GENES4/ANP2003, Sep. 15-19, 2003, Kyoto, JAPAN
Paper 1076

LMFBR Design and its Evolution (4)
An Innovative Concept of Sodium-Cooled Middle-Scale Modular Reactor Pursuing High Economic Competitiveness

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An innovative concept of sodium-cooled middle-scale modular reactor, which pursues high economic competitiveness, has been constructed as based on a large-scale advanced loop type fast reactor. This is a reactor concept, which is pursuing standardization and learning effects by designing as a modular plant consists of four reactors with the each electricity output of 750MWe (Total electricity output of 3,000MWe). The construction cost has been estimated approximately 2/3 times of that of LWRs at present.

KEYWORDS: fast reactor, sodium-cooled, modular reactor

I. Introduction

Japan Nuclear Cycle Development Institute (JNC) has started a 'feasibility study (FS) on commercialized fast reactor cycle systems[1)]' with participation of all parties concerned in Japan since July 1999.

In this FS, based on reviews and evaluations for a wide range of technical options incorporating innovative technologies, highly feasible candidate concepts of the FR system and the fuel cycle system, which have a well-balanced consistency, have been investigated from viewpoints of ensuring safety (fundamental condition), economic competitiveness, effective utilization of resources, reduction of environmental burden and enhancement of nuclear non-proliferation. Major design goals for the FR system are shown in **Table 1**.

Table 1 Major Design Goals for the FR System

Items	Goals
Construction cost	Below 200,000yens/kWe
Cycle length	12〜24 months
Availability	Approx. 90%
Construction period	Approx. 50 months
Burn-up	Approx. 150GWd/t (Core average discharge burn-up)
Breeding ratio	Approx. 1.2
Safety	Passive safety features Re-criticality free

In order to achieve high economic competitiveness comparable to that of LWRs and other base power sources, a goal for construction cost has been set to a high degree, i.e., 'below 200,000yens/kWe' in this FS. From a viewpoint of the FR system, it is important to achieve the economic goal with ensuring safety requirements.

This paper describes a plant design of sodium-cooled middle-scale modular reactor, which is one of the candidate concepts of the FR systems that have a potential to satisfy the goal of this FS, based on the preceding large scale reactor design[2)].

II. Design Principle

1. Approach to Achieve the Economic Goal

Figure 1 shows an approach to cost reduction. In order to achieve the economic goal, the plant design should be investigated from three different approaches, i.e., pursuit of scale merit, pursuit of standardization and learning effects, and design improvement.

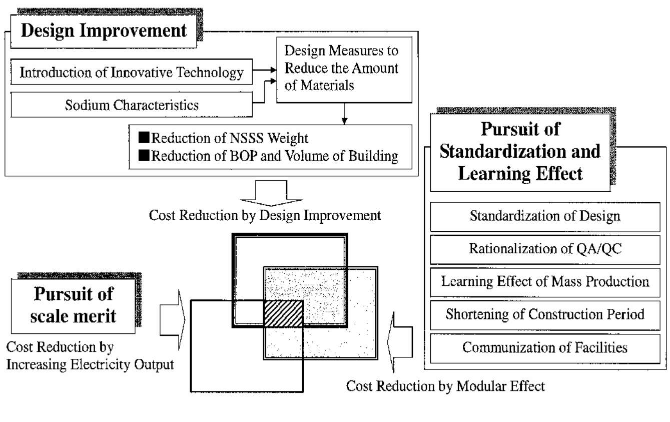

Fig.1 Fundamental Approach to Cost Reduction

The pursuit of scale merit aims to reduce the construction cost by increasing the electricity output per one reactor as large as possible, the pursuit of standardization and learning effects aims to reduce the construction cost by mass-production effect etc., and the design improvement intends to reduce an amount of materials for major components, the balance of plant (BOP), a reactor building,

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etc. through simplification of the plant system.

