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Safety Aspects of Future LMFBR Design in Japan

—PNC View—

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前田　清彦*

要旨

実用化をめざしたLMFBRの設計例につき、その安全性を高速実験炉「常陽」及び原型炉「もんじゅ」と対比しながら述べる。

安全性は、制御性、冷却性、格納性及び対象とした炉の固有の安全性の観点から検討した。

実用化をめざしたLMFBRの設計例として、2重管型蒸気発生器を使用した2次系削除型実用化炉をとりあげた。

このレポートは、平成元年8月28日から8月31日に米国のシカゴで開催されるIAEA主催の「the IAEA International Workshop on the Safety of Nuclear Installation of the Next Generation and Beyond」へ発表するために作成された。

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*：大洗工学センター技術開発部プラント工学室

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Safety Aspect of Future LMFBR Design in Japan
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Kiyohiko Maeda*

Abstract

Safety aspects of future LMFBR design in Japan, comparing with those of experimental plant “JOYO” and prototype plant “MONJU”, were shown.

Safety aspects were discussed from the viewpoint of Controllability, Coolability and Containability.

As a future plant of Japanese LMFBR, a plant design without secondary heat transport system using double walled tube steam generator was discussed.

This paper was prepared for Japanese contribution to the Session VI of **the IAEA International Workshop on the Safety of Nuclear Installations of the Next Generation and Beyond** held at Chicago.

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* : Plant Engineering Office, OEC, PNC

1. Introduction

LMFBR has the following characteristics.

·Reactor is controlled and shutdown by control rods.

·Sodium is used as the coolant at single phase flow.

·Operating temperature of the coolant has a large margin from the boiling temperature at normal atmospheric pressure.

These characteristics should be considered in discussion on safety of LMFBR.

Safety of reactor will be kept when ①reactor is controlled properly (to stop at any time necessary), ②reactor is cooled properly (to have enough capacity of heat transfer from core to the final heat sink and to keep coolant level above a necessary level even when coolant leakage occur) and ③reactor is contained properly (to reduce release of radioactive materials even when accident occur).

These safety function shall be satisfied consistent with construction cost reduction. Many ideas are proposed and discussed for construction cost reduction of future LMFBR in Japan.

As one type of future LMFBR plants, a design work is proceeding on a plant eliminating the secondary heat transport system (SHTS). The elimination of SHTS should be discussed from the viewpoint of safety feature of SHTS in ordinary type of LMFBR, that is a countermeasure of sodium water reaction.

In this paper, safety aspects of a future LMFBR eliminating SHTS comparing with the experimental reactor and the prototype reactor in Japan were shown.

2. Rough Description of Plants

Plants discussed in this paper were shown in table 1 through table 3 and Fig. 1 through Fig. 3.

JOYO has been operated for more than 12 years, in safe and stable since April 1977.

Construction work of MONJU is proceeding on schedule, and about 71% of construction work has been finished. MONJU will be first criticality at 1992.

From present status, it is important to reduce construction cost without cutting down safety for commercializing the LMFBR, and many ideas have been proposed. Among these ideas, a plant design eliminating SHTS is proceeding.

3. Control (Shutdown) System on Reactor

3.1 JOYO

Reactor core of JOYO has been given negative feedback characteristics, so its operation is very stable.

In addition, JOYO MK-II core has six control rods shown in Fig. 4. Each control rod has the same functions, i.e. reactor power control at normal operation and fast shutdown by rapid insertion.

When one of the control rods with largest worth is fully withdrawn and kept at its position, the reactor can be stopped and cooled down safely from any operating condition by the rest rods.

3.2 MONJU

In addition to a negative feedback characteristics, MONJU core has ten coarse control rods, three fine control rods and six back up rods. These three types of rods have different structures for diversity as shown in Fig. 5~7.

When one of thirteen primary (coarse and fine) control rods with largest worth is fully withdrawn and kept at its position, the reactor can be stopped and cooled down by the rest twelve control rods from any operating condition. And further more, if all thirteen primary control rods fail to drop at all, the reactor could be shutdown safely by six back up rods.

3.3 Future Plant

(1) Outline of Development

Development of Self Actuated Shutdown System (SASS) is proceeding in PNC.

