FEASIBILITY STUDIES ON COMMERCIALIZED FAST BREEDER REACTOR SYSTEM (1) -SODIUM COOLED FAST BREEDER REACTOR-

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ABSTRACT

JNC and the electric utilities in Japan are conducting feasibility studies in order to determine the promising FBR concept. In these studies, cost reduction measures in large-sized sodium-cooled reactors were investigated considering characteristics of sodium-coolant. As a result, the main cost reduction measures are followings.

1.Reduction of loop number

By utilizing of sodium advantages, for example "compact heat exchanger due to the high thermal conductivity" and "low pressure design due to the high boiling point", it is possible to increase the capacity of cooling system. As a result the loop number was reduced to two loops in 1500MWe loop-type FBR.

2.Integration of components

The static electro-magnetic pump will be used for a main recirculation pump due to the electro-magnetic fluid of sodium coolant. The compact exchanger will be also adapted.

Then, integration of a pump and intermediate heat exchanger(IHX) or steam generator(SG) are being studied. The reduction of piping, component space and so on contribute to cost reduction.

3.Passive decay hest removal

By utilizing excellent performance of natural circulation heat removal due to large alteration of density, the simple DHR with high reliability is adapted to plant designs.

4.Simplified upper core structure and fuel handling system

In order to pursue the compact reactor, single rotating plug is concentric with core, and pantograph type's fuel exchange machine can move through a narrow passage in upper internal structure (UIS) avoiding interaction with control rod guide tube.

These cost reduction measures above are based on adoption of new material (12Cr Steel), improvement of elevated temperature structural design guide, seismic isolation, etc.

1.INTRODUCTION

JNC and Electric Utilities have been conducting Feasibility Studies on Commercialized FBR Systems since July 1999 under the cooperation Agreement. In these studies several plant concepts are being studied considering the economical competitiveness to future light water reactors (LWRs). As for large-sized sodium-cooled reactors, our effort was focused on improvement of economical competence. Cost reduction measures were investigated considering characteristics of sodium-coolant.

In this paper, the concepts of a simplified structure of reactor, two loops cooling system, integration of a pump and intermediate heat exchanger (IHX), simplified fuel handling system, etc applied for cost reduction and feasibility studies of these concepts in 1500MWe loop-type FBR are presented.

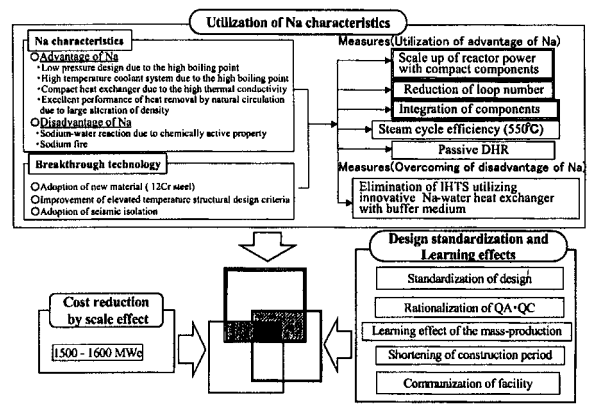


Fig 1 Cost reduction measures to attain the economical target

2. CHARACTERISTICS OF SODIUM-COOLANT AND COST REDUCTION MEASURES

Cost reduction measures considering sodium characteristics and a target of the study are shown Fig. 1. The low-pressure design and the large operation temperature range is applied due to the high boiling point of sodium coolant and as a result of these designs the large-scale component and piping could be constructed. The compact heat exchanger could be pursued due to the high thermal conductivity of sodium coolant. The concrete measures of utilizing sodium merits as described above are the reduction of loop number, the integration of components, the improvement of steam cycle efficiency, the passive decay hest removal (DHR) improved natural circulation performance, etc. On the other side, the design to overcome the disadvantages of sodium such as the simplification of equipment for sodium leakage, the localization of second cooling system, etc is investigated. Our final plant concept would be drown with taking account of the cost reduction by measures as described above, the cost reduction by scale effect and cost reduction by the design standardization and learning effects.

