A NEXT GENERATION SODIUM-COOLED FAST REACTOR CONCEPT AND ITS R&D PROGRAM

MASAKAZU ICHIMIYA*, TOMOYASU MIZUNO and SHOJI KOTAKE
Japan Atomic Energy Agency
4002, Naritacho, Oarai-machi, IBARAKI, Japan
*Corresponding author. E-mail : ichimiya.masakazu@jaea.go.jp

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Critical issues in the development targets for the future fast reactor (FR) cycle system, including sodium-cooled FR were to ensure safety assurance, efficient utilization of resources, reduction of environmental burden, assurance of nuclear non-proliferation, and economic competitiveness. A promising design concept of sodium-cooled fast reactor JSFR is proposed aiming at fully satisfaction of the development targets for the next generation nuclear energy system. A roadmap toward JSFR commercialization is described, to be followed up in a new framework of the Fast reactor Cycle Technology development (FaCT) Project launched in 2006.

KEYWORDS : Sodium-cooled Fast Reactor, Innovative Technology, Construction Cost, MA Burning, ISI & R, JSFR, Fast Reactor Cycle Technology Development (FaCT) Project

1. INTRODUCTION

Critical issues in the development targets for the future Fast Reactor (FR) cycle system, including Sodium-cooled Fast Reactor (SFR) were to ensure safety assurance, efficient utilization of resources, reduction of environmental burden, assurance of nuclear non-proliferation, and economic competitiveness. Several conceptual designs for next generation SFR have been developed aiming at fully satisfaction of the development targets. Among them, Japan Atomic Energy Agency (JAEA) Sodium Fast Reactor (JSFR) is a sodium-cooled, MOX fueled, advanced loop-type evolved from Japanese fast reactor technologies. Three key issues are incorporated for the JSFR plant system design to meet the development targets. (1) Reduction of construction and operation costs by innovative technologies; FR plant construction cost is the largest factor in the electricity generation cost among the fuel cycle system. To reduce the construction cost in JSFR plant system, various innovative technologies were required for the system concept and main components in JSFR. (2) Strategy for safety design improvements; Passive safety functions and re-criticality free core should be introduced to enhance the safety for Design Basis Events (DBEs) and Design Extension Conditions (DECs). (3) Conquering the drawbacks of sodium system; Possibility of sodium-water reaction in a steam generator (SG) should be minimized along with the higher availability and lower operation cost. In-service inspection and repair (ISI & R) capability and sodium-leak tight methodology should also be taken into account to ensure the reliability of the system for commercial operation.

This paper provides development targets for the next generation FR, a detailed description of JSFR and evaluation on the JSFR performances for safety and economic competitiveness. Furthermore, a roadmap toward JSFR commercialization is described, to be followed up in a new framework of the Fast reactor Cycle Technology development (FaCT) Project launched in 2006.

2. DEVELOPMENT TARGETS AND DESIGN REQUIREMENT FOR NEXT GENERATION FR

2.1 Development Targets

The development targets for the next generation SFR are summarized as follows [1]:

(1) Safety assurance

The safety design approach for the SFR places the highest priority on preventing the occurrence and evolution of abnormal conditions based on the concept of Defense in Depth. A safety level equivalent to or better than contemporary light-water reactor cycle systems should be achieved. Additionally, in light of the facility characteristics, a more reliable and clearer safety approach is required.

Passive safety functions should possibly be added or enhanced, and regarding the reactor, measures should be taken for the prevention of re-criticality in the case of any hypothetical core disruption, in order to ensure that the impact of such a hypothetical accident is confined within the boundary of the reactor vessel or the containment vessel.

The goal of the implementation of these measures is to render the risk of installing the SFR cycle system sufficiently small compared with other risks already existing in society.

(2) Economic competitiveness

For the commercialization of SFR system, it is important to achieve a level of economic competitiveness that enables the system installation in accordance with market principles. For this purpose, an important goal should be to ensure enough competitiveness in terms of energy cost (unit cost of power generation) compared with the competing energy sources in the future.

(3) Reduction of environmental burden

For the effective commercialization of SFR systems, it is necessary to bring into full play the advantages of a fast spectrum reactor with full recycle as the energy generation system that can minimize the impact on the global environment, with features such as its excellent thermal efficiency, the greater utilization of fuel resources, and the

Table 1. Major Design Requirements of the SFR System and Generation IV Goals

SFR System		Generation Ⅳ goals	
Breeding Capability	Breeding ratio: ca. 1.2, System doubling time: ca. 30 years	Sustainability	-1: Resource utilization
TRU Burning	TRU burning under fast reactor multi-recycle and long-term storage of LWR spent fuel		-2: Waste minimization and management
Radioactive Release	Equivalent or less than present LWR application		
PR&PP	Excludes pure-Pu state throughout system flow	Proliferation Resistance and Physical Protection	-1: Minimize diversion or undeclared production -2: Reactors have passive features that resist sabotage
Safety	Operability, maintenability and repairability	Safety and Reliability	-1: Operations will excel in safety and reliability
	Passive safety		-2: Very low likelihood and degree of reactor core damage
	re-criticality free, core damage frequency less than 10^{-6}/ry		-3: Eliminate the need for offsite emergency response
Electricity Generation Cost	Cost-competitiveness with other means of electricity production and a variety of market conditions, including highly competitive deregulated or reformed markets	Economics	-1: Life-cycle cost advantage over other energy sources (Low overnight construction cost, Low production cost)
Operation Cycle	ca. 18 months, and more		-2: A level of financial risk comparable to other energy project
Construction Duration	As a goal, large-scale: 42 months, medium-scale modular type: 36 months		

small amount of waste generated per energy output unit and the minimization of long-lived actinides with high heat generation rates. As other nuclear systems, the SFR contributes to the reduction of the greenhouse effect (CO_2 emissions) compared with electricity generated with fossil fuels.

With the excellent neutron economy characteristics of the SFR, there is a possibility of achieving further reductions in the exposure dose and risks associated with geological disposal, which are already at safe levels, by utilizing the transuranic (TRU) burning characteristics along with implementation of separation and transmutation methods.

(4) Efficient utilization of resources

The capacity for efficient burning of TRU materials, including degraded plutonium, and the excellent neutron economy are some of the advantages of the SFR, which enable the utilization of nuclear energy as a sustainable energy source over a very long time period of more than thousand years. Accordingly, the effective utilization of uranium resources includes the recycling of TRU.

The current outlook is that long-term demand for energy will keep increasing on a global scale, but because there is an element of uncertainty in any projection regarding energy supply and demand, an SFR system should possess the flexibility to adapt to changing energy needs by adjusting its actinide management capability (from net consumption to net generation of fissile material).

(5) Resistance to nuclear proliferation and enhanced physical protection

Resistance to nuclear proliferation and enhanced physical protection is a goal established for advanced systems and technologies that aims at (1) making a next generation system the least desirable route to obtaining nuclear material for use in nuclear weapons or other explosive devices, by a nation or a sub-national entities, and (2) making the system less vulnerable to acts of sabotage.

Among the technical features that contribute to the proliferation resistance of the SFR are the characteristics of the recycling process, which include the presence of minor actinides (MA) and highly radioactive (β, γ) fission products (FP) in the recycled fuel, rather than the separation of plutonium. This results in lowering the chemical purity and the fissile fraction of Pu, and in an increase in the surface dose rate of the recycled product. These features enhance the difficulty of accessing the nuclear materials in the fuel cycle and lower their attractiveness, since separated plutonium does not exist in its pure state in any of the system's processes. Regarding the organizational aspects, it is necessary to implement nuclear safeguards (IAEA safeguards agreements) and to always maintain an accurate material inventory through the utilization of advanced technologies.

2.2 Design Requirements

The design requirements for the SFR system, shown in Table 1, are established in order to satisfy the development targets. The design requirements are consistent with the Generation IV goals [2].

3. OUTLINE OF THE JSFR DESIGN

3.1 Key Design Parameters and Plant Configuration

JSFR is a sodium-cooled, TRU mixed oxide (TRU-MOX) fueled, advanced loop type fast reactor. The key plant design parameters for the JSFR are also listed in Table 2. The bird's eye view of the JSFR is depicted in Fig.1, and the schematic of the reactor and heat transport system is depicted in Fig. 2.