SASS is expected to reduce unavailability of reactor shutdown system in loss of flow type accidents.

(2) Details of Development

Various systems can be considered as the self actuated type shutdown systems in principle. However, taking performance and availability into consideration, a few system can be estimated practical, where temperature sensitive electromagnet (TSEM) type combined with articulated control rods was evaluated the best candidate.

Two kinds of shutdown system were provided for the research and development. The essential difference between the design of the two systems came from the location of TSEM as illustrated in Fig, 8.

(3) Outline of the Results and Future Plan

Tests of actuation properties of the TSEM materials, thermal hydraulic behavior of coolant, stability of the TSEM materials were performed successfully. Tests on seismic characteristics of TSEM and articulated control rods are proceeding.

The discussion of a possibility and an effectiveness of the demonstration test in JOYO is proceeding.

4. Decay Heat Removal System

4.1 JOYO

There are two main heat transport systems as shown in Fig. 9.

As JOYO is an experimental reactor, final heat sink is air by air blast coolers under normal operating condition. And the air blast coolers are also final heat sink in case of emergency, together with forced circulation by pony motors of primary pumps.

As for redundancy of decay heat removal systems, an auxiliary cooling system is prepared, which is driven by electromagnetic pump.

All components and piping of primary heat transport system (PHTS) are double walled to keep sodium level in the reactor vessel above a necessary level to maintain function of decay heat removal. And SHTS are separated from each other to keep independence.

To back up forced circulation, main heat transport systems were designed to have natural circulation force for decay heat removal.

A total black out test from full power operation was performed in JOYO to prove natural circulation capacity. Test results were shown in Fig. 10 together with calculated results by a computer code. The maximum temperature of the coolant at outlet of fuel located at center of the core was 519°C, and did not exceed the initial temperature, 548°C. And calculated value of maximum coolant temperature was less than 5°C higher than experimental data.

4.2 MONJU

MONJU was designed to have three main heat transport systems as shown in Fig. 11.

Parallel to steam generator system, auxiliary air blast cooler was installed in each secondary loop for decay heat removal. Each auxiliary air blast cooler was designed to have enough capacity to remove decay heat from core, together with forced circulation by pony motors of primary and secondary pumps. So, redundancy of decay heat removal was achieved by these three auxiliary heat transport systems.

All components and piping below a system level (the lowest limit of horizontal piping) were surrounded by guard vessels to keep sodium level above an emergency level (the necessary level for decay heat removal operation). And SHTS were separated from each other to keep independence.

To back up forced circulation, auxiliary heat transport systems were designed to have natural circulation force for decay heat removal.

Natural circulation capacity of auxiliary heat transport system was calculated by a computer code validated by experimental data of JOYO. The maximum value of the hot spot coolant temperature at outlet of the fuel was 763°C, and did not exceed the acceptable maximum clad temperature 830°C.

4.3 Future Plant

There are four main heat transport loops as shown in Fig. 12, but main heat transport systems are not expected to remove decay heat.

Two types of DRACS (Direct Reactor Auxiliary Cooling System) are designed to remove decay heat in case of emergency.

These systems are shown in Fig. 13.

One of DRACS is a sink type, and the other is a circulation type.

The sink type DRACS is system that a heat exchanger (DHX) is installed in a reactor vessel, and coolant in upper plenum of reactor vessel is to be cooled directly.

The circulation type DRACS is system that primary coolant is taken out directly from a reactor vessel and a heat exchanger (CHX) is provided outside the reactor vessel, just like auxiliary cooling system of JOYO.

Both types of DRACS have electromagnetic pumps (EMP) for coolant circulation.

Both types of DRACS are designed to have natural circulation force to be able to cool the core not to occur mechanical clad failure as back up of forced circulation.

Two loops of sink type DRACS and two loops of circulation type DRACS are to be installed to the future LMFBR.

Reactor vessel is surrounded by a guard vessel, and all other components and piping are to be separated from the reactor vessel by siphon breaker to maintain sodium level in reactor vessel in case of coolant leakage accident. The guard vessel is to be made of fine ceramics to eliminate steel cell liner for the reactor cavity.

5. Containment of Radioactive Materials

5.1 JOYO

The containment system of JOYO was shown in Fig. 14. Atmosphere at upper part of containment vessel is air, and at lower part is inert gas to avoid sodium fire.