In 1999 JFY, one concept of loop-type and three concepts of tank-type in 1500MWe FBR have been studied with being applied above measures [1]. In 2000 JFY, each one concept of loop-type and tank-type have been studied to reduce cost further and to confirm safety and structural integrity. The cost reduction measures applied in 1500MWe loop-type FBR is described below.

(1) Simplified structure of reactor

Reactor vessel diameter could be reduced due to compact reactor core and simplified fuel-handling method in reactor (single rotating plug and a shell-less column type upper internal structure with slit). The reactor vessel thickness could be reduced due to the mitigation of seismic force by 3 dimensions seismic isolation and the mitigation of CDA energy by evasion of re-critical state. Also the reduction of wall thickness could make a reactor vessel simplified by employing a hot vessel with non-cooling.

(2) Shortened piping

Main piping of primary and secondary cooling system could be shortened by adoption of new material (12Cr Steel) and improvement of elevated temperature structural design guide.

(3) Reduction of loop number

By utilizing of sodium advantages, low-pressure and the large operation temperature range design due to the high boiling point and compact heat exchanger due to the high thermal conductivity, by adopting of 12Cr steel, etc, it is possible to increase the capacity of heat exchanger per unit and the flow per loop. The capacity of cooling system and the diameter of piping could be designed to enlarge with integrity and manufacturing performance. As a result the loop number could be reduced.

(4) Integration of components

The primary cooling system is simplified by integration of a pump and intermediate heat exchanger (IHX), which could be easily designed because of above described large capacity of IHX. And the middle leg piping, which is not easy to access due to drawing around in a low position and is difficult to repair, could be eliminated.

(5) Simplified fuel handling system

A high decay spent fuel taken out from reactor is directly stored in the water pool. Accordingly EVST and its cooling system could be eliminated.

(6) Twin-plant

This plant concept is designed in twin-plant. According to this design some facilities could be used in common. The volume of structure could be reduced.

(7) Simplification of secondary systems

Elimination of the intermediate cooling system is being studied by applying an innovative steam-generator with buffer medium of lead or lead-bismuth.

Table 1 Major Specification

No	Items	Specifications
1	Reactor Type	Sodium Cooled Loop Type Reactor
2	Net Electric Output	1500MWe
3	Thermal Output	3570MWt
4	Number of the Loop	2
5	Primary Sodium Temperature	550℃/395℃
6	Secondary Sodium Temperature	520℃/335℃
7	Main Steam Temperature/Pressure	495℃/16.67MPa
8	Feed Water Temperature/Flow Rate	233℃/2.835×10^{3}t/h
9	Net Yield	~42%
10	Fuel	MOX
11	Burnup	~149GWd/t (Core Average Discharge Burnup)
12	Breeding Ratio	~1.17
13	Cycle Length	17 Months, 4 Batch

3. PLANT DESIGN

Fig. 2 and Table 1 show the basic concept of this plant and the major specifications. This plant is a loop type reactor with thermal output of 3,570MWt and electricity output of 1,500MWe (about 2.2 times of the demonstration FBR in Japan (DFBR)). Above-mentioned measures for the cost reduction are adopted in the plant design. For example, there are only 2 loops of the main cooling system, and the IHX and the primary pump are integrated to one component. Simplified design concept of the secondary cooling system is not applied in this plant.

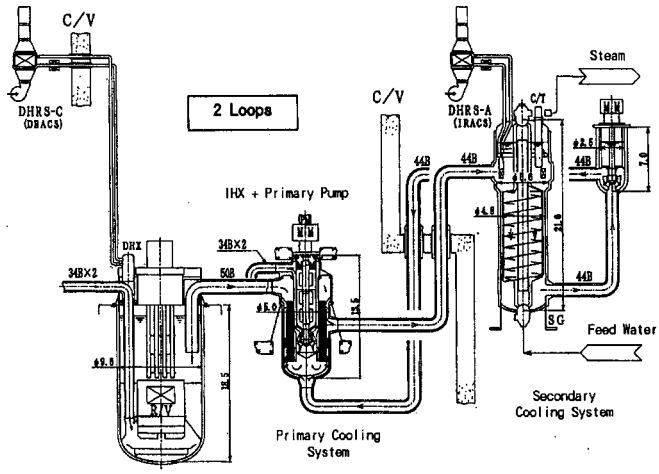


Fig 2 Plant concept of the sodium cooled large-scale loop type reactor

The followings are the outlines of the plant design.

