Feasibility Studies on Commercialized Fast Breeder Reactor Systems (3) - HLMC Fast Reactor -

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ABSTRACT

To seek for a promising concept of a heavy liquid metal coolant (HLMC) fast reactor plant, Japan Nuclear Cycle Development Institute (JNC) and the electric utilities conducted conceptual design study on various types of plant concepts and compared these concepts based on technical feasibility and economical perspective. Finally, Pb-Bi cooled medium tank type reactor was selected as a most promising concept.

1. INTRODUCTION

Japan Nuclear Cycle Development Institute (JNC) and the Electric Utilities have been conducting Feasibility Studies on Commercialized FBR Systems since July 1999 under the cooperation agreement [1]. In this research studies, we conducted conceptual design study for several kinds of FBR plants with not only sodium coolant but also heavy liquid metal coolant (HLMC), gas (CO_2, He) and water (pressurized light or heavy water, super critical water). HLMC such as Pb and Pb-Bi have some advantages as follows,

– *Chemical inertness;*

This means the reaction with water is less violent and less harmful compared with sodium coolant. It is easier to adopt a simplified heat transport system in which heat is transported from primary coolant to steam generators directly without any secondary heat transport systems. This simplification can reduce the plant construction cost. Also, the reaction between HLMC and air is mild and this character leads to a simplification of countermeasures for coolant leakage compared with sodium cooled plants.

–*Excellent neutronic characters* [2]

HLMC has excellent neutronic characters such as less moderating effect and higher scattering effect than those of sodium. Due to its less moderating effect, the neutron spectrum becomes harder and neutron economy and breeding parameters would be improved. The higher scattering effect decreases the neutron loss from the core and also decreases the burn up reactivity loss over the operating cycle. These neutronic characters can allow us to design lower pressure drop core design with increasing the pin pitch-to-diameter ratio. This can enhance the ability of natural circulation core cooling.

– *High boiling point*

The boiling points of HLMCs are higher than that of sodium. This gives us wider allowable coolant temperature rise in case of accidents and enhances the passive safety characteristics with negative reactivity feed back.

Of course, there are some disadvantages such as high load conditions on the structure due to HLMC's high density, less compatibility with structural material, needs to countermeasures for corrosion and erosion and the problem of Po210. To seek for a promising concept of a HLMC fast reactor plant, we conducted conceptual design study on various types of plant concepts and compared these concepts based on technical feasibility and economical perspective.

2. THE SCOPE OF THIS STUDY

Fig.1 shows the scope of this conceptual design study. Four types of plant concepts listed below are examined.

Concept 1: Large-scale pond type reactor with Pb as coolant.
Concept 2: Large-scale loop type reactor with Pb as coolant.
Concept 3: Medium-scale module tank type reactor with Pb as coolant.
Concept 4: Medium-scale module tank type reactor with Pb-Bi as coolant.

