JSFR: JAPAN’S CHALLENGE TOWARDS THE COMPETITIVE SFR DESIGN CONCEPT WITH INNOVATIVE TECHNOLOGIES

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Abstract

The economic competitiveness is one of the crucial points and has been emphasized in the design study of JSFR (JAEA Sodium Fast Reactor) concept. By employing innovative technologies for the NSSS cost reduction, and the complete passive Decay Heat Removal System that leads to BOP cost improvement, it is confirmed that the JSFR design concept is well suited to the development target equivalent to 1,000USD/kWe (as nth-of-a-kind, overnight cost). In this paper, the economical aspect in the JSFR design was summarized.

1. Introduction

JSFR is a sodium-cooled, MOX(or metal) fuelled, advanced loop type fast reactor design concept [1], [2] conducting by Japan Atomic Energy Agency(JAEA) through the Feasibility Study on commercialized Fast Reactor Cycle Systems with participation of all parties concerned in Japan since 1999. The Phase II study of this Feasibility Study project was initiated in 2001, aiming “to identify the most promising candidate concept for the commercialization of the Fast Reactor (FR) cycle, as well as to draw up the future R&D program” [3]. At the end of the Phase II study, in 2006, JSFR concept shown in Fig. 1 was selected as the most promising candidate of the fast reactor system among other fast reactor concepts such as gas-cooled FR and lead/lead bismuth-cooled FR.

2. The way for economical improvement in JSFR design

The economic competitiveness is one of the crucial points and has been emphasized in the design study of JSFR. Sodium cooled reactors (SFR) are operated under the coolant pressure nearly equal to the atmospheric condition. Coolant boundaries in SFRs are designed with thin-walled structure in contrast with that of LWRs. This is the potential that makes SFRs with less amount of steel material than LWRs. In general, however, the cost estimation of some existing SFR designs shows larger construction cost than future LWR designs. One of the reasons is secondary cooling system for mitigating the sodium-water reaction under steam generator tube rupture (SGTR) accident. In the past loop type SFRs, the piping system was designed to have many elbows to ease the thermal expansion stress. This caused an increase in
total piping length and in total area of the piping rooms. Consequently, the construction cost became deteriorated.

In the Feasibility Study, the economical competitiveness has been pursued through the JSFR design study. One of the ways for construction cost improvement is the compact NSSS design by introducing some innovative technologies that seem to be feasible after some R&D efforts. The other way is introducing passive decay heat removal system (DHRS) with natural circulation. The elimination of active components such as pony motors and blowers leads to reduction of the capacity of the BOP system: electricity supply system, emergency DG, “heating, ventilation, and air-conditioning (HVAC) system” and component cooling water system.

### 2.1 Innovative technology for NSSS cost improvement

In order to improve the JSFR construction cost, the following advanced plant design concept was introduced to reduce the amount of the steel for NSSS components.

- a) Simplified and compact design of Reactor Vessel (RV)
- b) Shortened piping layout with inverse L-shaped-pipes
- c) 2 loop cooling system even for the large thermal output (3570MWth)
- d) Integrated intermediate heat exchanger (IHX) with a mechanical pump.

Smaller sized NSSS leads to the reduction of the reactor building. This can also contribute the improvement of the economics. However, to realize these advanced plant design concept, the basic technology explained below are indispensable as shown in Fig. 2.

**Figure 2 Approach for NSSS cost improvement**

**High chromium steel**
Adoption of high chromium steel such as 12 Cr steel could facilitate the shortened piping layout by taking the advantage of its lower thermal expansion and higher strength property. In addition to that, the superior thermal conductivity of 12 Cr steel can contribute to the less heat transfer area that leads to the compact heat exchanger design (IHX and SG). In order to mature this material technology, development on material composition of the high chromium steel optimized for SFR application is needed. The material database and the material strength standard also have to be developed.