(1) Core design

Basic design approaches of the core are show as follows.

① In order to reduce the amount of materials, the core diameter and the pressure drop of the core are cut down in so far as fulfilling the design requirements for a burn-up (≧150GWd/t) and a breeding ratio (≧1.2). Those targets are 6.5m (inner diameter of the core barrel) and 0.2MPa (pressure drop of the bundle region) respectively.

② In order to fulfill the safety requirement for re-criticality free in case of typical core disruptive accidents (CDA), axial blanket pellets in fuel pins are eliminated at the center region of each fuel subassemblies to promote early discharge of the molten fuel from the core region.

(2) Design of the reactor vessel and the reactor internal structure

Fig. 3 shows the design of the reactor vessel and the reactor internal structure. Basic design approaches are shown as follows.

① In order to reduce the amount of materials, the diameter and the wall thickness of the reactor vessel are cut down to 9.6m and 30mm respectively. It should be noted that the 9m level designs make it possible to fabricate the reactor vessel with applying ring forging process by an existing machine tool.

② The reactor vessel diameter of 9.6m is realized by the above-mentioned reduction of the core diameter and a simplification of a closure head structure. In this plant, a shell-less column type upper internal structure (UIS), where a fuel-handling machine (FHM) can enter into the core center through control rod guide tubes, is adopted. This type of UIS makes it possible to conduct a fuel handling by a single rotating plug with small diameter, further makes it possible to simplify the closure head structure. A pantograph type FHM, which is slim

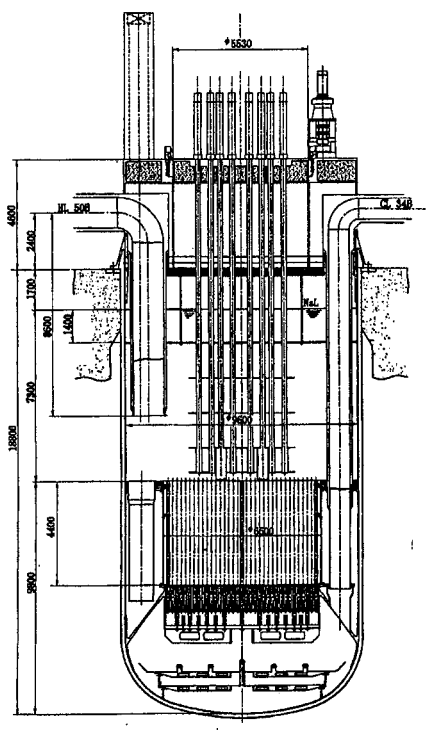


Fig 3 Concept of the reactor vessel and the reactor internal structure

enough to move through the control rod guide tubes, is adopted.

③ The reactor vessel wall thickness of 30mm is realized by adopting countermeasures for the re-criticality that can mitigate mechanical energy release at CDA and by employing a seismic isolation for the reactor building that can mitigate the seismic load. As the result of the reduction of the wall thickness, it becomes possible to attain structural integrity of the vessel against thermal stress with a simple thermal liner, and then heavily equipped vessel cooling structures that enlarge the reactor vessel diameter are not needed.

④ A top-entry type piping is adopted in the primary cooling system. The piping is inserted in the vessel from the top of the reactor. Though this type of piping enlarges the reactor vessel diameter compared with a side-entry type piping, it makes the reactor vessel nozzle-less that is expected to have higher reliability.

⑤ The core is supported by a simple support skirt structure considering the reduction of the amount of materials.

⑥ A dipped plate is adopted in order to prevent a cover gas entrainment from the liquid surface of the reactor vessel.