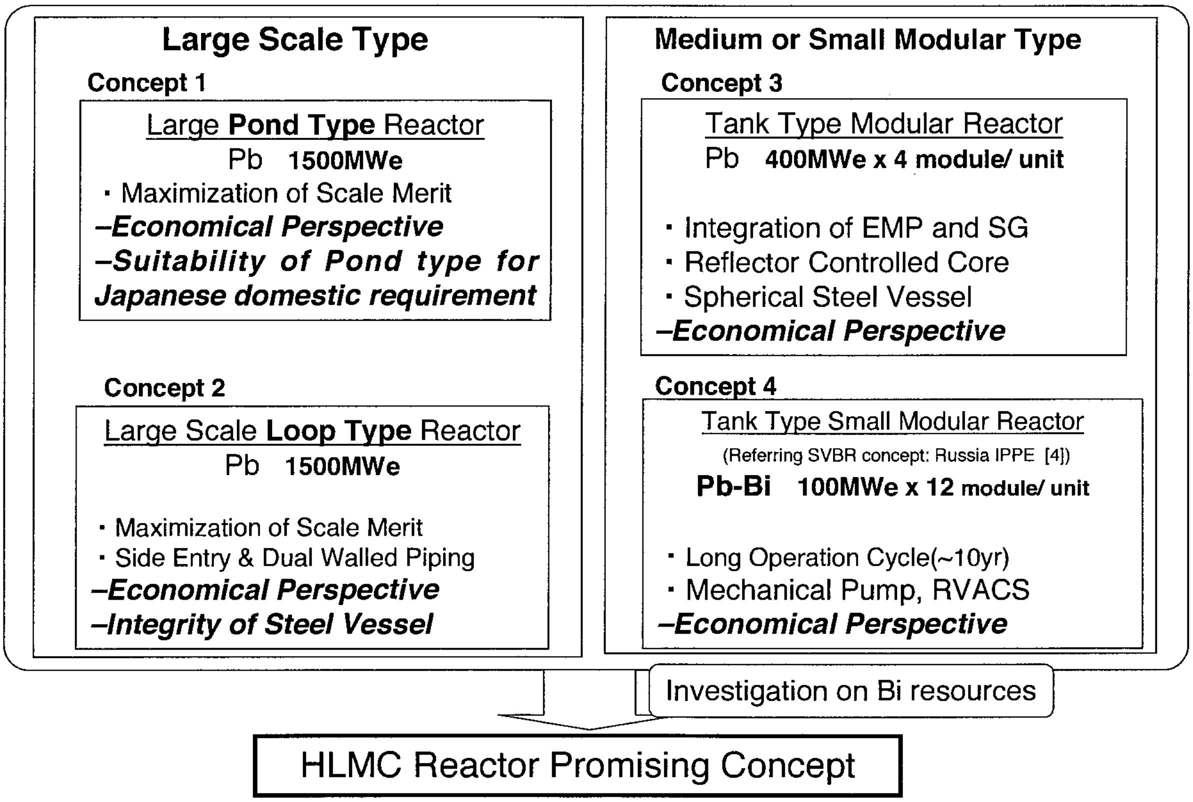


Fig. 1 Work Scope

Concept 1 and 2 are selected to seek for scale merit on economical aspect. In concept 3 and 4, we tried to reduce the inventory of HLMC and to ease the load conditions on structures and seek for competitiveness with module effect such as mass production and learning effect. Through this conceptual design study, we identified some technical features on the each concept and roughly evaluated economical competitiveness based on the total weight of Nuclear Steam Supply System (NSSS). The results of these considerations are described in the next section. In addition to the conceptual design study, we investigated the amount of Bi natural resources and the results of this estimation are explained in the section 4. In the section 5, we summarize our conclusion on the types of HLMC reactors. Finally, we briefly explain our ongoing design study on the complete natural circulation cooling reactor concept in the section 6.

3. SURVEY OF VARIOUS HLMC REACTOR CONCEPTS

3.1 Large-scale pond type reactor with Pb coolants (Concept 1)

The design concept is shown in Fig. 2. The coolant system is a pond type and the plant weight is supported by concrete that surrounds vessels. Referring the Russian BREST design [3], we tried to accommodate the concept to both the Japanese seismic design conditions and the regulatory requirement for in–service inspection on the coolant boundary. As a result, the structure of the coolant boundary is different with that of the BREST concept shown in Fig. 3. To keep the concrete temperature below the allowable limit (< 65°C), we adopted thermal shielding and concrete cooling system on the surface of the concrete. The reactor power was assumed to 1500MWe to seek for scale merit on economical aspect. As a result, huge amount of NSSS materials (nearly 9,500 tons; ~6.4t / MWe) is needed. One of reason of this huge amount of materials is the aseismatic structure under the Japanese seismic condition. The other reason is the amount of the thermal shielding structure(~3,000tons). Comparing the up to date sodium cooled fast reactor design concept in JNC (1500MWe, the weight of the NSSS; 2,700~3,300tons), this concept seems to be little economical advantage based on the Japanese seismic design standard.