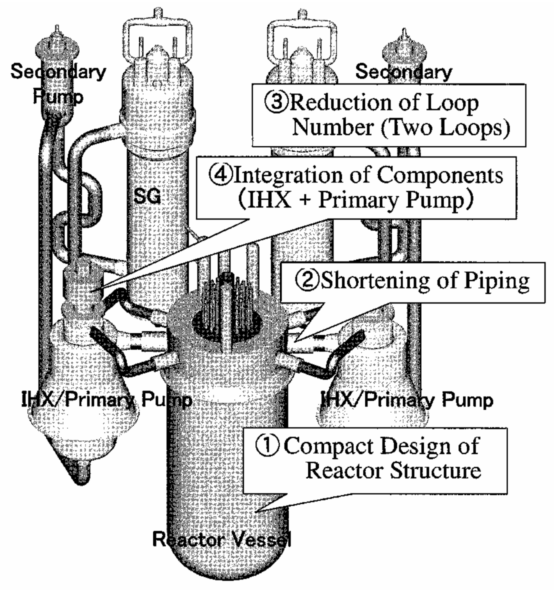

Fig.2 Design Improvement Measures

As shown in **Fig.2**, four items of design improvement measures for sodium-cooled reactor have been employed in this FS. Those are 'compact design of reactor structure', 'shortening of piping', 'reduction of loop number' and 'integration of components'. These measures are innovative design concepts stepping into a region over the conventional and practical design. However, these measures are expected to be more realistic by introducing some innovative technologies ('12Cr-steel with high strength', advanced elevated temperature structural design standards', 'three-dimensional seismic isolation' and 're-criticality free'), which have a prospect to be put to practical use by 2015, and by taking desirable characteristics of sodium coolant (operability in a low pressure system and excellent heat transfer characteristics) into account.

Considering the above, following two different concepts of sodium-cooled reactor are now under investigation in this FS. These concepts are designed as a loop-type reactor, which inherits Japanese FR technologies[3),4)].

One concept is large-scale sodium-cooled reactor, which is pursuing scale merit by setting the electricity output of 1500MWe, proceeding communization of facilities by designing as a twin-plant (Total electricity output of 3000MWe), and reducing the amount of materials by design improvement. Measures for design improvement are as follows;

a. Compact design of rector vessel
b. Reduction of primary loop number
c. Shortening of primary loop piping
d. Integration of intermediate heat exchanger (IHX) and a primary pump

The other concept is medium-scale modular sodium-cooled reactor, which is pursuing standardization and learning effects by designing as a modular plant consists of four reactors with the each electricity output of 750MWe (Total electricity output of 3000MWe) and reducing the amount of materials by design improvement. Measures for design improvement are as follows;

a. Application of design improvement methods on large-scale reactor concept
b. Adoption of straight tube type steam generator (SG)
c. Reduction of secondary loop number
d. Application of large-scale unit assembly construction method

2. Design Principle

The matter related to economic competitiveness by taking desirable characteristics of sodium coolant and safety by conquering weak points of sodium coolant is important from a viewpoint of the plant design.

As mentioned above, a high degree of the goal for construction cost has been set in order to achieve high economic competitiveness.

Concerning safety, a prevention of accidents based on a defense-in-depth principle is achieved as a first priority. In addition, passive safety features and measures for a re-criticality free are listed as a design goal required for the commercialized reactors[5)]. As for the shutdown heat removal system, a redundancy or diversity is also considered in the design of the decay heat removal system. The system design, which enhances a natural circulation capability, ensures a passive shutdown heat removal capability in such an event as a station blackout (SBO).

Considering chemical activities of sodium coolant, such designs that can minimize and localize the influence of chemical reactions between sodium coolant and air/water have been adopted in this plant.

12Cr-steel with high strength and low thermal expansion has been employed as a structural material of the cooling system. Due to this material selection, the drastically shortened piping, thinner heat transfer tubes and the tube sheets with larger diameter become available.

A seismic isolation technology has been introduced for the thin-wall design of major components.

III. Outline of Plant Design

1. Characteristics of Large-Scale Reactor Design

The characteristics of large-scale reactor design that is applied for a middle-scale modular reactor are summarized.

(1) Major Specifications

The major specifications are shown in **Table 2** and the conceptual design of the reactor and cooling system are shown in **Fig.4**.

The reactor is designed as a sodium-cooled loop-type reactor with the electricity output of 1500MWe, the reactor inlet/outlet temperature of 395°C/550°C, the plant efficiency of approximately 42%, and using Pu-U mixed oxide (MOX) type fuel. The plant operating cycle, core average discharge burn-up and breeding ratio are 17 months, about 150GWd/ton and about 1.2 respectively.