(3) Design of the main cooling system

① Major characteristics of the system construction

a. Reduction of the loop number

This plant has only 2 loops of the main cooling system. Compared with the 4-loop design, the 2-loop design can reduce the amount of materials drastically. About 13% of the nuclear steam supply system (NSSS) weight and about 10% of the reactor building volume are reduced by the reduction of loop number.

b. Shortening of the primary piping

Similar to the DFBR, this plant adopts the top-entry type piping in the primary cooling system. However, adopting 12Cr steel with high strength and low thermal expansion as a piping material, the number of elbow of the hot leg piping is reduced from 2 to 1, and the length of the primary piping is remarkably shortened.

c. Integration of components

In this plant, the IHX and the primary pump are integrated to one component. Compared with the separated design, the integrated design can reduce the amount of materials remarkably. About 12% of the primary system's weight and about 12% of the containment vessel volume are reduced by the integration of components. In addition, in case of the integrated design, improvements of maintainability are expected, i.e. the middle leg piping between the IHX and the primary pump, which is difficult to do maintenance, is eliminated, and in-place maintenance of the IHX tubes becomes easy accessing to the IHX tubes through the center hole after the withdrawal of the primary pump. An electromagnetic pump (EMP) is not applied in this plant considering various subjects for a scale-up of the EMP capacity.

② Specifications of components

a. IHX-Primary Sodium Pump Integrated Component

The main design features are followings.

i) A primary sodium pump is installed in the center of tube bundle of the integrated component. This pump is mechanical type because of its previous actual use in FBR plant.

ii) The integrated component is a non-cover gas type to reduce the amount of materials and to simplify its design.

iii) A heat transfer tube is a straight type and secondary sodium flows in a zigzag in the tube bundle. The tube material employed is the 12Cr steel to increase heat transfer performance and downsize the tube sheets and the tube bundle.

b. Steam Generator (SG)

The main design features are followings

i) The Steam Generator is the once-through type which is the same SG as the DFBR and its heat transfer tube is the helical coil type same as Monju SG. The tube material is the 12Cr-1Mo steel to increase heat transfer performance and downsize the tube sheets and the tube bundle.

ii) The steam Generator is a cover gas type to reduce pressure rising caused by a sodium/water reaction in case of tube failure.

iii) A DHX of IRACS and a cold trap are installed in the upper part of the SG.

iv) The tube sheets are spherical types to diminish stress. The properties of high-strength and low thermal expansion of the 12Cr steel makes it possible with keeping obtains the required structural integrity that only one spherical tube sheet are required on inlet and outlet nozzle.

③ Sodium leak measure

A primary sodium system is enclosed with guard vessels and outer pipes, and the vacancy between a sodium boundary and outer pipes is filled with nitrogen gas. In the same way, a secondary sodium system is surrounded with enclosures and its vacancy is filled with nitrogen gas.

(4) Decay heat removal system

2 IRACS and 1 DRACS are designed to accommodate to 2 main loops cooling system and achieve that the probability of a core disruptive accident (CDA) is below 10^{-6}/ry.

① The secondary main cooling sodium in the SG flows in the tube bundle of the DHX of IRACS and U-shape tubes are adopted to the DHX to lower pressure loss.

② Parallel flow and straight tubes are adopted to the DHX of DRACS to diminish pressure loss and accommodate to a reactor system. This DHX is the same concept as that of the DFBR [2].

③ A air cooling system has fin-less helical coil heat transfer tubes to reduce the possibility of a sodium leak and enable the outside inspection of tubes and the location of tube failure in case of leak.

(5) Fuel handling system

① View point of fuel handling system design

a. Instead of using an ex-vessel storage tank, a simple fuel handling system composed of only a fuel cleaning system, a under-water spent fuel storage system and the spent fuel cooling system which enhances cooling capability under treating a high decay heat spent fuel in Ar atmosphere is equipped to reduce the amount of material of the fuel handling system and the volume of building. Therefore, this new fuel handling system is brought closed to that of a light-water reactor.

b. The fuel cleaning system is wet type.

② Outline of fuel handling system

A new fuel is transferred from a new fuel storage rack to the in-vessel by a fuel changing cask machine and an in-vessel transfer machine. On the other side, a spent fuel with immersing in sodium is transferred from the in-vessel to a fuel-cleaning vessel by the fuel changing cask machine and the in-vessel transfer machine. And then, the fuel transfer machine of a cleaning vessel transfers spent fuel from the sodium pot to a cleaning pit with cooling fuel by argon gas. The spent fuel is cleaned in the pit, after that it is transferred to an under-water spent fuel storage rack.