Concept

- Scale Merit (1500MWe)
- Pond Type
  - Aseismatic Structure
  - Plant weight is supported by concrete which surrounds vessels
  - Seismic design based on Japanese standard

Plant Spec.

Reactor Power	3500 MWt/1500MWe
Coolant temp.	540℃ (H/L) /420℃ (C/L)
Fow rate	656,000 t/h
Fuel	MN (N-15)
Burnup	100GWd/t (average)
Breeding ratio	1.05~1. 2
Passive Safety	SASS
Primary Pump	Mechanical Pump × 4
Steam Generator	Helicalcoil × 8
DHRS	Reactor Exterior Cooling System
Seismic design	Aseismatic Structure

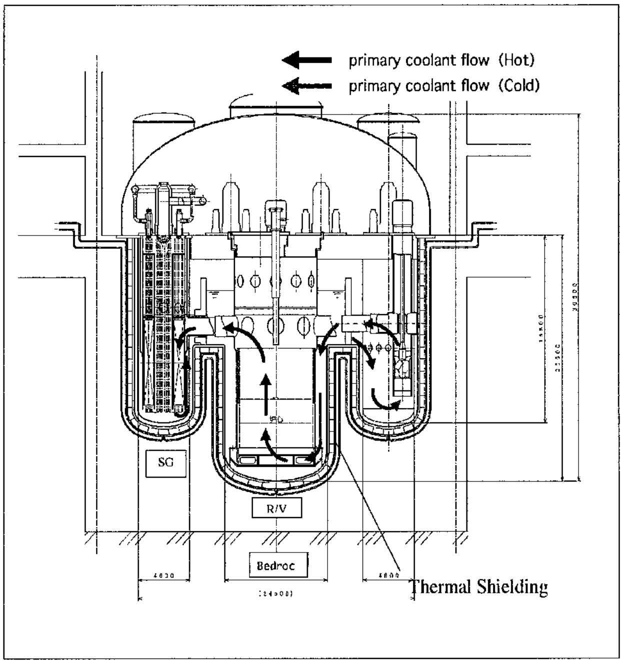


Fig. 2 Large Scale Pond Type Reactor (Pb) (1/2)