Table 2　Major Specifications of the Large-Scale Reactor

Items	Specifications
Reactor type	Sodium-cooled loop type reactor
Electricity output	1500MWe
Thermal output	3570MWt
Number of primary loops	2
Primary sodium temperature	550°C / 395°C
Secondary sodium temperature	520°C / 335°C
Main steam temperature / Pressure	495°C / 16.67MPa
Feed water temperature / Flow rate	233°C / 2.835×10^3t/h
Plant efficiency	Approx. 42%
Fuel type	MOX
Burn-up	Approx. 150GWd/t
Breeding ratio	Approx. 1.2
Cycle length	18month, 4batch

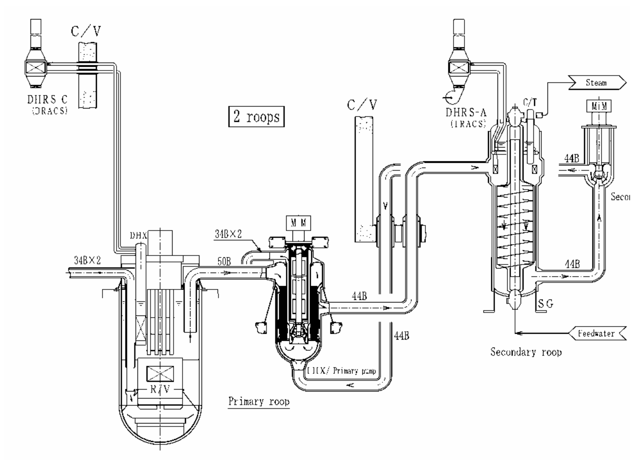

Fig.4 Conceptual Design of the Large-Scale Reactor and Cooling System

(2) Design of Core

Figure 5 shows a concept of a homogeneous MOX fueled core.

It is required to retain the influence of representative CDA consequences within the reactor vessel (in-vessel retention) together with no anxiety against energetic consequences of CDAs. In order to fulfill this safety requirement, countermeasures are adopted in the design. Axial blanket elimination (ABLE) concept is adopted for this purpose. This fuel assembly is also shown in **Fig.5**.

A compact core design has been adopted to reduce the reactor vessel diameter mainly by employing radial shields with high performance, which utilize zirconium hydride (ZrH) as a shielding material.　A pressure drop of the fuel bundle region has been reduced to approximately 0.2MPa in the core design, and it leads to the reduction of the primary pump power, mitigation of influences of a primary pump stick accident and enhancement of the decay heat removal capability by a natural circulation.

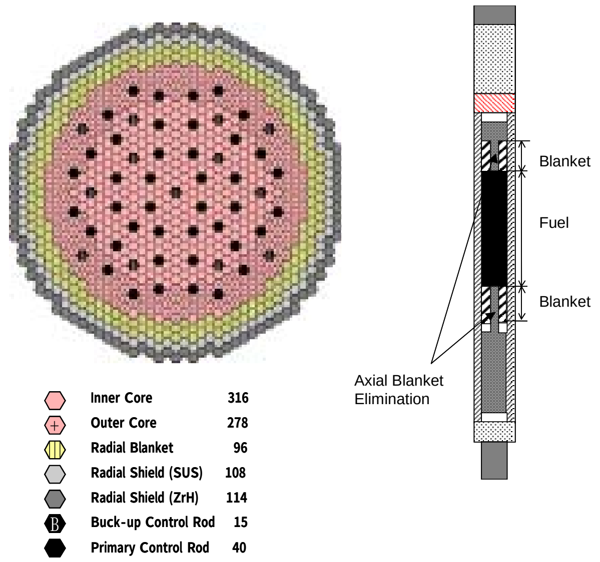

Fig.5 Core Concept

Furthermore, the control rods are arranged so that the fuel-handling machine (FHM) can enter into the upper internal structure (UIS) in the design, considering a consistency with the design of an in-vessel fuel transfer system.

(3) Design of Reactor Structure

Though the structural design is basically conducted in conformity with demonstration FBR design standard (DDS), the method of the advanced elevated temperature structural design standard[6)], which makes it possible to use an inelastic analysis, is partially anticipated against some parts that is critical for ensuring the structural integrity.

316FR has been employed as a structural material of the reactor vessel and reactor internal structure, considering its reliability on long-term sustainability of characteristics and its reliability on irradiation data.

The diameter and wall thickness of the reactor vessel are minimized and the reactor internal structures are simplified for reduction of the amount of materials.　Diameter, height and wall thicknesses of the reactor vessel are 9.6m, 18.8m and 30mm respectively. The reactor vessel diameter of 9.6m is realized by the compact design of the core and closure head structure.