Design specifications of the containment system were shown in Table 4.

These design conditions were decided based on thermal effects of a sodium fire at the upper part of the containment vessel caused by re-critical accident.

Annulus area between containment vessel and shielding building is always kept in negative pressure, and exhaust gas is to be filtered by emergency filtering system in case of emergency.

5.2 MONJU

The containment system of MONJU was shown in Fig. 15.

Design specifications of the containment system were shown in Table 5.

These design conditions were decided from engineering judgment to construct containment vessel as strong as reasonably achievable.

Major accident in containment vessel was primary coolant leakage, and radioactive materials except rare gas were assumed to act as the same way of sodium aerosol, considering chemical activity of sodium.

Leak tightness of cell liner and containment vessel was considered.

A filtering system, consisted of aerosol filter, fine particle filter and charcoal filter, was provided.

5.3 Future Plant

The containment system of the future LMFBR was designed to consist of concrete structure with steel liner, surrounded by confinement building with emergency gas filtering system as shown in Fig. 16.

Design basis source term was assumed to be inside the reactor vessel and retention factor of sodium against fission products (FP) and leak path from inside the reactor vessel to the environment was considered.

Main steam line and feed water line were arranged not to give influence to the containment system by high pressure piping rupture accidents.

6. Specific Safety Aspects of LMFBR without SHTS

6.1 Safety Functions of SHTS

Major safety function of SHTS in ordinary LMFBR is to prevent severe damage of the core caused by sodium water reaction.

(1) Double walled tube type SG and relating leak detection systems should be reliable enough to replace SHTS for prevention of severe core damage caused by sodium water reaction.

→Double walled tube can be considered as a double static barrier. When defect of one of the double barrier is detectable before

(2) Prevention systems or mitigation systems of sodium water reaction in a plant without SHTS should be much simpler than the SHTS with mitigation devices in a plant with SHTS.

→Mitigation systems might be more complex and large scaled. Much effort should be paid to develop prevention systems.

6.2 Design Basis Event

Based on the present status and prospects of R & D and requirements to make plant reasonable, it was concluded that failure mode of SG tubes as **design basis event** should be :

No leak through inner and outer tube.

(Sodium water reaction should be beyond design basis event.)

(1) Much more reliable SG will be developed by future R & D. PNC has operation experience of large scale SG test facility (50MW single walled tube SG) without tube leak for more than 20,000 hours.

(2) It is necessary to develop reliable leak detection systems to detect single wall failure before occurrence of failure of the opposite wall.

(3) It is necessary to study failure mode of double walled tube to remove common mode failure of double walled tube.

6.3 Process of Developing LMFBR without SHTS

(1) Establishing technologies of fabrication and examination on double walled tubes and related parts

(2) Development of inner tube leak detection systems and outer tube leak detection systems with redundancy and diversity respectively

(3) Development of ISI device for double walled tube

(4) Verification test of double walled tube and leak detection systems by small scale SG test facility

(5) Probabilistic assessment of demand failure on leak detection systems and steam blow down systems

(6) Analysis of tube failure by fracture mechanics technology and probabilistic assessment based on the research on failure mode of tubes, and on the validation tests

(7) Verification test of fabrication and examination techniques and getting operational data by large scale SG test facility

(8) Study of possibility and effectiveness of applying these logic to the actual plant JOYO before applying to a commercial plant to get affirmation of licensability and to get operational experience of actual plant

A draft of development flow is shown in Fig. 17.

6.4 Conceptual Design of LMFBR without SHTS

Main heat transport system of future LMFBR without SHTS is shown in Fig. 18. And double walled tube type steam generator is shown in Fig. 19.

Concept of leak detection systems is shown in Fig. 20.

Apparently simplification will be achieved by elimination of SHTS.

7. Conclusion

(1) JOYO has been operated in safe and stable for more than 12 years.

(2) Construction of MONJU is on schedule, and it will be critical at 1992.

(3) Design work to develop safe and economical large scale LMFBR is proceeding in Japan, based on the experience of design, construction and operation of JOYO and MONJU.

(4) Feasibility studies of advanced technologies are proceeding, such as SASS, elimination of SHTS, etc.