**Advanced elevated temperature structural design standard**
This advanced design standard [4] taking into account of inelastic analysis would be applied to the concept of hot vessel design of the RV and the shortened piping layout. To establish this innovative structural
design standard, the development on design methodology for elevated temperature and higher stress conditions and the investigation of inelastic analysis method are necessary.

**New fuel handling mechanism**
The fuel handling mechanism (FHM) in the JSFR design is composed of single rotational plug and pantograph fuel transfer machine. This type of FHM can contribute to the smaller radius RV design together with the upper core internal structure with a slit for fuel transfer movement. The development and the demonstration of this kind of FHM is one of the R&D items for JSFR concept.

**Zr-H reflector**
The better shielding performance of the Zr-H reflector can minimize the number of reflector zone in the core design. This technology can contribute to the smaller radius RV design. Further development such as irradiation test is needed for Zr-H reflector.

**Seismic isolation**
Seismic load is one of the major factors that define the thickness of coolant boundary of SFRs. Seismic isolation technology can ease the load on the components under sever earthquakes. A two-dimensional horizontal seismic isolation system is now feasible. The development of a three-dimensional seismic isolation system is ongoing to enhance the flexibility of siting of a JSFR plant.

**Advanced simulation technology**
Advanced thermal-hydraulic, structural and mechanical simulation technics are necessary to ensure the feasibility of JSFR design. For example, investigation of coolant flow in the reactor upper plenum is one of the cases to be addressed [5]. Because of compactness of the diameter of the RV and the asymmetric design of upper core internal structure with slit, the flow velocity is relatively high and the flow pattern is very complex. The crucial point is avoiding gas entrainment from free surface and vortex cavitations. Other example is investigation of vibration transfer mechanism from centrifugal pump to IHX tubes in the integrated pump-IHX component [6]. Of course, the validation experiment for the simulation code is necessary. Therefore, for these two example cases, reduced scale model tests are ongoing in JAEA.

**Large Reynolds number flow in the bent-piping**
The two loop cooling system with large thermal output leads to high velocity flow in the large diameter piping to gain enough core flow rate. This large Reynolds number liquid sodium coolant flow in the piping has a possibility of flow induced vibration. Investigation of this issue is ongoing using 1/3 scaled mock-up [5]. Ensuring erosion protection at the elbow section is another concern to be addressed.

By adopting the innovative technologies mentioned above, the significant NSSS reduction and the plant volume reduction would be attained as shown in Fig. 3.

![Prototype FBR MONJU](image1)

**Prototype FBR MONJU**
- Thermal Output: 714 MWt
- Electricity Output: 280 MWe
- Reactor Building Volume: 810,000 m³

![JSFR](image2)

**JSFR**
- Thermal Output: 3570 MWt
- Electricity Output: 1500 MWe
- Reactor Building Volume: 130,000 m³

**Figure 3**  **Comparison of Reactor Building Volume**
2.2 Passive DHRS that leads to BOP cost improvement

The other way for getting economical improvement is introducing passive decay heat removal system (DHRS) with natural circulation. In case of a DHRS design composed of active components such as blowers, pony motors and electromagnetic pumps (EMPs), it needs an emergency power supply system to feed power to the DHRS related active components. The emergency power supply system includes power cables, emergency power buses, transformers, emergency-diesel generators (E-DGs), and so on. The demand of the electrical power from the DHRS system is one of the main factors that define the total power capacity of the E-DGs. The sea water system (SWS) must be designed to have enough capacity that can maintain cooling function of the E-DGs in addition to other components. Furthermore, the plant has safety-grade HVAC system for cooling the electric equipment rooms related to the emergency power supply system. An example of such a kind of functional dependencies among the DHRS active components and the BOP is graphically shown in Fig. 4.

In contrast to the active DHRS design, a complete passive DHRS concept taking advantage of natural circulation ability of liquid sodium coolant could facilitate not only elimination of the active components, but also reduction of the BOP design capacity. Furthermore, the volume reduction of the buildings could be expected. As shown in Fig. 5, these spin-off effects coming from the passive DHRS design could contribute to the saving of the plant construction cost.