3.2 Reactor Core Design

3.2.1 High Burn-up MOX Fuels, TRU Bearing Fuels

The reference core of JSFR is TRU-MOX high burnup core [3]. Major targets of the core design are as follows:

(1) 150 GWd/t of discharge average burnup for core fuel
(2) 550℃ of reactor vessel outlet temperature
(3) More than 18 months of operation cycle length
(4) 6.9 m of envelope diameter of radial shielding region around the core

Table 2. Main Plant Specifications

Items	Specifications
Electricity output	1,500MWe
Thermal output	3,570MWt
Number of loops	2
Primary sodium Temperature and Flow rate	550 / 395°C 3.24×10^7 kg/h / loop
Secondary sodium Temperature and Flow rate	520 / 335°C 2.70×10^7 kg/h / loop
Main steam temperature / Pressure	497°C / 19.2MPa
Feed water temperature / Flow rate	240°C / 5.77×10^6 kg/h
Plant efficiency	Approx. 42%
Fuel type	TRU-MOX
Burn-up (Ave.)	Approx. 150GWd/t
Breeding ratio	Break even (1.03), 1.1
Cycle length	26months, 4batchs

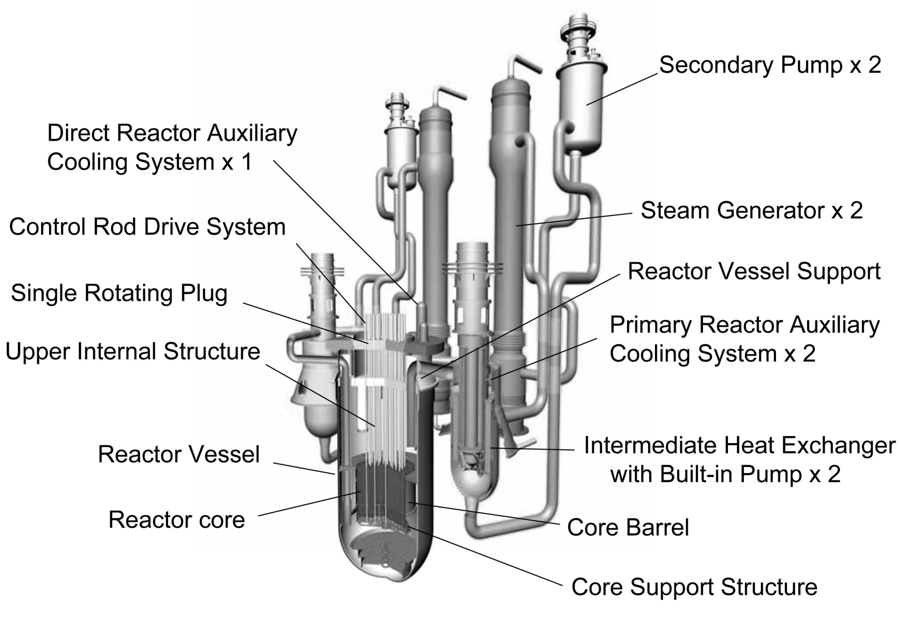


Fig. 1. JSFR Plant View

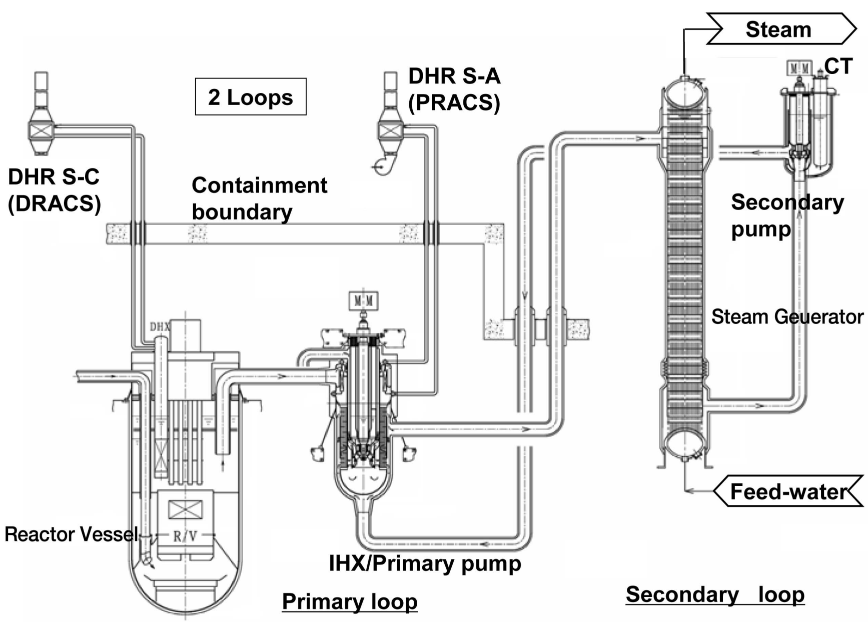


Fig. 2. Schematic of the Reactor and Heat Transport System

The maximum neutron dose and cladding temperature are $5x10^{23}$n/cm^2(E>0.1MeV, 250dpa(Fe)) and 700°C which correspond to 150GWd/t of average burnup and 550°C of reactor vessel outlet temperature. Dimensional stability and high creep rupture strength are required for core materials of JFSR. The ODS(oxide dispersion strengthened) ferritic steel and PNC-FMS(ferritic martensitic steel) sub-assembly duct are selected to achieve these values.

The reference TRU isotopic composition of TRU-MOX fuel is a typical fast reactor cycle equilibrium composition under homogeneous recycling of TRU, which contains about 5% of minor actinides in whole TRU. Other TRU

Table 3. Core and Fuel Specifications of JSFR Reference Design

Items	Breeding Core	Break Even Core
Nominal full power (MWe/MWt)	1,500 / 3,570	←
Coolant temperature [outlet/inlet] (°C)	550 / 395	←
Primary coolant flow (kg/s)	18,200	←
Core height (cm)	100	←
Axial blanket thickness [upper/lower] (cm)	20 / 20	15 / 20
Number of fuel assembly [core/radial blanket]	562 / 96	562 / -
Envelope diameter of radial shielding (m)	6.8	←
Fuel pin diameter [core] (mm)	10.4	←
Fuel pin cladding thickness [core] (mm)	0.71	←
Number of fuel pin per assembly [core]	255	←
Wrapper tube outer flat-flat width (mm)	201.6	←
Wrapper tube thickness (mm)	5.0	←

Table 4. Core Characteristics of JSFR Reference Design

Items		Breeding Core	Break Even Core
Nominal full power (MWt)		3,570	←
Operation cycle length (months)		26	←
Refueling batch [core/RB]		4 / 4	4 / -
Pu-enrichment [Pu/HM] (wt%)	inner core	18.3	18.3
	outer core	20.9	21.1
Burnup reactivity (% $\triangle$k/kk')		2.3	2.5
Breeding ratio		1.10	1.03
Discharge burnup (GWd/t)	core	147	150
	core+blanket	90	115
Maximum linear power (W/cm)		398	411
Core specific power (kW/kg-MOX)		41	41
Maximum neutron dose*1 (n/cm^2)		5.0×10^{23}	4.9×10^{23}
Pu fissile inventry (t/GWe)		5.7	5.8
Dobling time*2 (yr)		72	-
Doppler coefficient*3 [Tdk/dT]		-5.7×10^{-3}	-5.8×10^{-3}
Sodium void reactivity*3 ($)		5.3	5.3

*1 E > 0.1Mev *2 Compound system doubling time *3 EOEC

isotopic compositions such as LWR spent fuel origin compositions are also considered to evaluate the flexibility of the core.