Table 1 Rough Description Of JOYO

°Power	:100MWt	
°Core Size	:0.6mφ×0.55mH	
°Number of Control Rod	:6	
°Plant Type	:Loop Type	
°Number of Primary Loop	:2 (+1)*	*:Auxiliary Cooling System
°Number of IHX	:1 / Loop	
°Number of Secondary Loop	:2 (+1)*	*:Auxiliary Cooling System
°Number of Pump	:1+1 / Loop*	*:Primary+Secondary
°Number of SG	:None*	*:Air Cooled
°Coolant Temperature	:500°C / 370°C*	*:RV Out / In
°Containment System	:Steel Vessel / Concrete Outer Shield / Filter	

Table 2 Rough Description Of MONJU

°Power	:280MWe	
°Core Size	:1.8mφ×0.93mH	
°Number of Control Rod	:10+3+6*	*:Coarse + Fine + Back Up
°Plant Type	:Loop Type	
°Number of Primary Loop	:3	
°Number of IHX	:1 / Loop	
°Number of secondary Loop	:3 (+3)*	*:Auxiliary Cooling System
°Number of Pump	:1+1 / loop*	*:Primary+Secondary
°Number of SG	:2* / loop	*:EV & SH
°Coolant Temperature	:529°C / 397°C*	*:RV Out / In
°Containment System	:Steel Vessel / Concrete Outer Shield / Filter	

Table 3 Rough Description Of Future LMFBR

°Power	:1500MWe	
°Core Size	:4.2mφ×1.2mH	
°Number of Control Rod	:27+9*	*:Main + Back Up
°Plant Type	:Loop Type without SHTS	
°Number of Loop	:4 (+4)*	*:Auxiliary Cooling System
°Number of Pump	:1 / loop	
°Number of SG	:1* / loop	*:Double Walled Tube Type
°Coolant Temperature	:550°C / 370°C*	*:RV Out / In
°Containment System	:Steel Lined Concrete Structure / Confinement Building / Filter	

Table 4 Design Specification of Containment System (JOYO)

Containment Vessel

◦Design pressure :Inner 1.35 kg/cm^2, Outer 0.05 kg/cm^2
◦Design Temperature :150°C
◦Design Leak Rate :0.7 %/day at Design Pressure and Gas Temp. of 360°C
◦Acceptable Leak Rate at Leak Rate Test (Including Measuring Error) :3 %/day at Design Pressure and Reactor Halt Condition
◦Material :Carbon Steel
◦Diameter / Height :28 m / 54 m
◦Wall Thickness :25 mm

Outer shield structure

◦Diameter / Height :30 m / 27 m above Ground Level
◦Wall Thickness :0.5 m

Emergency filtering system

◦Efficiency :92 % for Organic Iodine
98 % for Particle

Table 5 Design Specification of Containment System (MONJU)

Containment Vessel

◦Design Pressure :Inner 0.5 kg/cm^2, Outer 0.05 kg/cm^2
◦Design Temperature :150 °C
◦Design Leak Rate :1 %/day at Design Pressure and Room Temp.
(0.1 %/day before accepting sodium)
◦Material :Carbon Steel
◦Diameter / Height :49.5 m / 79 m
◦Wall Thickness :38 mm

Outer shield structure

◦Diameter / Height :52.5 m / 46 m above Ground Level
◦Thickness of Wall :1.0~1.8 m
◦Thickness of Dome :0.45 m

Emergency filtering system

◦Efficiency :99 % for Gaseous Iodine
99 % for Particle

Table 6 Design Specification of Containment System (Future Plant)

Containment Structure

- Design Pressure :Inner 1.0 kg/cm^2, Outer 0.2 kg/cm^2
- Design Temperature :Gas 350 °C
- Design Leak Rate :1 %/day at Design Pressure and Room Temp.
- Material :Concrete / Steel Liner
- Width / Length / Height :27 m / 27 m / 33 m
- Wall Thickness :Concrete 1 m / Steel Liner 6.4 mm