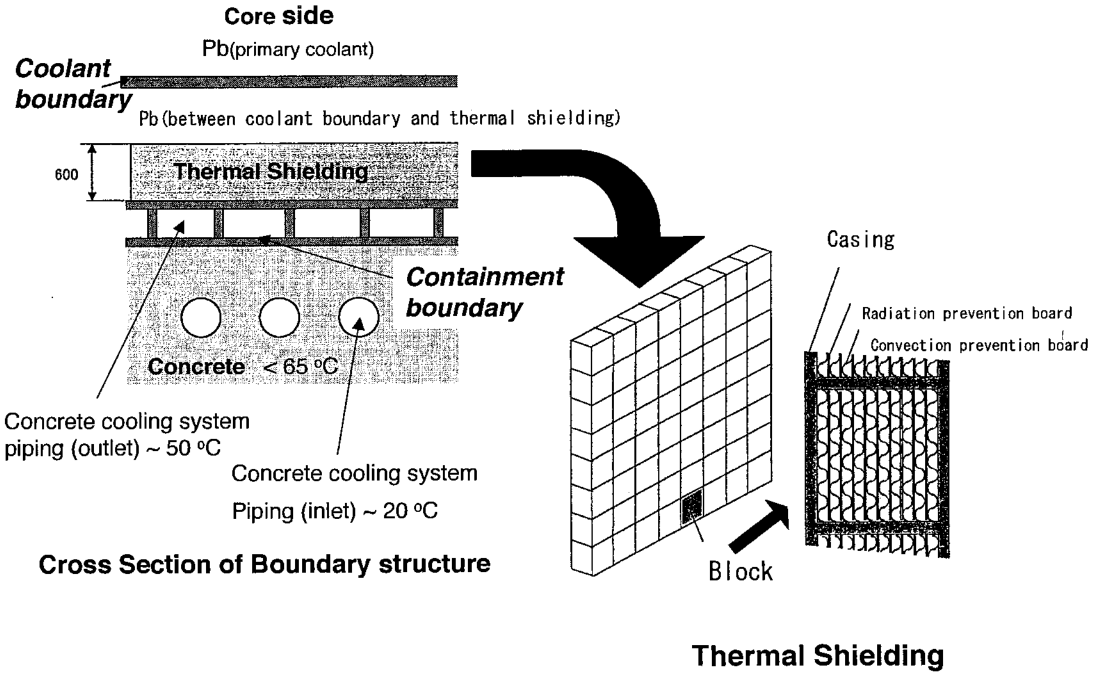


Fig. 3 Boundary structure of the "Concept 1 "

3.2 Large-scale loop type reactor with Pb coolants (Concept 2)

This concept (Fig.4) was also considered to seek for scale merit (1500MWe). To reduce the coolant inventory, we adopted a loop type concept. Based on the consideration on the type of piping system, we selected the side entry and dual walled piping concept with slide-joint inner wall to cope with thermal expansion on the piping system. With this new idea and the seismic isolation system, the amount of NSSS structural materials can be reduced to about 3,400tons (~2.3t/MWe). This weight of the NSSS is comparable to that of the sodium cooled tank type fast reactor concept (1500MWe, 3,100~3,300tons) but somewhat larger than that of the sodium cooled loop type fast reactor concept (1500MWe, 2,700tons). However, the concept of the dual walled tube has some engineering difficulties as follows.

- Inspection of inner boundary of dual walled piping.
- Tricky structure such as slide-joint is inevitable
- Incompatibility between the slide-joint and the corrosion prevention measures; mechanical tearing of the oxide thin layer

Further R&D efforts are needed to solve the above issues.

Concept

- Scale Merit (1500MWe)
- Loop Type-Side Entry
  - Dual Walled Piping
  - Seismic Isolation

Plant Spec.

Reactor power	3656MWt／1500MWe
Number of loop	4
Coolant temp.	540℃ (H/L) ／420℃ (C/L)
Flow rate	684,000t/h
Fuel	MOX or MN (N-15)
Burn up	150GWD/T (average)
Breeding ratio	1.04~1.15 : MOX
	1.15~1.28 : MN
Passive Safety	SASS
Primary Pump	Mechanical Pump × 4
Steam Generator	Helical coil × 4
DHRS	PRACS × 4
Seismic design	Seismic Isolation (2D)

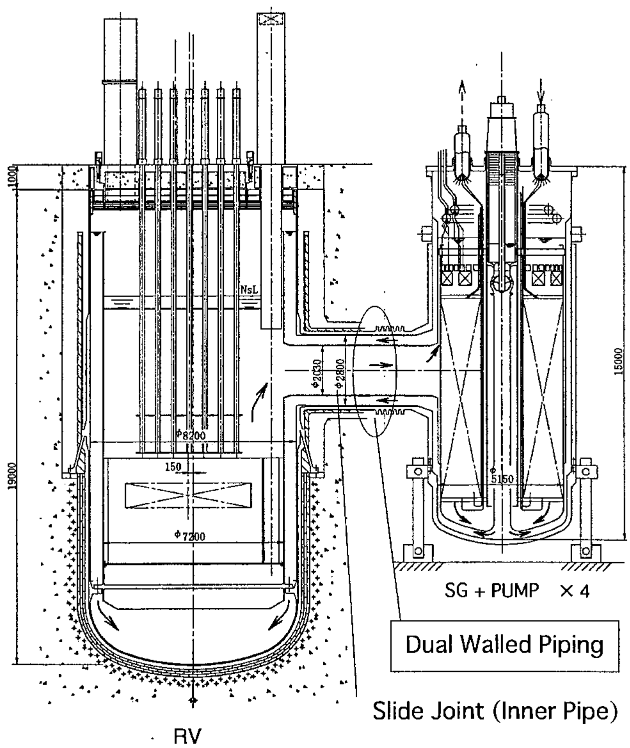


Fig. 4 Large Scale Loop Type Reactor (Pb)