Table 3 and 4 show the core and fuel specifications and the core characteristics, respectively, of a JSFR large scale reference design. Figure 3 shows large scale core configuration. Large diameter fuel pin, 10.4mm in diameter, is applied to the reference JSFR design. Table 3 shows two compatible cores, breeding core and break even breeding core. Average burnup of core fuel reaches 150GWd/t for both cases. In

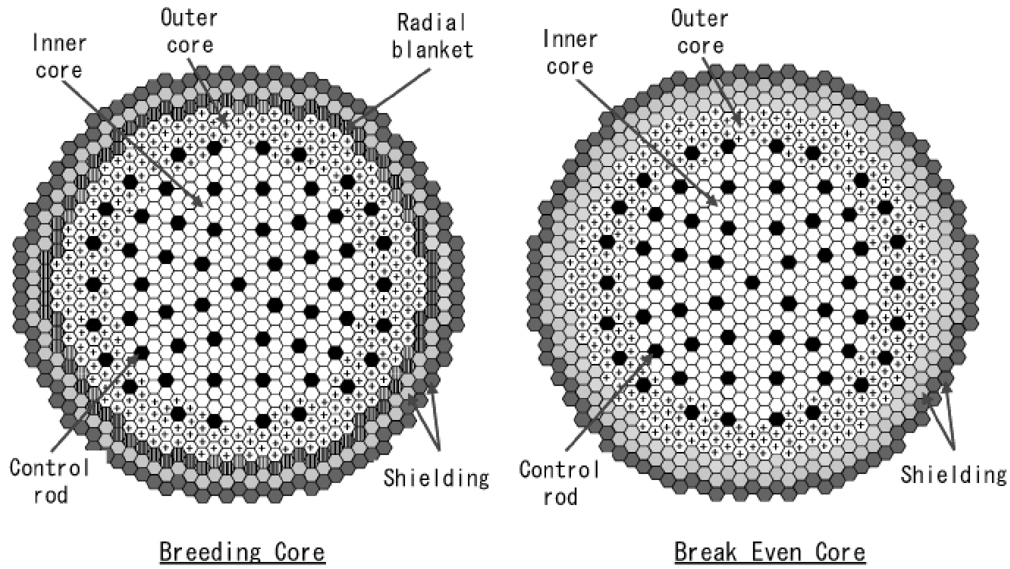


Fig. 3. Core Configuration of JSFR Reference Design

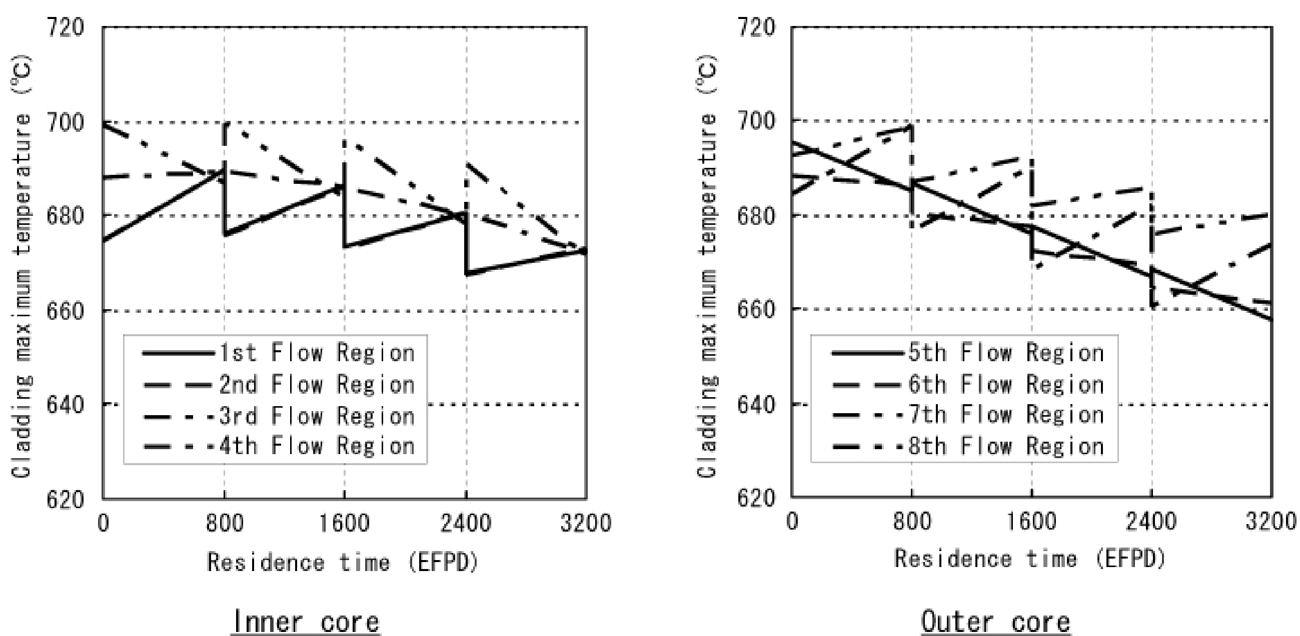


Fig. 4. Fuel Cladding Mid-wall Temperatures of JSFR Reference Design

case of break even breeding core, breeding ratio reaches 1.03 without radial blanket and its average burnup including axial blanket reaches as high as 100GWd/t. Operation cycle length is 26 months with low value of burnup reactivity swing. These excellent characteristics attribute to high fuel volume fraction of the core due to large diameter fuel pin. The envelope diameter of radial shielding region satisfies the target value.

The plutonium enrichments are around 20% and corresponding minor actinide contents are around 1%, which does not give significant degradation of fuel performance.

Other characteristics of the core such as plutonium inventory and core void reactivity satisfy the Japanese domestic scenario of fast reactor deployment and safety consideration, respectively.

The core thermal hydraulic design achieved less than 700℃ of cladding maximum temperature. Figure 4 shows the result of cladding temperature evaluation, which includes uncertainties to be considered in the thermal hydraulic design, such as sub-assembly coolant flow rate and power distribution. The cladding creep damage evaluation confirmed fuel pin integrity based on the ODS cladding creep rupture strength.

The shielding calculation showed satisfactory capability of shielding around the core.

3.3 System Design

3.3.1 Reactor Vessel and Internal Structure

Compact Design of Reactor Structure

The JSFR reactor vessel and internal structures are designed compact as shown Fig.5 in order to reduce construction cost. The cross sectional view of the reactor vessel is also shown in Fig.6.

Diameter, height and wall thickness of the JSFR reactor vessel are 10.7 m, 21.2 m and 30 mm, respectively. The reactor vessel accommodates a large core barrel of 7.0 m in diameter. The slit Upper Internal Structure (UIS) allows for a fuel handling machine [4] to access any fuel subassembly with a compacted single rotating plug. While the inlet and outlet piping come from the top of the reactor vessel shown in Fig.5, such piping arrangement contributes to enhance the structural integrity of the reactor vessel by suppressing local structural discontinuity like nozzles in its wall. Another feature is four ISI holes arranged at the roof deck from which a special ISI device (under sodium viewer) enters. This inspection hole extends from the top of the roof deck through the reactor core support skirt. The four inspection holes shown in Fig.6 should be sufficient to access all the reactor core support skirt and the lower plenum region.

The reactor vessel and reactor internal structure are made of modified 316 stainless steels because of improved long-term strength and ductility. The reactor vessel wall thickness is determined to be 30 mm taking account of a horizontal seismic isolation design and no significant pressure owing to re-criticality free core.

Extensive experimental studies [5, 6] have been conducted in order to manage the coolant flow in the upper plenum without gas entrainment from the free surface which is one of the critical issues for the compact design.