The reactor vessel wall thickness of 30mm is realized by introducing the re-criticality free technology and the seismic isolation technology.

(4) Design of Cooling System

(a) Reduction and Shortening of Primary Loop Number

In this design, the capacity of heat exchangers, that is the heat transfer capacity per one cooling loop, has been enlarged as far as the fabricability and the structural integrity of components are expected to be ensured, and then the number of primary loop has been reduced to two loops. As a result, the cooling system has been remarkably simplified.

The primary hot-leg piping has been simplified by using a simple L-shaped top-entry type piping and has a structure that absorbs a thermal expansion by only one elbow. Though the shortening of the piping leads to a larger thermal expansion stress, an adoption of 12Cr-steel with high strength and low thermal expansion ensures the structural integrity.

By adopting these concepts shortening of the primary piping results in a compact plant configuration through a close arrangement of components, as well as a reduction of the amount of piping materials.

(b) Integration of IHX and a Primary Pump

By integrating an IHX and a primary pump and reducing of middle-leg piping, the primary cooling system has been remarkably simplified. Though the integration of IHX and primary pump leads to a larger tube plate diameter of the IHX, an adoption of 12Cr-steel with high strength and low thermal expansion ensures the structural integrity.

(c) Countermeasures to Sodium Leakage

The influence of sodium leakage coming from defects of materials is localized within the guard vessel or guard piping in this plant.

2. Characteristics of Middle-Scale Reactor Design

(1) Major Specifications

The major specifications are shown in **Table 3** and the conceptual design of the reactor and cooling system are shown in **Fig.6**.

Table 3 Major Specifications of the Middle-Scale Module Reactor

Items	Specifications
Reactor type	Sodium-cooled loop type reactor
Electricity output	750MWe×4
Thermal output	1785MWt / Reactor
Number of primary loops	2 / Reactor
Primary sodium temperature	550°C / 395°C
Secondary sodium temperature	520°C / 335°C
Main steam temperature / Pressure	495°C / 16.67MPa
Feed water temperature / Flow rate	233°C / 2.835×10^3t/h
Plant efficiency	Approx. 42%
Fuel type	MOX
Burn-up	Approx. 150GWd/t
Breeding ratio	Approx. 1.2
Cycle length	18month, 4batch

(2) Outline of the Plant Design

(a) Design of Core

Figure 7 shows a concept of a homogeneous MOX fueled core. A compact core design has been adopted to reduce the reactor vessel diameter. This core design is adopted the same concept as the large-scale reactor design.