3.3 Medium-scale module tank type reactor with Pb coolants (Concept 3)

Fig.5 shows the plant concept of the medium-scale module tank type reactor (400MWe X 4 module/unit). In this concept we tried to reduce the inventory of HLMC and to ease the load conditions on structures and seek for competitiveness with module effect such as mass production and learning effect. The Pb coolant is circulated by the Pb electromagnetic pumps (EMPs). The EMP and the steam generator (SG) are integrated into one component to simplify the coolant circuit in the reactor tank. The reflector control system is employed as the reactivity control system; the absorber rods are located only around the circumference of the core. This idea can simplify the upper core structure and increase the flexibility on the design of fuel handling mechanism in the reactor tank. The amount of NSSS structural materials was evaluated to about 1496tons (~3.7tons/MWe). The estimated construction cost is about ¥300,000/kWe. But this estimated value has not reached our requirement (¥200,000/kWe). It is desired to make further efforts for reduction of the amount of structural material. Also, there are some disadvantages with EMP as follows.

- The EMP has been combined with SG. This makes the repair work difficult.
- Large-capacity Pb electromagnetic pump is supposed to need long R&D term.

Concept

- Medium Scale & Module
  (400MWe× 4 module/unit)
- Tank Type
  - Pb Electromagnetic Pump
    -- Integration of EMP and SG
  - Seismic Isolation

Plant Spec.

Reactor power	1000MWt／400MWe
Number of module	4 module
Coolant temp.	550℃ (H/L) ／395℃ (C/L)
Flow rate	183000t/h
Fuel	MOX or MN (N-15)
Burn up	150GWD/T (average)
Breeding ratio	0. 9～1. 2
Passive safety	SASS
Primary pump	Pb Electromagnetic Pump ×8
Steam generator	Helical coil× 8
DHRS	SGHRS + RVACS(vessel exterior cooling with water)
Seismic design	Seismic Isolation (2D)

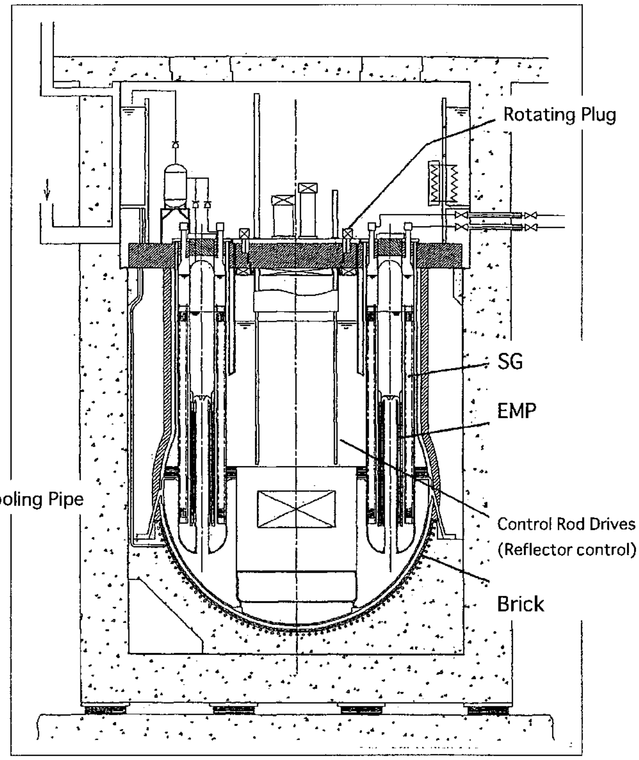


Fig. 5 Medium Scale Module Tank Type Reactor (Pb)