3.3.2 Primary Heat Transport System (PHTS)

Reduction of Loop Number

The JSFR utilizes the advantage of the economy of scale with regard to component in the heat transport system

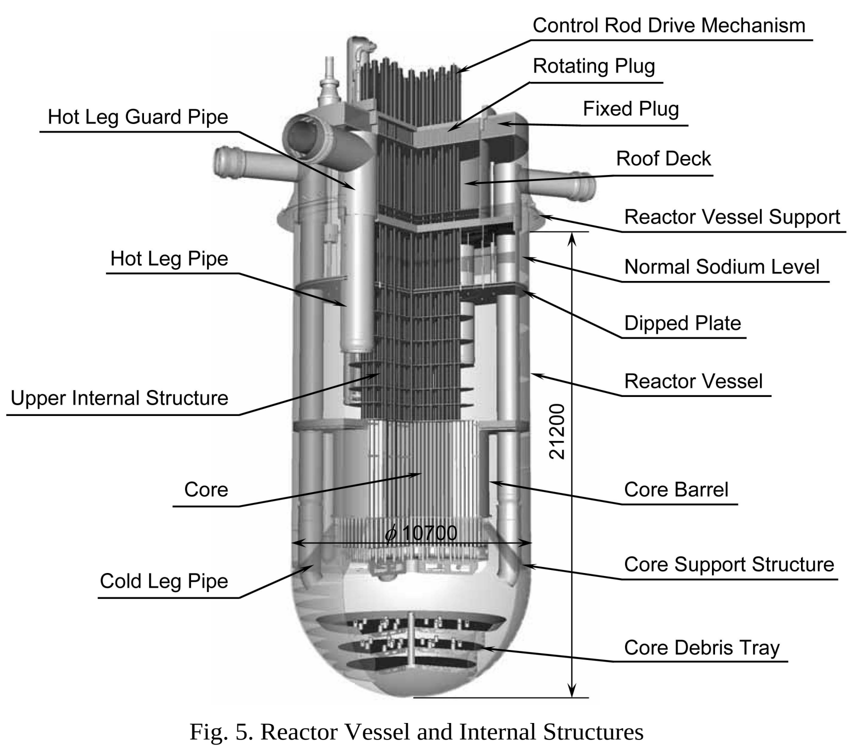


Fig. 5. Reactor Vessel and Internal Structures

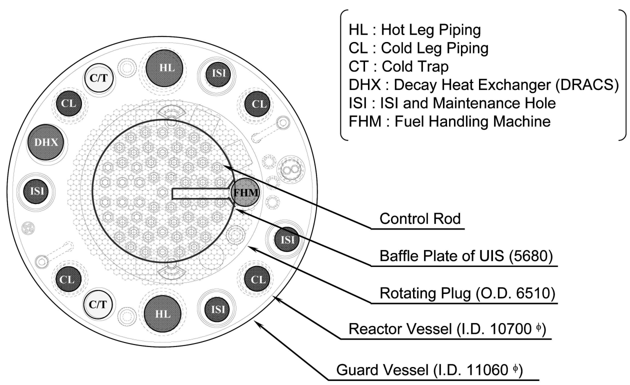


Fig. 6. Cross Sectional View of Reactor Vessel

by reduction of loop number. The number of main primary transport loop is set to two even for 1500 MWe power output, as shown in Fig.1. As a result, the heat transport system of the JSFR accompanies with a large volumetric flow rates in a large diameter piping system. The coolant velocities are 9.2m/sec and 9.8m/sec for the hot leg piping of 1.27m in inner diameter and the cold leg piping of 0.863m in inner diameter, respectively. Intensive experimental studies have been conducted to resolve resistance and fluctuating pressure of a large elbow in high Reynolds number [7].

Reduction of the loop number from four to two reduces the amount of materials for NSSS (Nuclear Steam Supply System) and the volume for the reactor building by 13% and 10%, respectively. Regarding the safety, the transient analysis shows that one loop is enough to cope with an instantaneous loss of flow caused by a primary pump seizure event.

Shortened Piping Layout

The primary hot leg piping has been simplified by using a simple L-shaped piping as shown in Fig.1. The shortened primary piping layout results in a compact plant configuration through a close arrangement of components, as well as a reduction of the amount of piping materials.

The design of the shortened piping layout and reduction of the loop number benefits from adopting high chromium ferritic steel, in place of an austenitic stainless steel, for the primary components and pipes, except the reactor vessel. The reason was that, thanks to the advances in steel production technology, ferritic steels can be used as the structural material of the primary sodium components and the high chromium pipes with confidence. In fact, high chromium steels with improved creep strength and weldability have been developed for fossil power plant applications. High chromium forged steel was realized through some major technical breakthroughs that took place in 1990s, including the technology of eliminating gaseous elements from the steel and new knowledge about the effect of tungsten/molybdenum to improve high temperature strength. The superior strength of the high chromium steel against thermal stresses comes from its low thermal expansion property and sufficient creep strength. Since the most important property required for JSFR structural materials is to accommodate the steady and transient thermal stresses, high chromium steels possess great potential as a JSFR structural material.

IHX with a Built-in Pump

The primary cooling system has been significantly simplified by adoption of an IHX with a built-in primary pump and elimination of middle leg piping. As shown in Fig.7, the baffle plates are installed to support the tube bundle as well as to improve heat exchange capability while maintaining gaps of 0.1-0.3 mm. Though the IHX with a built-in primary pump requires a larger tube sheet, an adoption of the high chromium ferritic steel ensures its structural integrity.

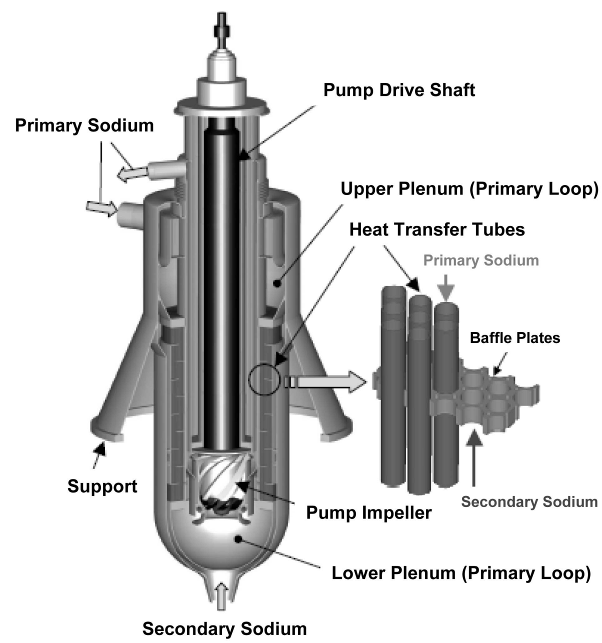


Fig. 7. IHX with Built-in Primary Pump

A critical issue in this component is the fretting wear of the heat transfer tubes by the baffle plate. For the tube integrity, vibrations transferred from the primary pump shaft to the tubes must be suppressed to an allowable limit. The experimental investigation is in progress to control the vibration of the tubes [8].

3.3.3 Measures Against Chemical Reaction of Sodium

Double-Walled Tube SG

It is desirable that a sodium heated SGs of a commercialized FR should minimize the possibility of sodium / water reaction, because the failure of plural heat transfer tubes by sodium / water reaction jets or reaction products significantly affects the availability of the plant. A double-walled tube SG system, shown in Fig.8, whose wall are mechanically contacted by pre-stress can minimize the possibility of sodium-water reactions, since the frequency of simultaneous penetration through both walls can be kept low enough with proper ISI of tubes by such methods as an ultrasonic test (UT) and an eddy current test (ECT). The tube sheet is a single hemi-sphere for simplicity and strength against the water-side pressure. Thermal-hydraulic design of the sodium inlet plenum is refined to make uniform the radial sodium flow distribution into the tube bundle region [9]. This horizontally uniform sodium flow contributes to flatten the temperature distribution in the bundle region. This is indispensable for preventing tube buckling or tube to tube sheet junction failure. The convoluted shell expansion joint (CSEJ) are expected to compensate for a thermal expansion difference between the SG shell and the tube bundle. Sodium and water flow directions are counter to each other, and sodium flow is parallel about the axis to reduce the pressure loss and to avoid tube-fretting. No flow dynamic instability of water is expected to occur at an operating steam pressure of 19.2 MPa without orifice. This orifice-less method favors tube with reliability in that there are no undesirable phenomena like erosion or blockage at an orifice.