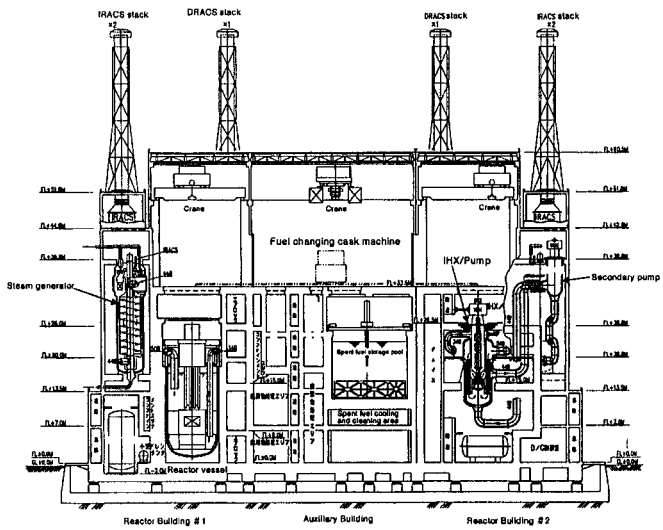


Fig 4 The location of main components of this design

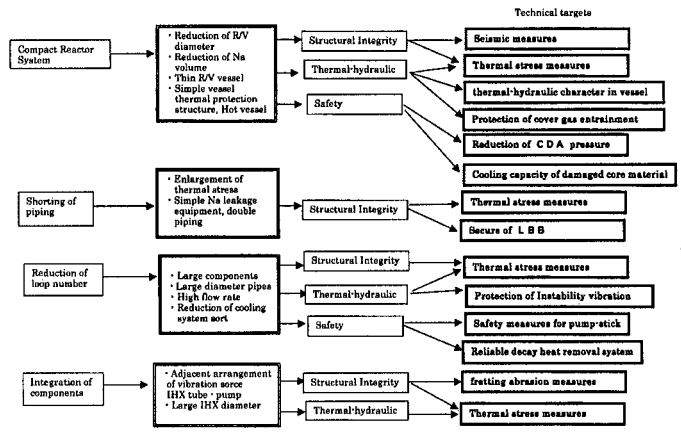
(6) Building and location

Fig.4 shows the location of facilities of this FBR plant. The reactor building and the auxiliary building are unified with their foundations with 3D seismic isolated system. The dimension of the unified building is 94.7m×57.2m×H60.5m and its volume is approximately 240000m^3 (120000m^3/plant)

4. SURVEY RESULTS OF THE MAIN DESIGN SUBJECTS

As mentioned in Section 3, main design subjects of this plant are 1) Compact Reactor System, 2) Shortening of the piping, 3) Reduction of the loop-number in the main cooling system, 2 loops system, 4) Integration of the components, Primary pump and IHX. To adopt these design subjects, the technical targets are listed as table2. A part of the survey results is presented here.

Table 2 Cost down methods and technical targets



(1) Integration of IHX and primary pump

①Fretting abrasion in the heat-transfer tube

Integrated mechanical pump would induce the mechanical vibration of the heat-transfer tubes. Therefore increasing of fretting abrasion is one of the design concerns. By using calculation code that is developed for 660MWe DFBR, rough estimation of the fretting abrasion depth for the lifetime is calculated. As the result, the total fretting abrasion depth is 0.13mm/40 years. Therefore the thickness of the design is decided as 0.23mm with safe margin.

(2) 2 loops system

①Primary pump stick

In the 2 loops system, core flow rate drops down larger than 3 or 4 loops system in one of the primary pump stick event. Thermal effects for reactor core and fuel become severe, and some counter-measures will be needed.

In the present design, shortening of response-time in the safety-protection system, extension of pump trip delay-time in the normal loop, extension of halving-time of primary pump, and shortening of insert time for back-up control rod reactivity are considered reasonably so that the peak temperature of cladding tube and coolant under the primary pump stick are shown as figure 5. These safety analyses indicate to ensure the integrity of the core and fuel.