Confinement structure

- Pressure :Slightly Negative

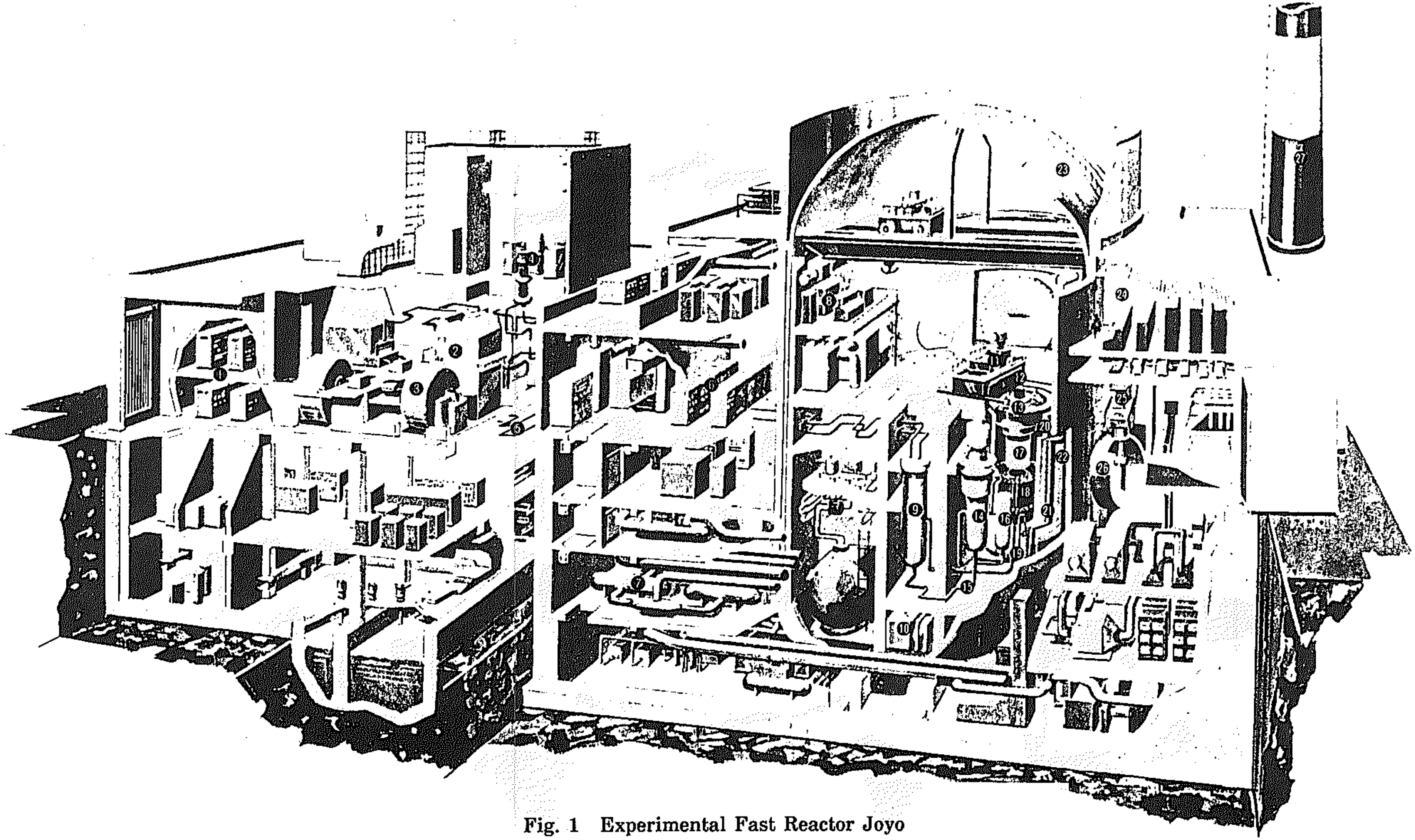
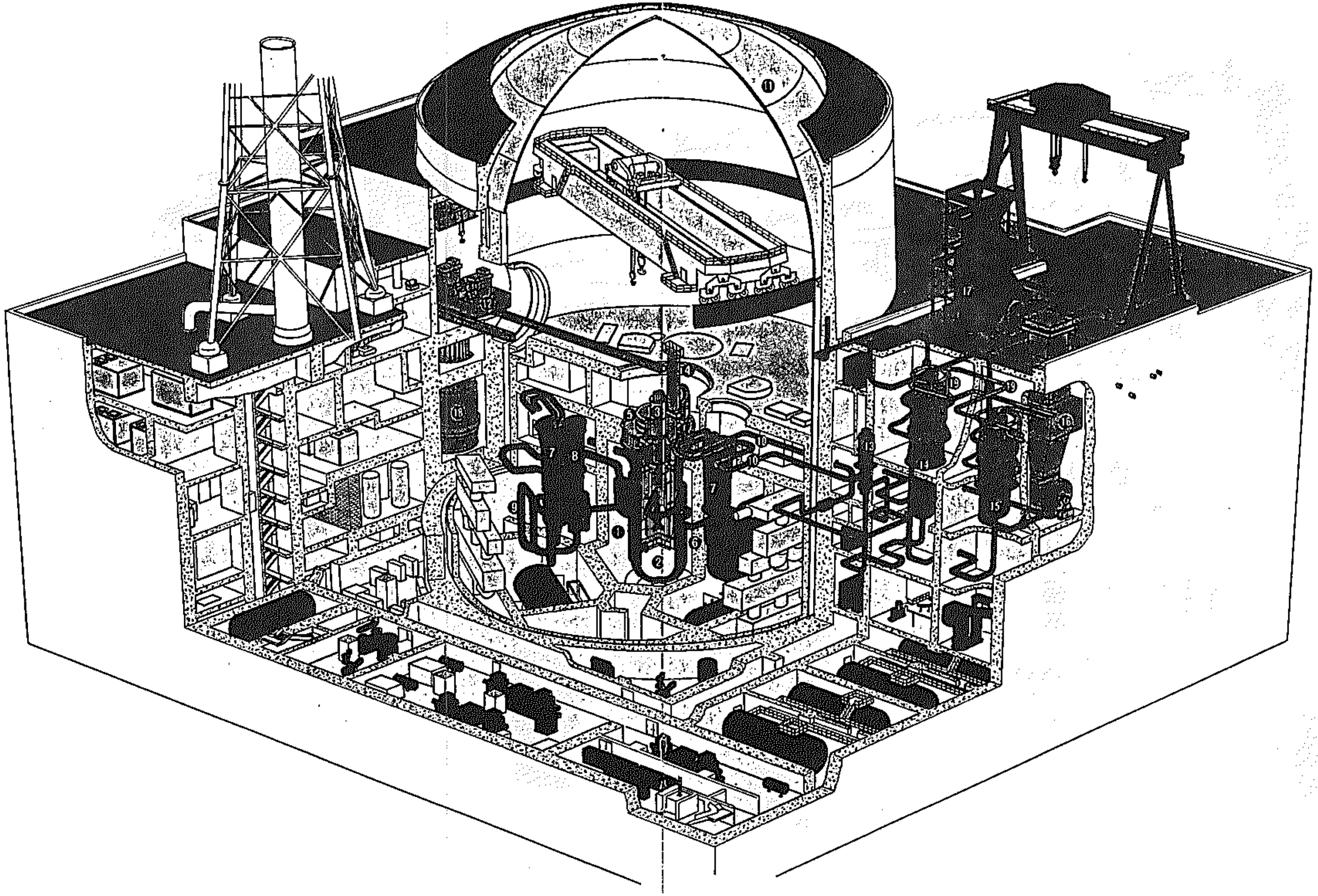