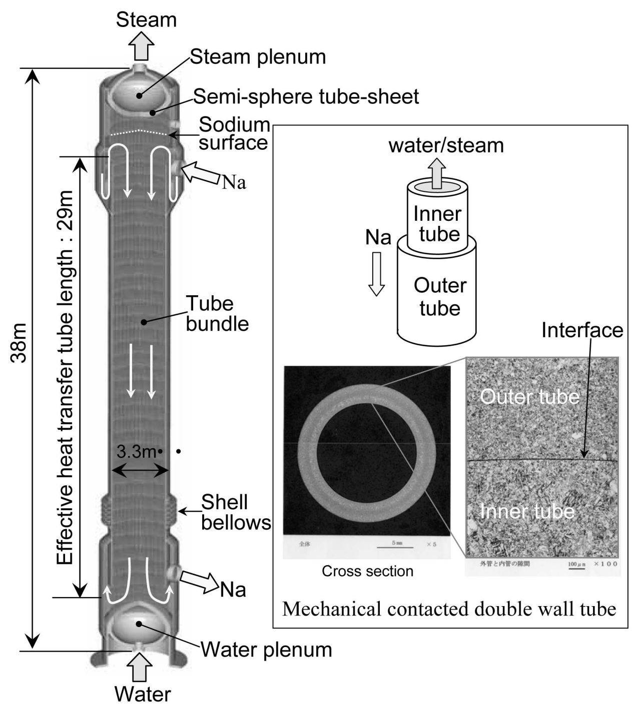


Fig. 8. Double-walled Tube Stream Generator System

Sodium-Leak-Tight Piping

One of the countermeasures against sodium leakage is that the whole sodium boundary of the primary and secondary heat transport systems and DHRS are covered with a guard vessel and/or guard piping structure. These measures restrict the amount of leaked sodium by accommodating it within the limited area of the guard vessel or guard piping structure, thus the sodium-surface level in the reactor vessel is maintained enough high for core cooling function. Further, sodium combustion accompanied by leakage is prevented, since the closed space between inside the outer wall is filled with inert nitrogen gas which is of lower cost than argon gas. The outer wall structure is welded to keep its sodium-leak-tightness.

In-Service Inspection and Repair

While structures and components of a nuclear power plant should be correctly designed, manufactured and operated at all times within design limits, it is essential to provide some detection methods for unforeseen degradations. This can be provided by continuous monitoring of sensitive parameters chosen as representative of the structure or component condition, which is carried out during reactor operation and complemented by planned periodic inspections during reactor shut down.

3.4 Safety Design

A deterministic approach for both DBEs and DECs are taken into account for the system design, although appropriate design margins are provided by adopting conservative design evaluations for DBEs and by best estimate design evaluations for DECs. The deterministic approach according to the Defense in Depth is adopted to specify safety functions, such as reactor shutdown system (RSS) and decay heat removal system (DHRS) for prevention of core damage. Figure 9 shows a framework of safety assurance for JSFR design [10].

RSS consists of two independent sub-systems, i.e., primary RSS and back-up RSS. Each of them is designed to prevent fuel failure against DBEs. In addition, a Self-actuated Shutdown System (SASS) is incorporated for the backup RSS as a passive shutdown feature. One direct reactor auxiliary cooling system (DRACS) and two primary reactor auxiliary cooling system (PRACS) are adopted as the DHRS. They are designed for fully passive operation as well as redundant capacity to achieve sufficient reliability.

In the consideration of DECs, the mitigation of CDAs is important. In order to achieve both of social acceptance and rational plant design, it is crucial to show that severe mechanical energy release due to re-criticality events can be eliminated from CDA scenarios [11]. For this purpose, a special fuel assembly design features are considered for

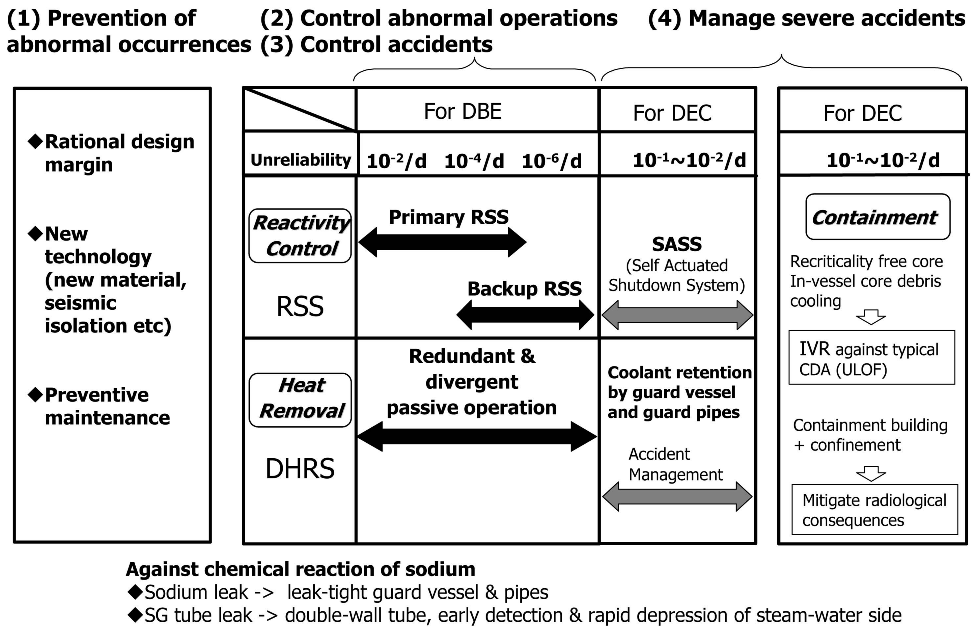


Fig. 9. Framework of Safety Assurance in JSFR

molten fuel discharge from the core in cases of CDA as well as the limitation of the core sodium void worth. At the bottom of the reactor vessel, a multi-layered structure is considered for the debris retention within the reactor vessel. These design features reduce the design loads on the containment significantly and allow compact containment design.

3.4.1 SASS; Self-Actuated Shutdown System

The Curie point electromagnet SASS consists of an electromagnet and an armature that are parts of its magnetic circuit containing a temperature-sensing alloy as shown in Fig.10. The magnetic force is abruptly lost when the alloy is heated up to its Curie point by the heated coolant from the core. Then the armature de-latches at the detach surface and drop together with the control rod into the reactor core. The Curie point SASS is a simple structure and has flexibility of the detaching position [12, 13].

3.4.2 Natural Circulation with DRACS and PRACS in Decay Heat Removals

The JSFR adopts a combination of one loop of DRACS and two loops of PRACS. PRACS are located in the upper plenum of IHXs. Heat exchangers of DRACS are arranged in the reactor vessel. These DHRSs can be operated under fully passive conditions, which mean that, without pumps and blowers, it is required only to activate the DC-power-operated dampers of the air coolers. The damper system

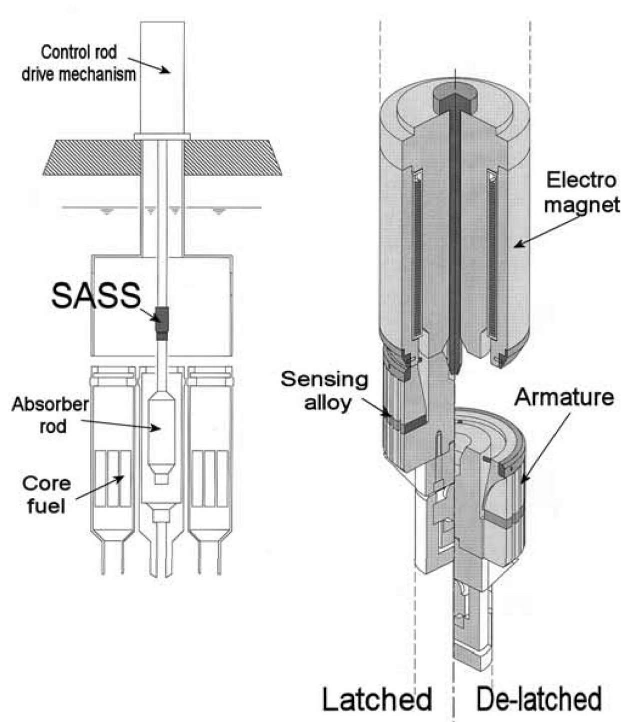


Fig. 10. Self-actuated Shutdown System

has redundancy so that it does not lose its function even considering the single-failure criterion, i.e., each air cooler has two dampers in parallel so that an opening failure of a single damper causes less than a 50 % reduction in the air flow rate. In addition, diversity is taken into account in the mechanical design of the dampers between DRACS and PRACS. JSFR is suitable for natural circulation cooling due to its simple and short piping connection and due to the lower pressure loss of the core design, as well as the sufficient height difference between the core and the heat exchangers. Since both DRACS and PRACS have a sodium-sodium heat exchanger inside the primary heat transport system, they are not affected by the abnormal conditions initiated in the secondary heat transport system and the steam-water systems. Regarding the DRACS, the primary sodium flow consists of natural circulation in primary loops and also the gap flow between fuel subassemblies.

