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A Review of PSA Technical Issues in the Development of Korean SFR

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1. Introduction

The sodium-cooled fast reactor (SFR) under development in KAERI, in which the fuel is a metal fuel based on U-TRU-Zr and the coolant is sodium, is excellent from the aspects of an uranium resource utilization, inherent safety features, and non-proliferation.

The Probabilistic Safety Assessment (PSA) will take an important role in designing the Korean SFR from the aspects of a Risk informed design (RID) and a Technology-neutral licensing (TNL).

In this paper, the technical issues in performing a PSA for an SFR design are reviewed and compared with those of the current generation Pressurized Water Reactors (PWR).

2. Overseas SFR Development Status and PSA Status

Up to now United States of America, European countries, Russia, and Japan have much experience in the construction and operation of experimental and prototype SFRs.

Gen-IV International Forum (GIF) selected Korea and Japan as demonstration countries for developing Gen-IV SFRs and requires a PSA for developing reactors.

In the United States of America, Experimental Breeder Reactor, EBR-II is constructed and used for the demonstration of the inherent safety features of a metal fuel fast reactor. Prototype or commercial grade reactor, CRBRP or PRISM is designed but not constructed. In the design of the PRISM (Power Reactor Innovative Small Module) plant, the project led by General Electric, performed a Level-3 PSA to confirm USNRC's Safety Goal. In the PRISM PSA, 21 initiating events are selected. They are composed of 3 transient overpower (TOP) events, 3 earthquake induced events, 5 loss of flow or reduced flow capability events in the primary side, 9 loss of or reduced heat removal capability events in the intermediate loop or balance-of-plant (BOP).

In Japan, 750MWe / 1,500MWe JSFR is under development now. They are using a Risk-Inform Design (RID) in the development of the JSFR and now a Level-1 PSA is being performed. The CDF (Core Damage Frequency) is estimated according to the design varieties (redundancy and diversity) of the reactor shutdown system, the primary and intermediate shutdown heat removal systems, and the single/double tube wall steam generators.

3. Safety Design Characteristics of KALIMER-600

In Korea, KAERI (Korea Atomic Energy Research Institute) developed KALIMER-150 and KALIMER-600 in 2002 and 2006, respectively. Now KAERI starts also to develop burner reactor types to burn actinides in spent fuels in PWR.

The SFR under development in KAERI has excellent safety characteristics which consist of inherent safety features due to the use of a metal fuel such as U-TRU-Zr. Use of U-TRU-Zr as a fuel has many other good characteristics such as a non-proliferation and uranium resource utilization, etc.

The SFR which uses a metal fuel has negative reactivity feedback effects that even when the ATWS (Anticipated Transient Without Scram) event occurs the reactor can shutdown naturally. To remove the decay heat, PDRCs (passive decay heat removal circuits) are installed in the primary reactor vessel.

4. General Design Characteristics of SFR

- Current generation light water reactors are all designed as LOOP type, but SFRs are designed as a POOL type (KALIMER, PRISM, EFR) and a LOOP type (JSFR).
- Current generation light water reactors are operated in a 150 atmospheric pressure and about 300℃ in temperature, but a fast reactor will be operated in the temperature range of 350-550℃. Therefore the thickness of reactor vessel of a fast reactor can be in the range of less than 5 cm.
- In general, two kinds of fuel types are used in the world, one is a metal fuel (USA and Korea) and the other is a MOX (mixed oxide) type fuel (Japan and European countries).
- The cladding of a metal fuel has a characteristic of eutectic phenomena, which starts to lose its thickness above 750℃, but the normal operating temperature of a metal fuel is not so high that the stored heat in a fuel is not so high.
- Metal fuel has a melting point of about 1,000℃ but MOX fuel melts at about 2,300℃. The difference in the melting point gives rise to different source term characteristics between a metal fual and an oxide fuel.
- To reduce the possibility of a Sodium-Water Reaction (SWR), the intermediate heat transport system (IHTS) is devised and it is operated about a 10 atmospheric pressure in a SFR. Now to reduce more the possibility of a SWR, a double wall tube steam generator (DWTSG) is also under research and development.

5. Technical Issues of SFR Level-1 PSA

The methodology and procedure of a PSA of an SFR has no big difference compared to the current generation light water reactors from the following aspects.

- Depth of a PSA : Level 1, 2, 3 PSA

- Scope of the events considered : Internal events and External events

But there exists much difference in the definition of core damage and the source term characteristics due to the difference according to the fuel type used (metal fuel vs oxide fuel), in the reactor types (LOOP or POOL), and the operating temperature and pressures. Therefore, computer codes to simulate the transients and severe accidents should be developed first.

KAERI is developing transient simulation codes such as SSC-K and MARS-LMR now. But the severe accident analysis codes are not being developed yet.

- Now the level-1 event scenarios are under investigation now for the KALIMER-600 reactor concept.
- A few accident scenarios are under simulation for the Transient Overpower (TOP), the Loss of Flow (LOF), and the Loss of Heat Sink (LOHS) events. Each accident scenario is under simulation and analysis with available cases and unavailable cases of the safety systems such as reactor shutdown systems, RCP coastdown feature, inherent reactivity features (Doppler, Sodium void, core axial expansion, control rod axial expansion, core radial expansion, etc.)

6. Technical Issues of SFR level-2 PSA

- The metal fuel, which is supposed to be used in the KALIMER-600 design, has different fission product release modes from a conventional PWR reactor. During a normal operation, the fission gas and volatile fission products produced by a fuel burnup may escape from the fuel and collect in the fission gas plenum. In the course of an accident, the fuel may interact with a clad to form a low melting-point eutectic. Under more severe accidents, the fuel may melt or vaporize.
- The release fraction of gaseous or volatile fission products into the gas plenum is significantly larger due to the interconnected porosities and unimpeded release. On the other hand, a release fraction of solid fission products into the gas plenum is significantly smaller due to the lower operating temperature which impedes the mobility of solid fission products.
- The rate of eutectic formation in a metal fuel increases exponentially for the fuel temperatures greater than about 725℃, and noble gases, halogens and alkali metals have a chance of being released from the fuel.
- The melting point of a metal fuel (~1,150℃) is much less than that of an oxide fuel (~2,300℃). Consequently, a smaller fraction for fission products with boiling points greater than 1,150℃ is expected to be released from the molten metal fuel.
- For extreme accidents where a portion of a fuel is vaporized, all the fission products will be released from the fuel.

7. Future Prospects

The Gen-IV SFRs under design in each country are emphasizing an enforced redundancy/diversity, passive safety systems, and inherent safety features. To implement the risk-informed design and to confirm the enhanced safety, a PSA is being performed or under plan in each country. Moreover, Technology-Neutral approach in a regulatory framework is also selected in each country. This means that we have to perform a Level-3 PSA (consequence analysis) to compare the safety levels between the different Generation IV reactor types such as an SFR and a VHTR, etc.

The Generation-IV reactors will be operated with higher operating temperatures compared to the current light water reactors. Therefore it requires the development of different materials and new codes and standards in a regulatory framework.

To perform a PSA and licensing activities according to the development of a Gen-IV SFR, the methodology and reliability database are not enough or not fully developed, thus an international consensus will be needed.

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