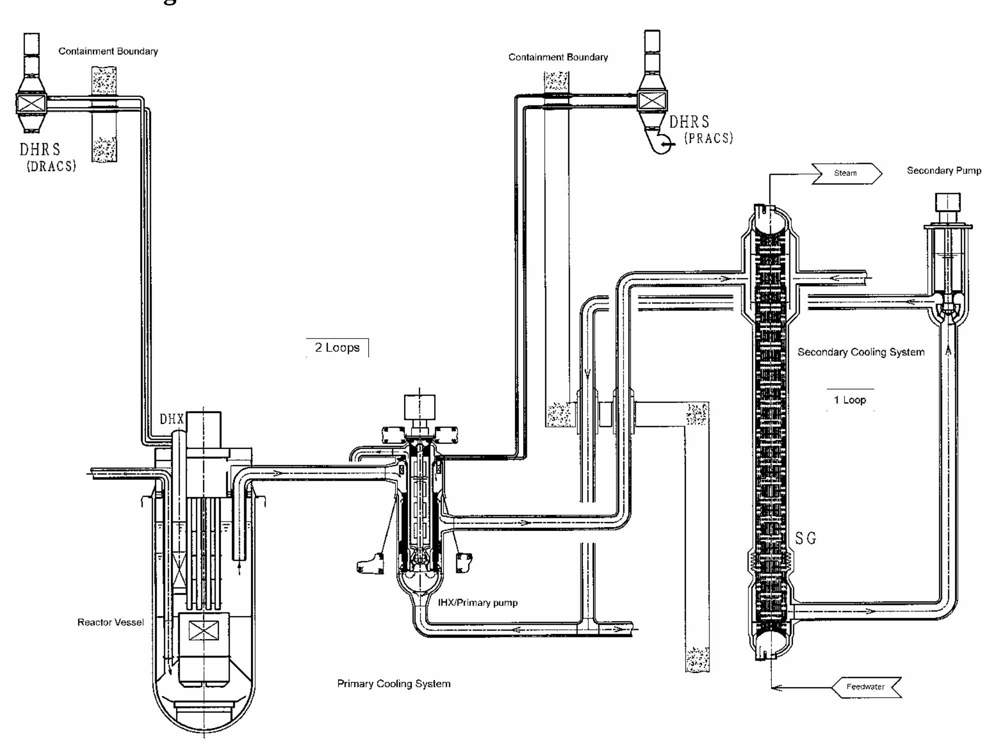

Fig.6 Conceptual Design of the Middle-Scale Reactor and Cooling System

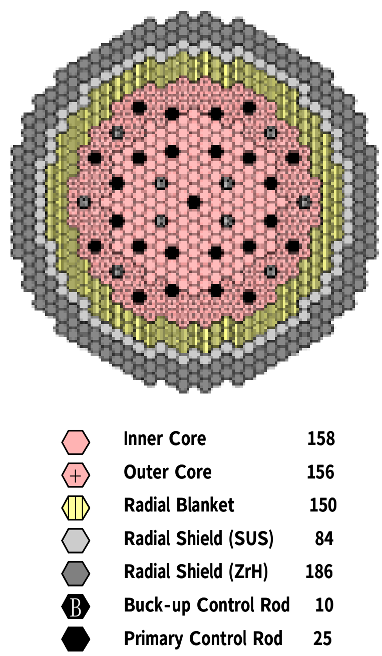

Fig.7 Core Concept

This is a modular plant which consists of four reactors with the each electricity output of 750MWe (Total electricity output of 3000MWe).

(b) Design of Reactor Structure

Diameter, height and wall thicknesses of the reactor vessel are 8.5m, 19.3m and 30mm respectively. The reactor vessel diameter of 8.5m is realized by the compact design of the core and closure head structure. The concept of large-scale reactor design is adopted.

(c) Design of Decay Heat Removal System

Two primary reactor auxiliary cooling systems (PRACSs) and one direct reactor auxiliary cooling system (DRACS) have been applied as a decay heat removal system suitable for the two primary loops and one secondary loop cooling system. Each system is designed to have 100% of required heat removal capacity (11MWt×2 for PRACSs and 10MWt for DRACS).

In order to enhance passive decay heat removal capability by a natural circulation at SBO, a pressure drop of the core has been limited below 0.2MPa and a difference of height between the core and heat exchangers has been enlarged, such as 29.5m between the core and the air cooler of PRACSs, 34.5m between the core and the air cooler of DRACS.

The primary heat exchanger of PRACS is located upper plenum of IHX.

(d) Design of Cooling System

As for the primary piping system, the design results in a compact plant configuration and a reduction of the amount of materials same as the concept of large-scale reactor. Moreover, the number of secondary loop has been reduced to one loop and then the number of SG has been reduced to one SG by enlarging the SG capacity.

By adopting straight tube type SG, the amount of materials and the cost of processing are reduced. The major specifications of SG are shown in **Table 4**. As the effective length of heat transfer tube of the SG is about 28m, the SG becomes enlargement. But the power is same as the SG of the large-scale reactor. By using thinner heat transfer tubes made of 12Cr-steel, the heat transfer performance has been improved and the tube bundle has become compact. The diameter and height of the SG are about 2.5m and 36m respectively.

Table 4 Major Specifications of SG

Items		Specifications
SG type		Straight Tube Type
Thermal capacity		1785MWt
Heat transfer area		9228m^2
Heat transfer tube	Outer diameter	15.9mm
	Thickness	1.9mm
	Heat transfer length	28m
	Tube number	5551
	Pitch	31.8mm
Tube material		12Cr steel
Flow rate	Water/steam	2.835×10^{3}t/h
	Sodium	2.73×10^{7}t/h
SG size	Height	36.2m
	Diameter	2.515m

As for countermeasures to sodium-water reaction, an acoustic detector and an electro-chemical hydrogen detector are set for early detection of SG heat transfer tube damage and for quick start-up of the ceasing sequence such as water blow-down, SG isolation, etc. Through these measures, a propagation of the SG tube damage is properly limited and localized.

(e) Electric Power Supply of Safety System

As localizing of safety system reduces the capacity of the emergency electric power supply system, small gas turbine is adopted.

(f) Design of Turbine System

As one turbine is shared with two reactors, the capacity of the turbine system is 1500MWe.