4. EVALUATION OF THE JSFR PERFORMANCES

4.1 Ensuring Safety

Some preliminary safety evaluation were conducted to examine the feasibility of the safety design concept. As typical DBEs, the primary pump seizure accident, the control rod withdrawal and loss of offsite power were evaluated. In the evaluation for DBEs, some typical conservative conditions, which includes the single failure criteria, were applied. As the typical DECs, the prevention and mitigation performances against ATWS are discussed.

4.1.1 Enhancement of Plant Reliability

The JSFR is designed with emphasis on simplification to enhance reliability, availability and maintainability. The design features relevant to enhancement of reliability are identified as follows;

(1) Since the major components can be designed with small diameter such as 10m for the reactor vessel, these can be fabricated in factories with higher quality (no need on-site fabrication).

(2) The total length of welding line for the JSFR is deemed to be shorter owing to the simplified design. In particular, major components can be fabricated without any vertical weldings which could be critical from the structural integrity point of view.

(3) The JSFR is favored with easier maintenance due to the simplified design for vessel internals such as simple core support structure.

(4) The JSFR has the technical feasibility to the severe seismic condition by adoption of the horizontal seismic isolation which has been already developed.

4.1.2 Evaluation for DBEs

(a) Loss-of-flow type events

In JSFR, due to a two-loop system, the PHTS pump seizure accident would become severer than that of conventional three- or four-loop design. However, some design adjustments make it possible to accommodate the maximum cladding temperature within the safety criterion. Each RSS was designed so as to independently shut the core down within the cladding temperature limit. The primary and backup RSSs are activated by signals indicating “low primary pump speed” and “low primary flow rate,” respectively. Figure 11 shows a calculated result for the primary RSS case. The activation signal was the “low primary pump speed” signal corresponding to 80% of the normal speed. The maximum temperatures of cladding and coolant were lower than the criteria, i.e., 900°C.

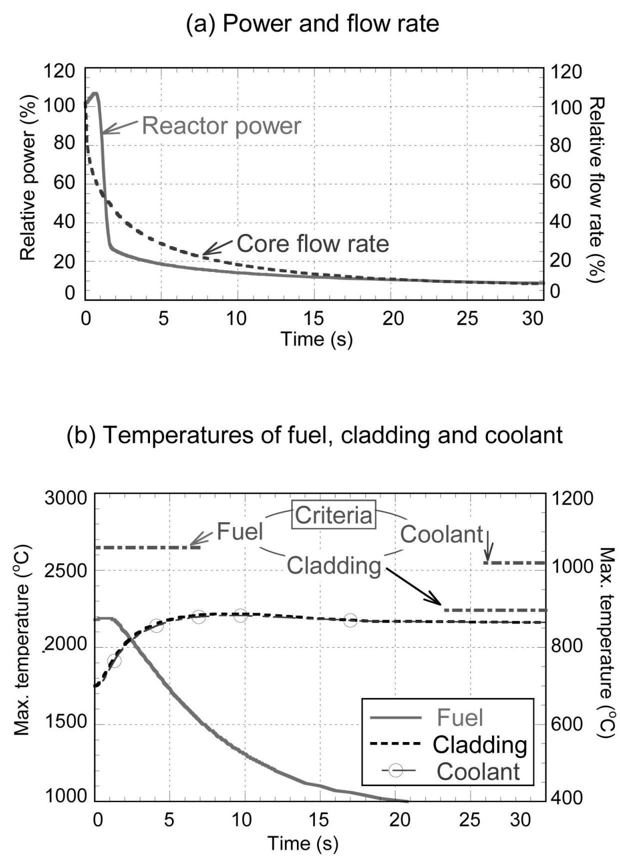


Fig. 11. Evaluated Results for Primary Coolant Recirculation Pump Seizure Event

(b) Transient-over-power type events

Control rod withdrawal events were also analyzed for a medium-scale reactor earlier than a large-scale reactor, and the result met the criteria as presented in Fig.12. It was assumed in this calculation that the primary RSS was activated by the “high power range neutron flux” signal.

In spite of the larger size of the core, the neutron monitor array installed outside the core, which is used for the power range neutron flux, can detect the entire range of reactivity insertion rate, from 0.1 cent/s to 10 cent/s, and can safely shut the core down.

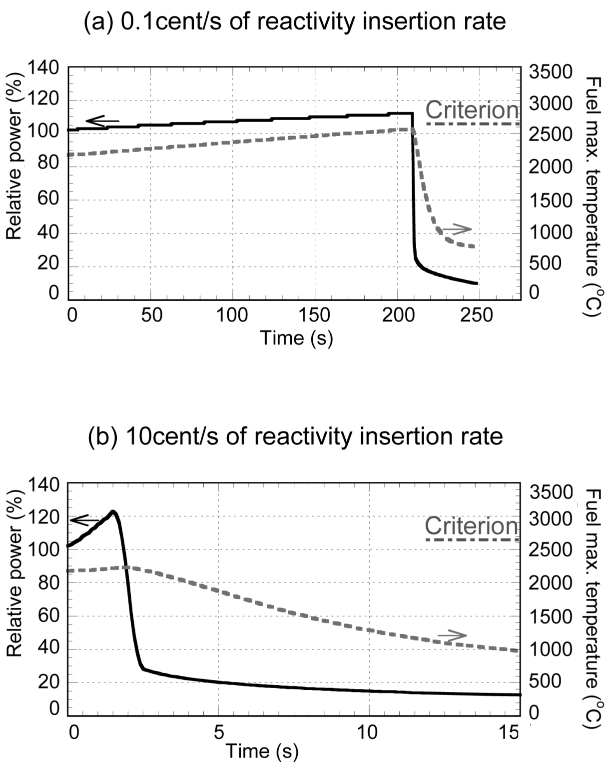


Fig. 12. Evaluated Results for Control Rod Withdrawal Event

Using different activation signals, both the primary and backup RSSs are effective at preventing fuel pin failure. The outlet coolant temperature of fuel assemblies around a withdrawn control rod can be a favorable signal for a low reactivity insertion rate, while the relative deviation of the control rod position can be a good signal for a high reactivity insertion rate. In case of single rod withdrawal, a local power peak, which causes a local coolant temperature increase, appears in the vicinity of the withdrawn rod. This local temperature peak is more pronounced in the low reactivity insertion rate due to its longer transient time. In the high reactivity insertion rate, it is effective to limit the amount of the inserted reactivity by the rod position change. In this case, the coolant temperature increase is rather small due to its shorter transient time. With the aid of these diverse detection means, fuel melting due to control rod withdrawal events can be safely prevented.

(c) Decay heat removal

For a fully passive feature like the DHRS, the evaluation for abnormal transient events is very important, especially from the viewpoint of assuring fuel integrity by the establishment of a coolant circulation system that is stable during slower transient events. A typical result of loss-of-offsite-power transient analysis for a large-scale reactor is shown in Fig.13. After the first peak in the maximum cladding temperature just after reactor shutdown, second and third peaks appeared at around 200s and 1000s, respectively, in the course of the transient event. However, the temperature fluctuation was rather small, and the cumulative damage fraction of the cladding tube was still within the acceptable range. The severest condition among the DBEs is one PRACS outage due to sodium leakage in the loop of the relevant PRACS. In this case, either 100% capacity of DRACS and 50% capacity of one PRACS, or 100% capacity of one PRACS and 50% capacity of DRACS is available, taking into account the single damper failure and loss of offsite power. Our analysis showed that the core was coolable under such conditions. On the other hand, the plant behavior in the long-term station blackout, although it is a typical DEC, becomes almost the same as a loss-of-offsite-power transient event because the cooling system is passive.