3.4 Medium/small-scale module tank type reactor with Pb-Bi as coolant (Concept 4)

Referring to the Russian SVBR concept [4], we considered the technical feasibility and economical perspective of this type of HLMC reactor. Fig. 6 shows this concept. One of the advantages of this module tank type reactor (100MWe X 12 module/unit) concept seems to be minimization of the coolant inventory. Small amount of the coolant inventory makes the NSSS weight decrease and the earthquake resistance can be improved. Also, it is advantageous from the viewpoint of the Bi resource problem. The estimated weight of the NSSS per unit power is around 2.8t/MWe and is larger than that of sodium cooled fast reactor concept (1500MWe, pool type; ~2.0 ton/MWe, loop type; ~1.7 ton/MWe). It seemed necessary to further optimize the design concept. To achieve further construction cost reduction, there are some ways as follows.

- -Seeking for scale merit with increasing the reactor power.
- -Reconsidering the number of SG unit and optimization of its heat transfer tube type (bayonet or helical coil)

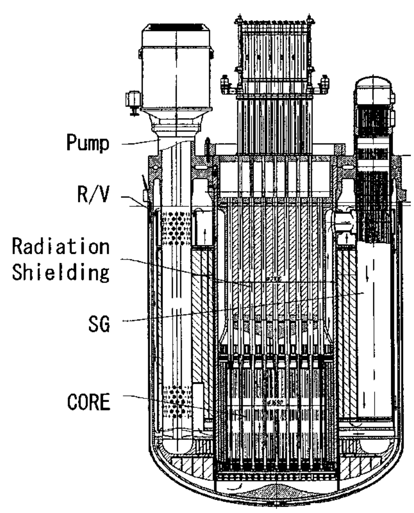
It is important for a Japanese plant user to make sure that the seismic design is satisfying the Japanese design standard.

Concept

- **Small Scale Module**
  (100MWe × 12 module/unit)
- **Tank Type**
  - **Minimization of the coolant inventory**
  - **Aseismatic Structure**

Plant Spec.

Reactor power	260MWt／100MWe
Number of module	12 module
Coolant temp.	460℃ (H/L) ／310℃ (C/L)
Flow rate	4200t/h
Fuel	MOX or MN (N-15)
Burn up	90GWD/T
Breeding ratio	1. 02～
Passive safety	SASS
Primary pump	Mechanical Pump × 2
Steam generator	Bayonet× 12
DHRS	RVACS
Seismic design	Aseismatic Structure



SVBR－75／100

Fig.6 Medium/Small Scale Module Tank Type Reactor(Pb-Bi): SVBR
- referring Russian SVBR concept [4]

4. CONSIDERATION ON THE Pb-Bi AS REACTOR COOLANT

4.1 Estimation on the amount of Bi natural resources

According to the US geological survey published as "Minerals Yearbook Mineral Commodity Summaries 1999" [5], the amount of Bi resources is estimated 260,000 ton. This estimated value is mainly based on existing mines. We examined the total amount of Bi resources taking into account the undeveloped area on the earth. To estimate the amount of the natural resource value, we assumed some geological conditions listed below with some extent of conservatism.

- Total mass of the earth's crust form surface to 3km depth: 1.2E+18 ton
- Possibility of mine development: 20% of the upper part of the crust
- Possibility of mining & ore dressing: 0.01% of the total mineral in the crust
- Abundance of Bi in the earth's crust: 0.2ppm
- There was a tendency of concentration near the surface due to relatively low melting point of Bi

Multiplying all of the above numbers and rates, we can roughly estimate that the amount of available Bi resources is around 5,000,000 ton. Based on the conceptual design study described above, Pb-Bi coolant inventory can be supposed to be (1,100 ~ 18,000 t/GWe. Therefore, the expected power by Pb-Bi cooled power reactor is deduced by the below calculation.