Fig. 1 Experimental Fast Reactor Joyo



Fig, 2 Prototype FBR Monju

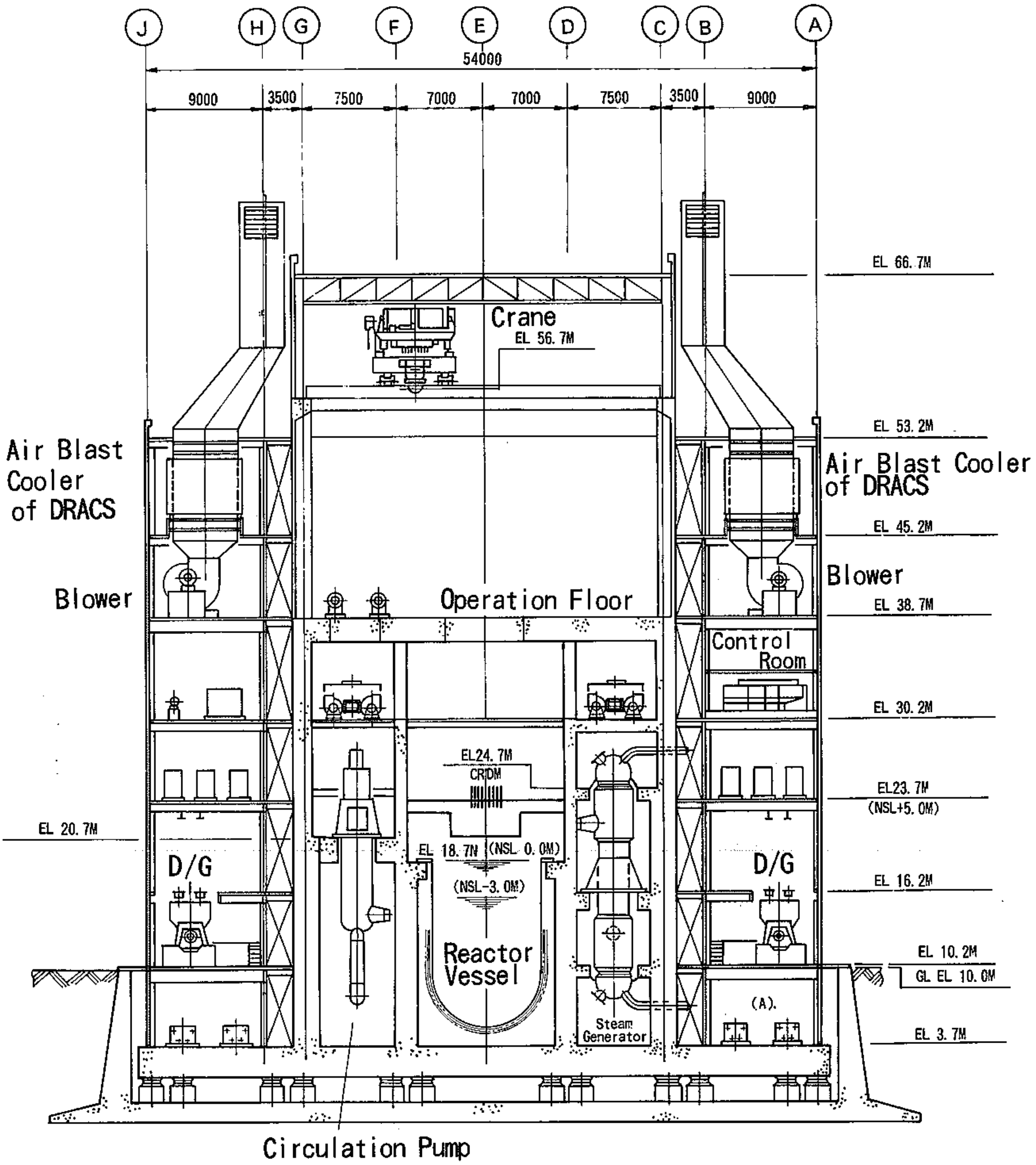


Fig. 3 Concept of Future LMFBE