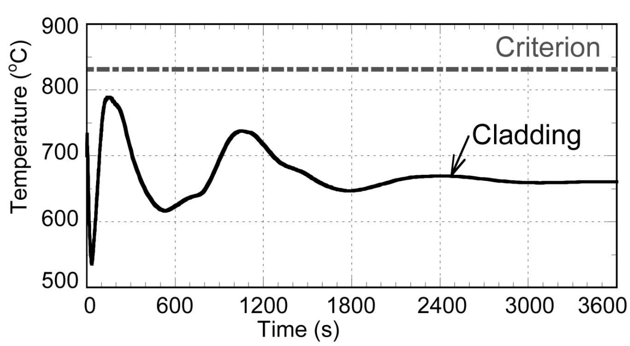


Fig. 13. Evaluated Results for Loss of Offsite Power Event With DHRS of Two PRACS and One PRACS

4.1.3 Evaluation for DECs

Some transient calculations were conducted in order to confirm the feasibility of the SASS under ATWS conditions for a large-scale reactor with compact core [3]. The conditions for the calculation were determined based on both the experiment and analysis in the Japanese Demonstration Fast Breeder Reactor (DFBR) design study as the following:. The de-touch temperature of the SASS was set at 680°C. The coolant transport duration from the top of the neighboring fuel assemblies around the control rod with SASS to the temperature-sensing alloy was assumed to be 1.0s, which becomes longer in ULOF due to the reduction of flow rate. The response delay time of the temperature-sensing alloy itself was set 1.0s. The necessary time for 85% insertion of CR is assumed for 1.5 s by the gravitational insertion.

Figure 14 shows a typical result for ULOF, where the halving time of the coolant flow rate was 6.5s, leading to the severest consequence among the ATWS conditions. The calculated coolant temperature around the armature reached 680°C at 11.8s after the transient event onset, and SASS de-tough the control rods at 12.8s. Although the maximum coolant temperature approached the criterion that is defined the boiling point, it was below the boiling temperature at the pressure condition of the core outlet because the cover gas in the reactor vessel is slightly pressurized in this plant. Accordingly, the SASS averted bulk coolant boiling, so that core cooling could be maintained.

A UTOP calculation with 3 cent/s resulted in less than 30% of areal melt fraction of the fuel pellet at the peak power position. A ULOHS calculation with simultaneous loss of the SHTS resulted in a maximum coolant temperature of 730°C. From these results, the SASS can prevent core damage in typical ATWS events, categorized as DECs.

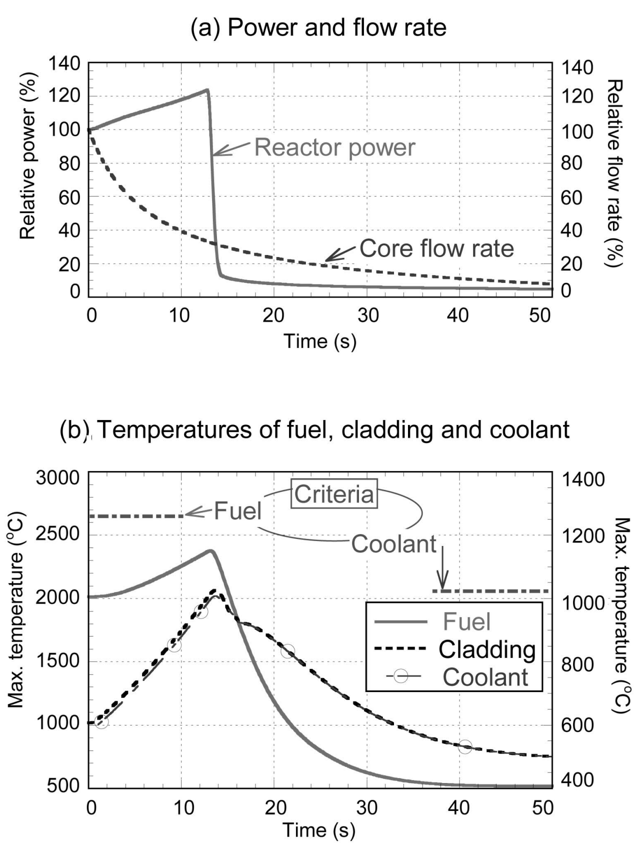


Fig. 14. Evaluated Results for ULOF Event
(Flow Having Time : 6.5 sec, Activating SASS : 680℃)

4.2 Economic Competitiveness

The current target values for economy are as follows;

- Electricity generation cost < 4.0 Japanese Yen/kWh for a First-of-a-kind (FOAK) plant
- Construction cost < 200,000 Japanese Yen/kWe for a FOAK plant (includes interest)

The target value for electricity generation cost is set to have the competitiveness in the introduction stage of the FR systems. This cost consists of plant construction costs as well as operation costs including fuel processing and fabrication costs, i.e., fuel cycle costs.

The target value for construction cost is applied to FOAK plant, and includes the interest during the construction. It is noted that this target value would be equivalent to 1000 US$/kWe for an Nth-of-a-kind (NOAK) plant (overnight cost) if the standardization effect is taken into account. Eventually the target value for the electricity generation cost would be expected to be close to 2.0 US¢/kWh for a future NOAK plant.

JSFR are expected to achieve around 90 % of the target value of construction cost, since as shown in Figure 15, JSFR is favorable in the amount of materials for main reactor components, volume of reactor building and containment facility. The compacted reactor vessel with 1500 MWe core and simple and large capacity two loop for heat transport system are the major contributors to the reduction of construction cost. It is also to be noted that construction period can be short, since JSFR doesn't need any on-site assembling of the major reactor components and installation of these components can be done in parallel.

In addition to the reduction in the construction cost, reduction in the fuel costs by increasing the core fuel burnup (150GWd/t; core-averaged value) and the operating costs by extending the possible continuous operation period (18-26 months) resulted in the possibility of achieving the goal of electricity generating costs [14]. This fact to satisfy the target value of electricity generating cost for JSFR is investigated independently by GIF EMWG [15].

4.3 Efficient Utilization of Resources

The reference TRU-MOX core has breeding ratio enough to efficiently utilize uranium resource. That is the nature of fast neutron spectrum system. The core burns MA as fuel with low minor actinide content, which is also advantage of fast neutron spectrum system. Thermal efficiency of plant system reaches as high as 42%, which is due to the high core outlet temperature with 700°C of fuel cladding maximum temperature.

4.4 Reduction of Environmental Burden

JSFR reference core burns minor actinide as described above. Core neutronic calculation showed homogenous feeding of TRU from LWR spent fuel is feasible for JSFR core. The JSFR core reveals possibility to contribute the environmental burden reduction due to its MA burning capability.

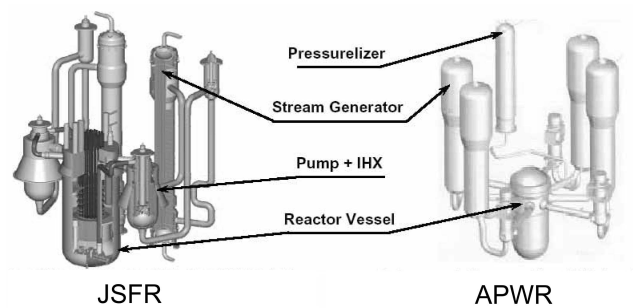
4.5 Proliferation Resistance and Physical Protection

JSFR and related fuel cycle facilities are designed with proliferation resistance and physical protection only for peaceful use, including application of IAEA safeguards and physical protection, prevention of pure Pu handling, and limit accessibility by using low decontaminated TRU fuels such as MA bearing fuels.