By using motor-driven pump for main feed-water pump, water-steam system is rationalized, start-up pump is reduced and feed-water pump system consists of 3 pumps with 33% capacity respectively.

(g) Design of Reactor Building

Figure 8 shows a layout in a reactor building. A simplified design of the reactor containment facility (reinforced concrete structure with an inner lining) is adopted from the point of view of a radionuclide confinement, which is more important than a pressure resistance same as the building of large-scale reactor.

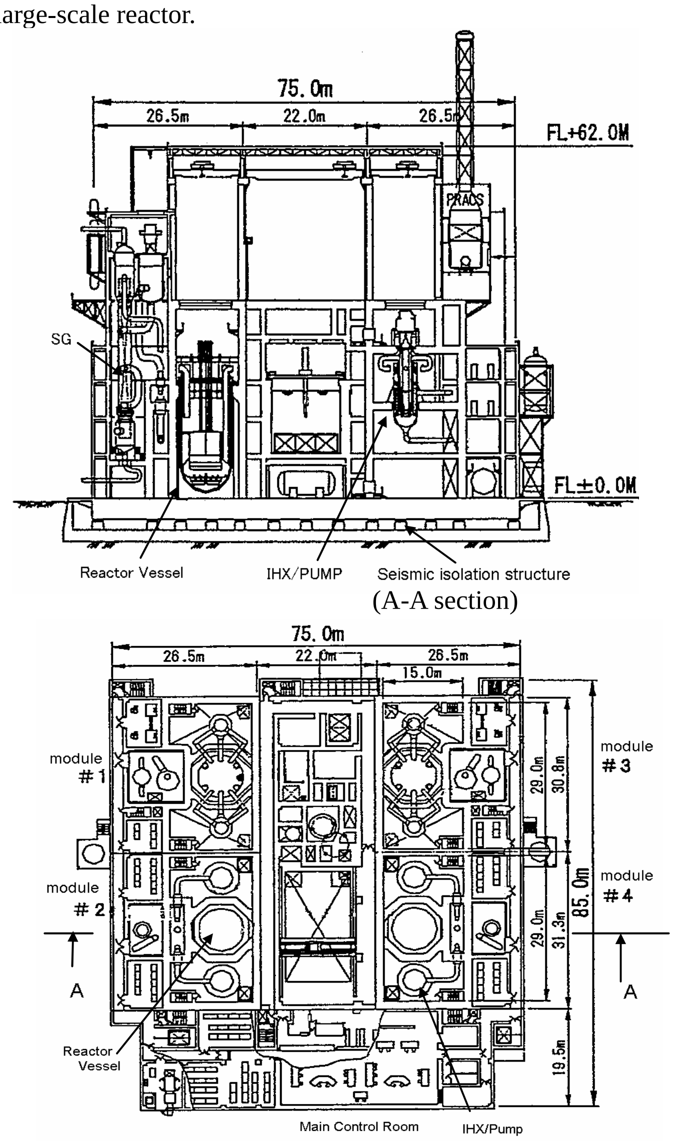

Fig.8 Layout in a Reactor Building

An earthquake-proof design is based on the adoption of a two-dimensional (horizontal) or three-dimensional seismic isolation technology. [7),8)]

(h) Construction Method

A construction period of this plant is estimated within 33 months by using the large-scale unit construction method. One unit size is about 5000tons in this method.

3. Estimation of Economic Competitiveness on Middle-Scale Modular Reactor

(1) Amount of Steel Materials

For one module, the amount of steel materials of the reactor, primary system and secondary system are evaluated 728tons, 582tons and 557tons respectively, and the total amount of steel materials of the NSSS is evaluated 1870tons.

The volume of the reactor building is evaluated 69,000m^3/one module.

(2) Construction Cost

Based on the estimation of the amount of materials, the construction period, the plant internal load etc., a construction cost of this plant is evaluated approximately 2/3 times of that of LWRs at present by considering with module effect. Therefore, the economic goal of this FS (below 200,000yens/kWe) is almost achieved.

IV. Evaluation of Major Design Subjects

In order to reduce the amount of steel materials drastically, innovative design concepts, i.e., 'compact design of reactor structure', 'shortening of piping', 'reduction of loop number' and 'integration of components' are adopted in this plant. In adopting these design concepts, it is required to solve some technical subjects.

In the design of large-scale reactor, it is estimated that the structural integrity of the reactor vessel and the primary piping are ensured. These results are same as the middle-scale modular reactor.