The drawbacks of the passive DHRS concept is a possibility of increased steel material in the cooling system to gain needed natural circulation heat removal capacity: an increase in the heat exchanger surface area, a larger elevation difference for enhancing natural circulation head and so on. At the start of the Feasibility Study, the initial design of the DHRS was based on active components. In the progress of design study, the complete passive DHRS concept was employed to seek for rationalization of the BOP design. To meet the safety requirement such as core cooling function under the design basis events, the heat transfer area at the air cooler heat exchanger had to be increased. However the increase in the amount
of steel in the DHRS design was found to be small thanks to the loop type concept that has enhanced natural circulation capability without any significant modification. The main heat transport system and the DHRS of JSFR concept are shown in Fig. 6.

![Figure 6: The cooling system of JSFR](image)

The re-criticality free core and in-vessel-retention safety design concept [7] can allow employing the steel plate reinforced concrete (SC) containment vessel that also contributes to the economical improvement.

3. The achievement of the economic competitiveness

The target value of construction cost is less than 200,000yen/kWe (as FOAK, with interest) in the JSFR design study. As a result of design study, it is confirmed that the JSFR design concept would attain around 90% of the development target while ensuring safety [7], [8]. This attained construction cost is nearly equivalent to 1,000USD/kWe (as NOAK, overnight cost). As a result of the construction cost comparison between the active DHRS design and the passive one, about 2.5% reduction would be expected by employing the passive DHRS. This reduction rate is not so large, but its absolute value is not insignificant. One of the merits with adopting the passive DHRS is less safety grade SSC (system, structure and component) and more non-safety grade SSC in the BOP. The estimated 2.5% reduction did not consider the change of SCC grade. This kind of grade change may bring some benefits to the operation and maintenance (O&M) cost through the ease of maintenance burden, rather than the construction cost.

The most of the construction cost reduction comes from the innovative technologies mentioned in the 2.1. The R&D plan of these technologies was summarized as a roadmap and the R&D efforts are ongoing for establishing a technical scheme of FR cycle systems by around 2015 [8].

4. Power generation cost reduction

In order to attain lower power generation cost, not only less construction cost but also less operational cost including fuel cycle cost is crucial. As shown in Fig. 7, higher burn-up of the averaged core, more than 150GWd/t, has been applied in the JSFR design by introducing ODS steel cladding material [9]. In the core design [2], longer reactor cycle length more than 18 months is pursued in order to improve the plant operational availability. The low pressure drop core design (~ 0.2MPa) could contribute not only to the passive DHRS design but also the operational cost due to less in-house load power.

The shorter restore or recovery time from the accidental situation would result in higher operational availability. Therefore, the localization of the damage by sodium-air or sodium-water reaction is essential way for quickly restoration. For that reason, the double-wall sodium boundary design is pursued in the JSFR design study. All the sodium coolant piping has outer boundary structure without significant material increase because of the shortened piping layout concept. In the SG design, the double-wall straight-tube type SG design is adopted to minimize the possibility of failure propagation following one tube rupture in
the SG. This innovative SG technology is based on the high chromium steel and the advanced elevated temperature structural design standard.

-- Diagram --

Basic key technology or design option

- ODS steel fuel pin cladding
- Long reactor cycle length
- Low pressure drop core
- Advanced elevated temperature structural design standard
- High chromium Steel
- Shortened piping layout

Fuel cycle cost improvement

- Higher burn up core
- Break even breeding and less blanket
- O&M cost improvement
- Higher operational availability
- Less in-house load power

O&M cost improvement

- Power generation cost reduction

5. Conclusion

By adopting the systematic cost improvement measures in the JSFR design, the economical target could be satisfied in the future. The progress of the necessary R&D program related to the innovative technology and the base technology is crucial to realize the cost competitive JSFR concept as the Generation –IV reactor concept.

6. References


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