5. ROADMAP TOWARD JSFR COMMERCIALIZATION

The candidates of innovative system technologies for the JSFR to fully meet the development targets are identified as follows;

(1) Shortened piping using high chromium steels
(2) Two loop cooling system with large-diameter piping
(3) BIHX with built-in pump
(4) Compact reactor vessel and related internal structure
(5) Fuel handling system
(6) Containment vessel with a steel plate reinforce concrete structure built
(7) ODS cladding
(8) Double walled piping for countermeasure of sodium leak and fire event
(9) Higher reliable SG with double walled tube
(10) ISI and repair technology
(11) Passive reactor shutdown and natural circulation decay heat removal



	JSFR	APWR
Electricity Output (MWe)	1500	1530
Number of loops	2	4
R/V (ton)	465	590
IHX (ton)	576 (2 units)	-
SG (ton)	1000 (2 units)	1760 (4 units)
Total Weight (ton) (R/V + IHX + SG)	2041 (APWR×0.87)	2350

Fig. 15. Comparison of Amount for Main Components between JSFR and APWR

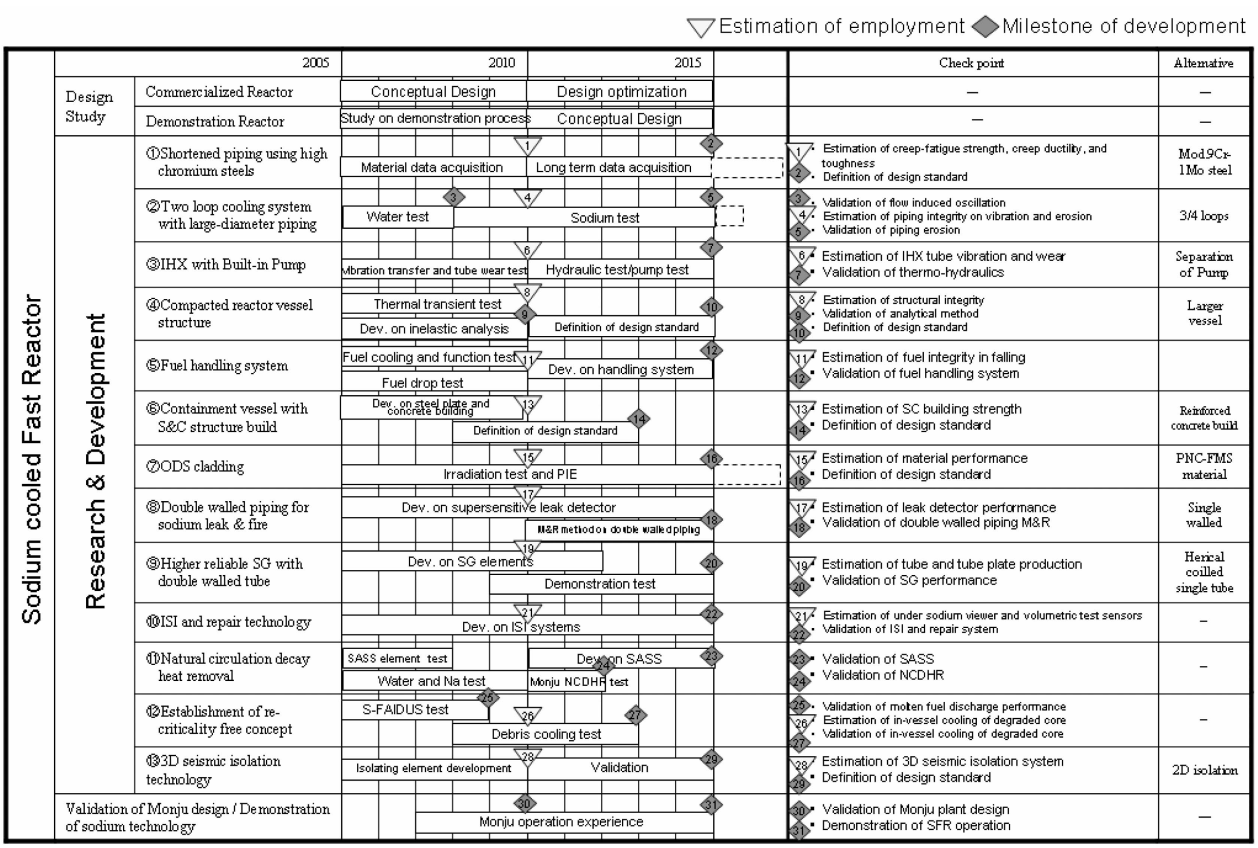


Fig. 16. Technology Roadmap for the JSFR Developments

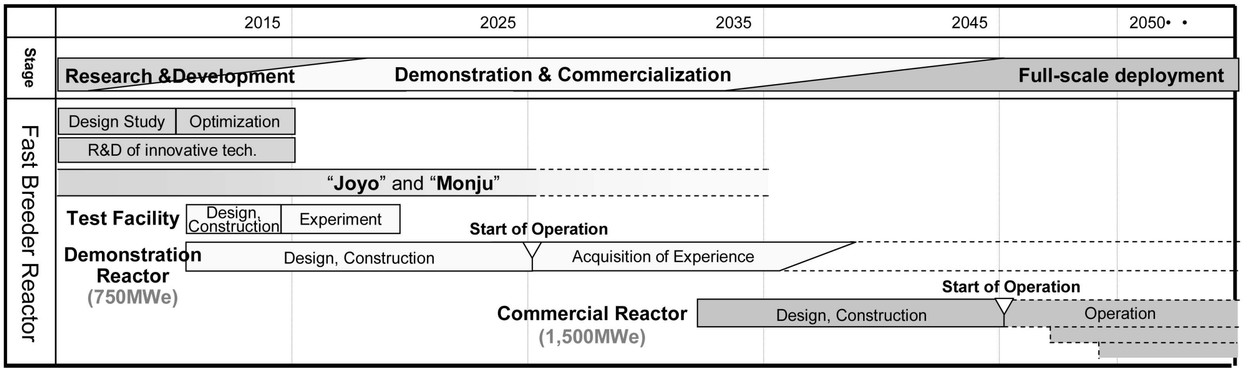


Fig. 17. Roadmap Toward JSFR Commercialization (Tentative in FY 2006)

(12) Re-criticality free core technology
(13) Seismic structural design methodology for a large scale core under a horizontal seismic isolation

All the system technologies are planned to be developed in these 10 years. These innovative technologies will be decided by judging the applicability at the end of 2010, and the development of system technologies would be completed by around 2015 as shown in Fig.16 in which check points are described for the technical judgments and alternative options are added for the flexible technology development. The FR cycle development project, thereafter, will enter into the introduction stage of a first system demonstration. The demonstration FR will start to operate in around 2025, after the establishments of innovative technologies due 2015. Before around 2050, the commercialized FBR system will be deployed based on the experience of the demonstration FR cycle system. Thereafter, the full-scale replacement of light water reactors to FRs will be continued until 2110. In summary, a roadmap toward JSFR commercialization in Japan is indicated in Fig.17.

As for the R&D works for FRs, the experimental Joyo reactor and prototype Monju reactor will play important roles. Major plans are: (1) Monju is expected to restart in 2008 after current modification work; (2) Monju will resume its operations and be operating for 10years towards the initial goals, which are "demonstration of a reliable power plant" and "establishment of the sodium technology"; (3) JOYO and Monju will be also used for MA burning, irradiation of materials.

6. CONCLUSIONS

A promising design concept of sodium-cooled fast reactor JSFR is proposed aiming at fully satisfaction of the development targets for the next generation nuclear energy system, such as Generation IV system.

(1) The construction cost would be reduced by the adoption of innovative technologies with quite clear feasibility and R&Ds of several issues are in progress now.
(2) The core performance characteristics such as the breeding capability, MA burning characteristics, fuel burn-up, and operation cycle length are well suited to meet the design requirements for an oxide fuel core which satisfies safety design requirements, safety research being the most advanced regarding the oxide fuel.
(3) The drawbacks of sodium, on the other hand, are overcome by system design features such as double boundary structures for sodium. Thus, the plant reliability can be ensured together and ISI&R capability can be provided.

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