(5,000,000 ton) / (1,100 ~ 18,000 ton/GWe) = 280 ~ 4,500 GWe

On the other hand, the future demand for nuclear power in Japan at 2100 is estimated about 120Gwe. Based on the above consideration, the amount of Bi resources seems not to be a significant issue. But the price of Bi depends on not only the amount of the Bi resources but also the principle of the market such as demand and supply. Further consideration may be needed for the cost aspect of Bi resources.

4.2 Comparison between Pb and Pb-Bi

Pb-Bi coolant with lower melting point seems to be more attractive than Pb coolant because,

- No need for maintenance work under high temperature (~ 400°C).

- Lower temperature of SG feed water (FW) gives us the possibility of more compact SG and better controllability of FW system.

- Compatibility for passive decay heat removal system (DHRS) due to wider operational temperature range.

According to the Russian researcher [6], Amount of Po in the cover gas system in a Pb-Bi cooled reactor plant may not so higher than that of a Pb cooled reactor because lower shutdown temperature of a Pb-Bi reactor may mitigate the amount of Po210 release during maintenance and refueling duration. Further consideration is needed based on the specific plant design and operating condition.

5. CONSIDERATON ON THE HLMC REACTOR TYPES

From the consideration described in the section 3 and 4, we concluded,

- Under the Japanese seismic condition, aseismatic structure makes the amount of material increase. For the large-scale pond type reactor, total amount of the thermal shielding material became huge. (Concept 1)

- For the large-scale loop type reactor, we selected a side entry and dual walled piping concept with slide-joint inner wall to cope with thermal expansion on the piping system. However, there seemed to be difficulty of compatibility between the slide-joint and oxide film corrosion prevention measures. (Concept 2)

- The medium modular types seemed to be preferable to large types but the total weight of NSSS was lager than that of the evolutional sodium cooled fast rector concept that had been studied at the same time in JNC [7]. It is necessary to further optimize the design concept. (Concept 3&4)

- Lower melting point of Pb-Bi coolant makes it more attractive than Pb coolant. Based on roughly but conservative estimation, the amount of Bi resources seems not to be a significant issue.

6. CONCEPTUAL DESIGN STUDY OF MEDIUM SCALE MODULE TANK TYPE REACTOR

One of the important ways to attain competitiveness is simplification of NSSS and Balance-of–plant (BOP) design by employing passive features. As described in the section 1, compared with sodium cooled core, the neutronic characters of HLMC can allow us to design lower pressure drop core with less deteriorating the core breeding parameters. This advantage leads to the idea of a complete natural circulation cooled tank type reactor concept. We are now performing design study on this type of reactor with Pb-Bi coolant.

6.1 Concept of HLMC reactor plant with complete natural circulation

The concept of this medium tank type and modular reactor (400MWe × 4 module / unit) is shown in Fig. 7. Eliminating the coolant circulation pumps from the reactor vessel makes the heat transport system simple and can decrease the amount of the weight of NSSS.

Concept

- **Medium Tank Type & Modular reactor (400MWe × 4 module / unit)**
- **Complete natural circulation cooling**
  - **Simplification of heat transport system**
  - **Reduction of the weight of the NSSS**
  - **Reduction of the BOP system**
- **Mix-nitride fuel**
  - **Breeding Ratio ~ 1.2**
  - **Seeking for passive safety**

Plant Spec.

