction like the PWR case. However, metal fuel is compatible with the liquid metal sodium and its behavior during a postulated severe accident is different from the oxide fuel SFR [3]. This will be explained in the chapter 4.

3. Inherent safety features

In order to investigate the inherent safety features for both PWR and SFR, this chapter compares three characteristics: reactivity feedback and passive cooling capability.

3.1 Reactivity feedback

Firstly, the capability to mitigate the uncontrolled reactivity increase would be crucial to terminate the severe accident progression. The parameters that affect the reactivity feedback are listed in the following.

▪ Doppler feedback: for both PWR and SFR, fuel Doppler feedback is negative by increasing neutron capture in U-238 with an increase in fuel temperature.

▪ Coolant density: in a severe accident, coolant density decreases by increasing the coolant temperature. In PWR, the chance of moderation of neutron is decreased and it leads to a large negative reactivity feedback. However in SFR, a decrease of sodium density reduces a neutron absorption in the coolant channel and increases the fission absorption in the fuel, introducing a positive reactivity feedback. At the core boundaries, neutron leakage is enhanced with the decrease of sodium coolant density. If core diameter is much larger than the core height, neutron leakage is significantly promoted and hence it leads to a negative reactivity feedback [4].

▪ Fuel thermal expansion: in SFR, the fuel expands axially and radially with the increase of fuel temperature. This leads to a large negative reactivity feedback by enhancing the neutron leakage.

In summary, both PWR and SFR have net negative reactivity feedback, but its contribution to negative reactivity value is depending on their core design.

3.2 Passive cooling capability

As already described in chapter 2.1, sodium coolant has much higher thermal conductivity than that of water coolant. In addition, SFR has much larger temperature difference at core outlet/inlet than that of PWR. Moreover, sodium coolant has a very wide margin to boiling. All these properties contribute to an excellent passive cooling capability during a severe accident. However, a large temperature difference for a long time may accumulate the thermal stress in a core structures and may lead to a thermally induced creep rupture. In case of PWR, natural circulation is also effective only for a limited period in comparison to the SFR case. Therefore, there would be more time for the operator to perform an appropriate accident management, if needed. The more detailed analysis would be required to assess the passive cooling capability by the natural circulation for both PWR and SFR severe accident scenarios.

4. A comparison of oxide and metal fuel SFR

As mentioned briefly before, the behaviors of metal fuel during a postulated severe accident is different from the oxide fuel SFR, in the following aspects.

▪ Development of inter-connected porosity: during a normal operation of metal fuel SFR, low fuel smear density promotes to develop the inter-connected porosity as shown in Fig. 2.

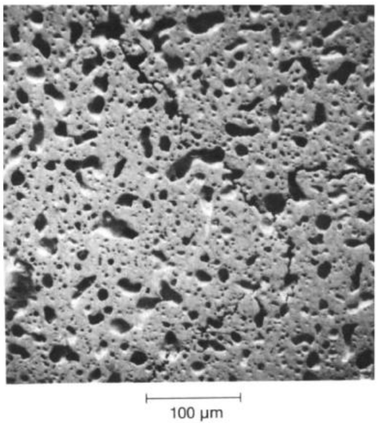

Fig. 2 Inter-connected porosity development of irradiated U-10Zr fuel (excerpted from [3])

Through this porosity, the fission gas get easily released to the upper plenum of fuel pin. Thanks to this effective fission gas release to the upper plenum, the metal fuel itself is not pressurized and eliminates the risk of fuel-cladding mechanical interaction.

▪ Formation of low melting point eutectic alloys: since the melting point of metal fuel is below the melting temperature of stainless steel cladding, it is expected that fuel melt would be formed earlier than the cladding failure, and melt would move axially due to the internal pressure. At the top of fuel, the melt get expelled to the upper pin plenum. In addition, the melt gets not freeze, since the eutectic temperature would be close to the sodium coolant due to a high thermal conductivity of metal fuel.

▪ Cladding failure above the top of fuel: once the metal fuel melts, the melt moves axially due to the internal pressure. When the melt get contacts with the cladding the eutectic penetrates the cladding. Due to a high thermal conductivity of metal fuel, the axial temperature profile at the fuel-cladding interface get close to the cladding temperature profile. At the top of fuel where the cladding temperature would be highest, the cladding would be breached.

▪ Dispersion of melt into sodium coolant: once the cladding is breached at the top of fuel, the eutectic mix is forced to move to the coolant channel. Since, the metal fuel is compatible with liquid sodium, it gets dispersed and fragmented well into the sodium coolant and get rid of the risk of flow blockage and the energetic fuel-coolant reaction as expected between the oxide fuel and sodium coolant. The schematic of pin failure mode of metal fuel SFR is illustrated in Fig. 3.

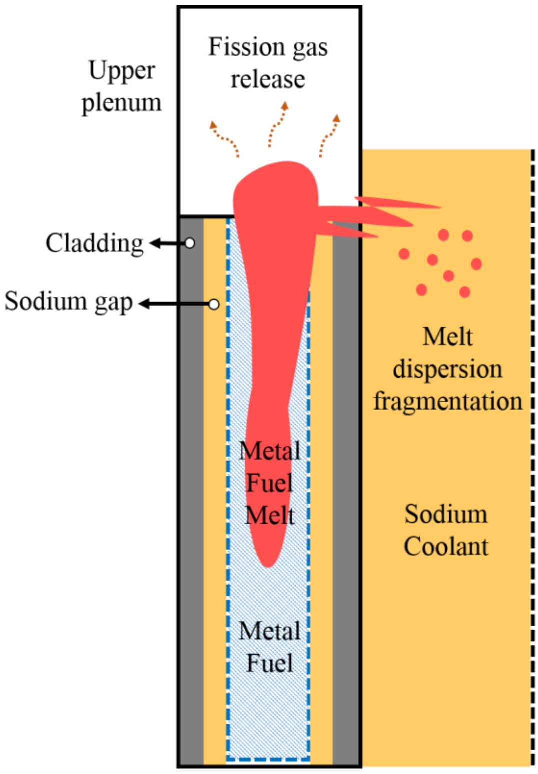

Fig. 3 Schematic of pin failure mode of metal fuel SFR

On the contrary, due to its relatively high melting temperature, the oxide fuel firstly mechanically reacts with cladding by swelling and leads to loss of coolable geometry and a subsequent cladding rupture. Since the oxide fuel is not well compatible with sodium coolant, the melt gets not dispersed and fragmented well and potentially leads to the high energetic reaction by the re-criticality of the compacted melt. Furthermore, due to relatively low (10 times lower; ca. 20 W/m/℃ for the metal fuel and ca. 2 W/m/℃ for the oxide fuel) thermal conductivity, the oxide fuel melt would freeze and block the flow path.

4. Conclusion

The PWR and SFR in-vessel design concepts and their effects under a postulate severe accident are investigated in this paper. Although this work is a preliminary study to compare the in-vessel behaviors for both PWR and SFR, it seems that there is no possibility to lead a significant core damage in the metal fuel SFR concept. In the oxide fuel SFR, there might be a chance to progress to the severe accident initiators such as the energetic reaction, flow blockage and so on. From this study, only preliminary conclusion can be drawn such that the metal fueled SFR could have much benign results upon various postulated severe accident initiators due to its excellent inherent safety features which early terminate the pin failure and eliminate the possible initiators that lead to core disruptive accidents.

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