Followings are states of investigations for some representative subjects on the middle-scale reactor.

1. Subjects Related to Safety

(1) Safety against a Primary Pump Stick Accident

As the primary cooling system of this plant consists of only two loops and has no check valves, a decrease of the core flow rate at the primary pump stick accident is larger than that of the conventional three or four loops design. Therefore, careful examinations for the fuel integrity by the accident are required from the thermal point of view.

Figure 9 shows the analytical result of the primary pump stick accident scrammed by a first signal 'Primary pump speed low' and it has been shown that the peak cladding temperature does not exceed the preliminary safety criteria and that the fuel integrity through the accident is ensured. Even if the primary pump stick accident scrammed by a second signal 'Primary flow rate low', the peak cladding temperature is about 875 °C and does not exceed the criteria.

(2) Decay Heat Removal Capability

For the representative incidents and accidents, it is important to ensure that the decay heat removal system has efficient capability and has ability of stable heat removal operation. **Figure 10** shows the typical transients.

As the results, it is confirmed that the decay heat removal capability is ensured. However, it is necessary that secondary coolant system should be designed for safety system as the peak cladding temperature exceeds the preliminary safety criteria in case where the heat capacity of secondary loop is not available.

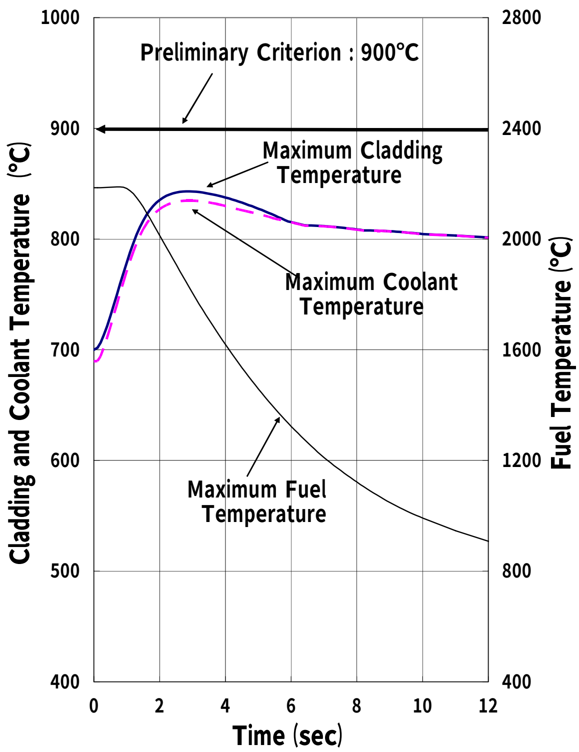

Fig.9 Analytical Result of the Primary Pump Stick Accident

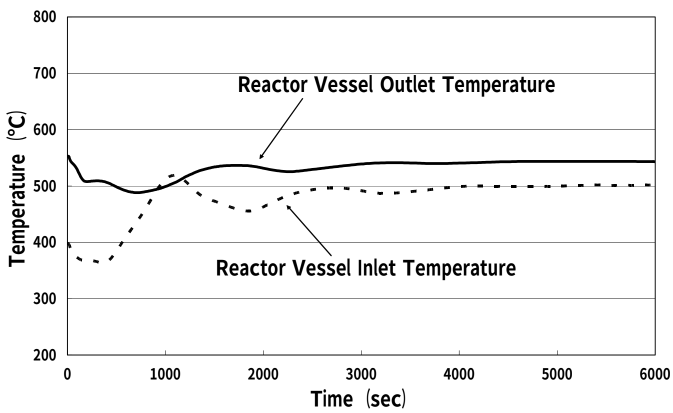

Fig.10 Analytical Result of SBO (DRACS + 2PRACS condition)

2. Hydraulic Stability in of Straight Tube SG

One of the issues for straight tube SG is the instability of water/steam hydraulics. As the SG of this plant has long-length tubes as shown in Table 4, there is a high possibility that water/steam hydraulics of this SG is stable without installing inlet orifice. The discriminant parameter for hydraulics instability is an orifice factor (k_{in}). DALMA code analyzes the orifice factor. Water/steam hydraulics is stable when calculated $k_{in} < 0$.

Hhydraulic instability of this SG has been analyzed by DALMA code, which is verified with the test data within 5% accuracy. **Table 5** shows the analytical result. The stability has been shown at full power condition, which is the severest condition for stability.