② Decay heat removal system

As the 2 loops system adopted, decay heat removal system is consisted by two IRACS system and one DRACS system. And each system is designed to ensure 100% decay heat removal capacity. In addition, IRACS design is adopted to ensure large natural circulation heat removal capacity, by means of lower pressure

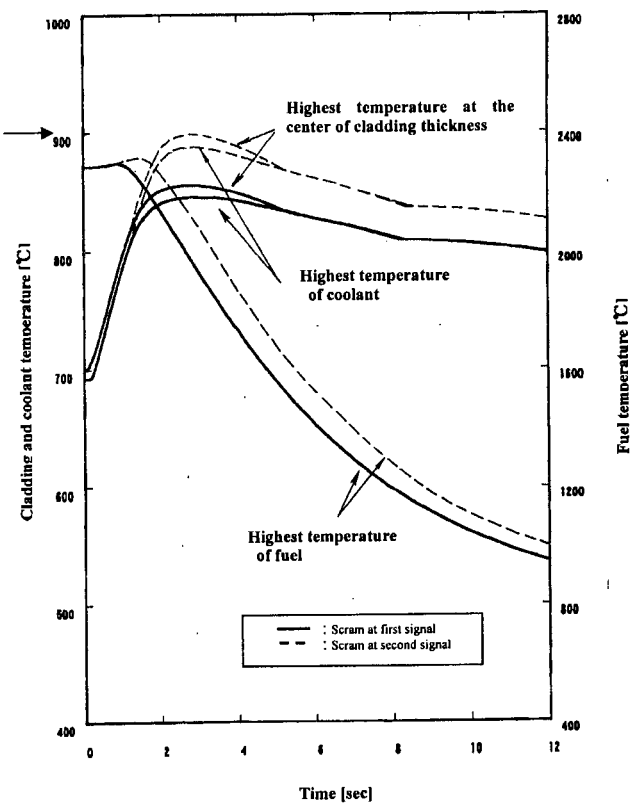


Fig 5 Temperature profiles of primary pump stick

loss in the core and cooling system and large difference of the height between core and IHX makes.

Heat removal profiles are calculated for typical safety events included station blackout. As a result, capacity of decay heat removal system including natural circulation heat removal is enough for such typical events, therefore the integrity of the core, fuel and reactor coolant boundary will be ensured.

Rough PSA analysis shows that probability of PLOHS is enough low and it will be under 10^{-7}/reactor year.

(3) Re-criticality free

In order to fulfill the safety requirement for re-criticality free in case of typical CDA, following countermeasures are adopted in this plant.

① Initiating phase

Limiting a maximum void worth less than 6$, total reactivity through the ULOF initiating phase is possible to be suppressed less than 1$ coupled with negative reactivity feedback caused by Doppler effect and fuel dispersion.

② Transition phase

In case of a large-scale molten fuel pool is formed in the transition phase, there is a possibility of re-criticality caused by concentration of the molten fuel thorough a sloshing motion. Then, in order to discharge the molten fuel from the core region before the large-scale pool formation, an ABLE (Axial Blanket Eliminated) subassembly concept is adopted in the core design. In the ABLE concept, axial blanket pellets in fuel pins are eliminated at the center region of each fuel subassemblies to promote early discharge of the molten fuel.

③ Post accident material relocation (PAMR) and post accident heat removal (PAHR)

Devising the design of the lower internal structure, sodium inventory of the lower plenum needed for a quenching of the molten fuel and surface area needed for stable cooling of the debris are secured.

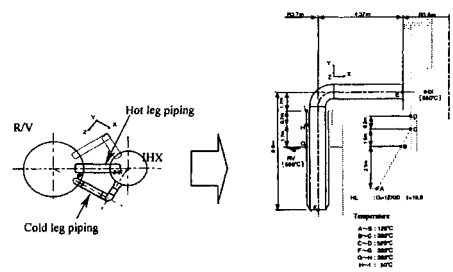
(4) Seismic characteristic

Two points should be considered in order to ensure the integrity for equivalent to M6.8 class earthquake. One is the buckling of reactor vessel and the other is the core integrity concerning with reactivity insertion and jumping of core assembly. From these points of view, three dimensional isolation systems are adopted in the nuclear reactor building.