Reactor power	1053MWt／400 MWe
Number of module	4 module
Coolant temp.	492℃ (H/L) ／312℃ (C/L)
Flow rate	144000 t/h
Burn up	150GWd/t (average)
Passive safety	SASS
Steam generator	Helical coil × 1 /module
DHRS	PRACS (natural circulation)
Seismic design	seismic Isolation (3D)

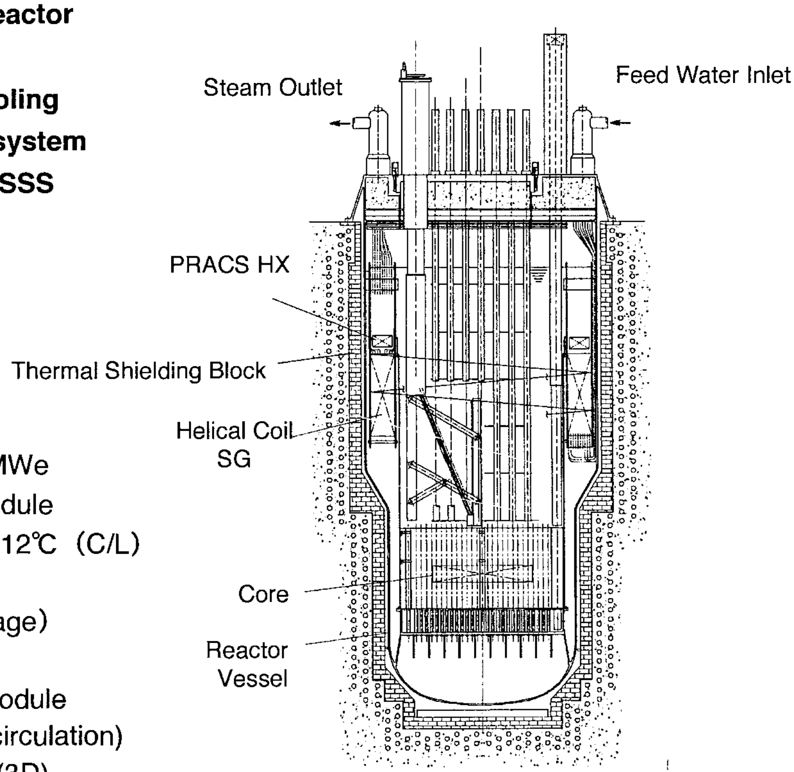


Fig.7 Medium Scale Module Tank Type Reactor with Complete Natural Circulation

The capacity of BOP system such as the electricity supply system, the HVAC system and the component cooling water system would be reduced because there is no need to supply electricity for the circulation pumps and no need the circulation pump cooling system. Therefore, the reduction of the plant construction would be expected.

Based on the preliminary study, height difference between thermal centers became about 8 m and the amount of NSSS structural materials was evaluated to about 2.3tons/MWe. The estimated construction cost accounting module effect was about ¥250,000/kWe and this value is larger than our target value ¥200,000/kWe. However, by increasing the core power from 400MWe to 550MWe and by introducing the idea of BOP function sharing among the modules, the construction cost about ¥ 206,000 / kWe can be expected.

The core is mix-nitride fuel and the breeding ratio was evaluated to ~ 1.2. To attain enough natural circulation flow rate and to keep the maximum cladding temperature less than 650°C, the core pressure drop had to be very low (~ 0.1kg/cm^2, fuel pin pitch/fuel pin outer diameter: p/d ~1.5) and also the core liner power density had to be very low (~ 75W/cm (ave.)). This results in the huge amount of heavy metal inventory in the core (~35t (core), 120t(blanket) / 400MWe) and lower core outlet temperature: 492°C (inlet temp.312°C). This huge amount of heavy metal inventory has negative effect on the plant operating cost because of higher fuel cost. The complete natural circulation cooling concept has various advantage due to its simplification but the further effort for optimizing the core performance is needed.

7. CONCLUSION

Medium tank type & modular reactor concept was selected as a promising concept. To seek for economic competitiveness, the way of complete natural circulation core cooling was selected because of its lower amount of NSSS weights. From the economical perspective, this concept may attain our construction cost goal (¥ 200,000 / kWe). However, optimization of the core performance considering the safety performance is needed.

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