Table 5 Analytical Result on Hydraulic Instability

Condition	Flow- rate of Feed-water	Instability (k_{in})	Evaluation
Full Power	100%	-10.1	stable
Feed-water Flow rate -5%	95%	-1.41	stable

In the case of 'Feed-water Flow rate -5%', the accuracy of DALMA code is considered as the severest condition. It is contributed for the hydraulic stability of this SG to make the heat transfer tube longer.

3. Characteristics of Plant Control System

As one turbine is shared with two reactors, on the case of a one-reactor trip, it is necessary to confirm that the other reactor, which is normal condition, will continue to operation on purpose of increasing the utilization.

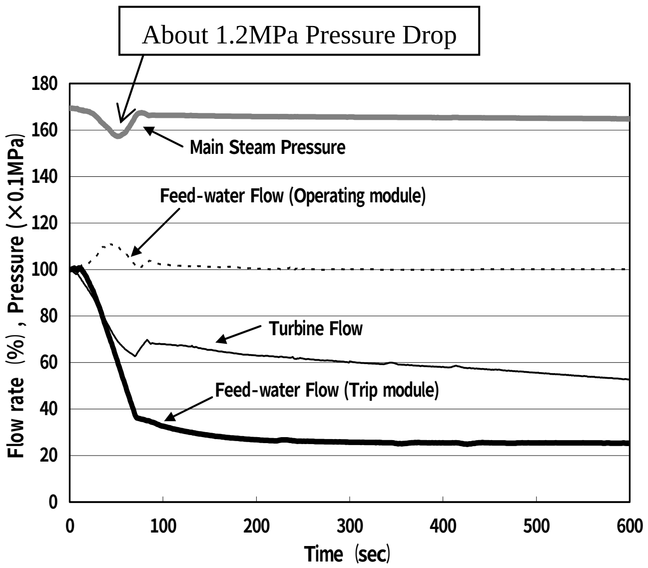

Fig.11 Analytical Result of one-reactor trip

Figure 11 shows the analytical results. Main steam pressure decreases about 1.2MPa with decreasing of feed-water after a one-reactor trip. As the result of this transient, feed-water flow-rate of the other reactor increases and SG outlet sodium temperature decreases about 9°C. However, it has been confirmed that continuous operation on normal reactor is possible.

V. Future Plan

Reflecting the results of elemental experiments, the preliminary conceptual design of this plant will be preceded.

The FS on commercialized FR cycle system has progressed to its Phase 2 step since JFY2001. During Phase 2 (by 2005), candidate concepts for commercialized FR cycle screened in Phase 1 will be selected to two or three promising concepts and R&D themes for their commercialization will be identified.

As for sodium-cooled reactor, in-depth design studies and examinations for critical technical subjects as listed in **Table 6** will be carried out, and then the design concepts of the promising sodium-cooled reactors will be clarified during Phase 2 through these investigations.

Table 6 Major R&D Items concerning the Plant Design

Items	Category*
Development of the advanced elevated temperature structural design standard and the thermal load assumption method	A
Development of the 12Cr-steel and improvement of material design standard	A
Establishment of the evaluation method of LBB for the 12Cr-steel piping	B
Evaluation of thermal-hydraulics in the reactor upper plenum and large diameter piping	B
Verification of effectiveness of measures for the re-criticality free	A
Development of the increased reliability steam generators	B
Development of the integrated components (IHX and Pump)	B

* A: Development of innovative technologies introduced as a premise of innovative designs

B: Development of design-oriented subjects

VI. Conclusion

An innovative concept of middle-scale modular sodium-cooled reactor (Advanced Loop Type Fast Reactor), which pursues high economic competitiveness, has been constructed.

Five main design measures, i.e., 'compact design of reactor structure', 'shortening of piping', 'reduction of loop number', 'integration of components' and 'characteristics of middle-scale modular reactor' are employed for cost reduction, and then drastic improvement of economic competitiveness has been attained by reducing the amount of materials by these design measures. The construction cost has been estimated approximately 2/3 times of that of LWRs at present.

This plant concept will be studied in order to make a detailed design by 2015 through the outcome of R&D programs related to innovative technologies and some design-oriented subjects.

Acknowledgment

This paper includes the outcome of collaborative study between JNC and JAPC (that is the representative of 9 electric utilities, Electric Power Development Company and JAPC) in the accordance with “the agreement about the development of a commercialized fast breeder reactor cycle system”.

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