(5) Structural integrity

In this plant, material of cooling system, i.e. IHX, SG and piping, are selected from 12Cr steels. Because 12Cr steel like HCM12A has high strength, high thermal conductivity, and low thermal expansion rate, low thermal stress could be expected. As figure 6 shows, structural integrity of piping is ensured by stress analysis. And creep-fatigue evaluations of IHX and SG tube-sheet are calculated, and structural integrity for creep-fatigue is confirmed. Although HCM12A is utilized in the field of thermal power plants, material design standard should be modified with consideration of utilized temperature for FBR condition.

Analysis model



Analysis results

piping	place	Stress(MPa)	Limit (MPa)	Evaluation
Hot leg	Y piece-side nozzle F	212	250	○
	elbow	306	600	○
	IHX-side nozzle E	65	250	○
Cold leg	Y piece-side nozzle	88	175	○
	support	16	175	○
	R/V-side elbow	241	420	○
	elbow	122	420	○
	IHX-side elbow	76	420	○
	IHX-side nozzle	5	175	○

Fig 6 Results of stress analysis at primary piping

Basically these structural and material design is calculated by DDS, Demonstration plant Design Standard. Some advanced evaluation methods are adopted, such as use of inelastic analysis and improvement of material strength margin. These advanced methods should be systematized by developing new structural and material design

standard as FDS, FBR design standard.

5.EVALUATION OF ECONOMY

(1) Weight of nuclear steam supply system (NSSS)

Fig7 shows unit weight (ton/MWe) comparison of NSSS between the DFBR and the present design. The NSSS unit weight of the present design is the half of 1500MWe reactor which is the same model of the DFBR.

Weight of NSSS is as follows. The total weight is 2628t.

①reactor system : about 855t
②primary loop : about 753t
③secondary loop : about 1020t

The dimension of major component is as follows.

①reactor vessel : ϕ 9.6×18.8mH
②IHX : ϕ 5.0×13.5mH
③SG : ϕ 4.8×21mH

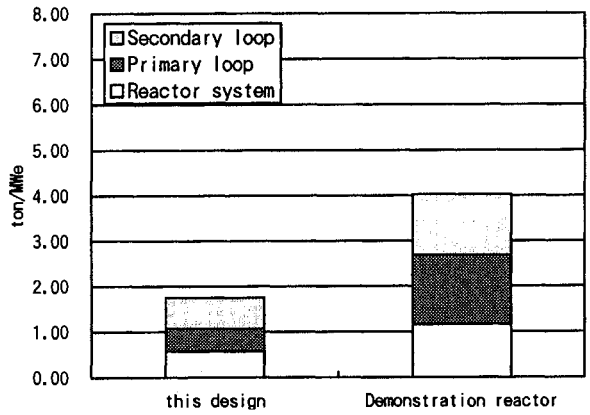


Fig 7 Weight of NSSS

(2) Volume of nuclear building

The mirror arrangement is adapted for twin plant. This arrangement can decrease the volume of nuclear building. The volume of nuclear building is about 12 million m3/plant. The volume of containment is about 1.7 million m3/plant.

(3) Construction term

Construction term of this design can be achieved about 46 month. This term is 4 months shorter than that of the DFBR. Reason why 4 month shorter is mainly the reduction of building volume.

(4) Availability factor

The term of periodical inspection of the DFBR is estimated 45 days. The critical path is inspection of primary pump and fuel exchange. The periodical inspection term of this design can be achieved about 40 days. (If non-standard periodical inspection is considered, the average term of periodical inspection is 46.3 days and the availability factor is about 92%) Reason why shorter inspection term than the DFBR is mainly the loop number of this design smaller than the DFBR.

6. CONCLUSION

The large sodium cooled FBR is designed by thoroughly applying cost down measures with taking account of the sodium characteristics. This design shows that its NSSS weight is a half of the DFBR. Some development subjects concerned with thermal & hydraulic, structural integrity and safety are listed to realize this design.

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