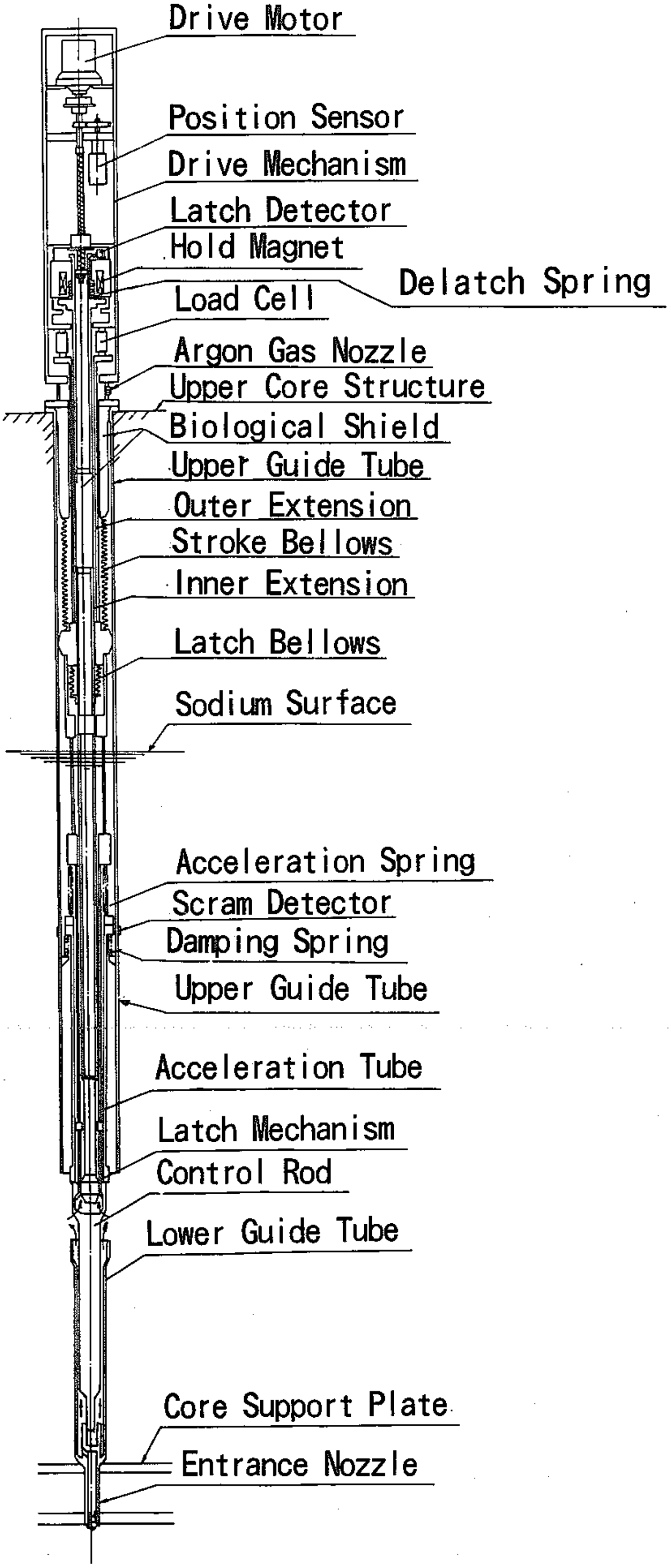


Fig. 4 Control Rod and Drive Mechanism of Joyo

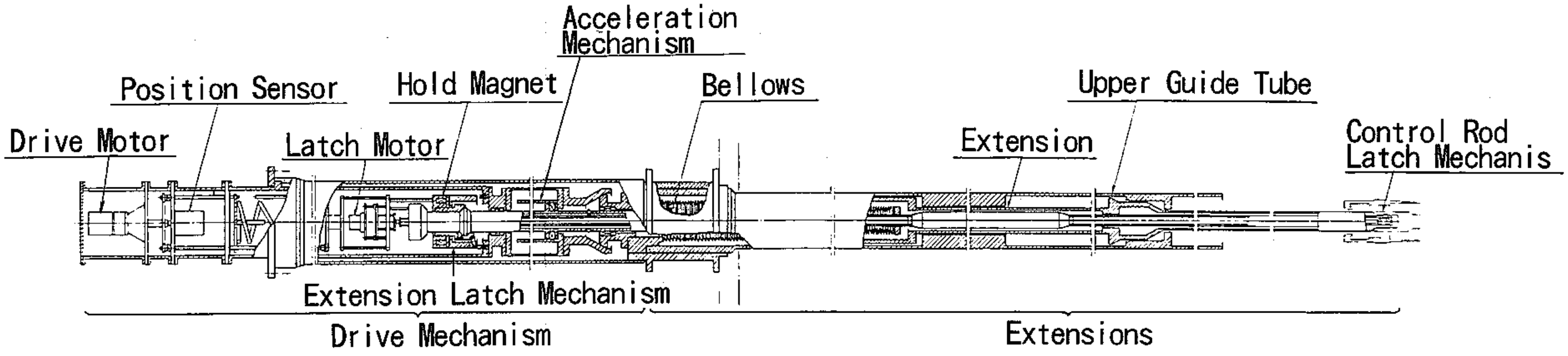


Fig. 5 Fine Control Rod Drive Mechanism

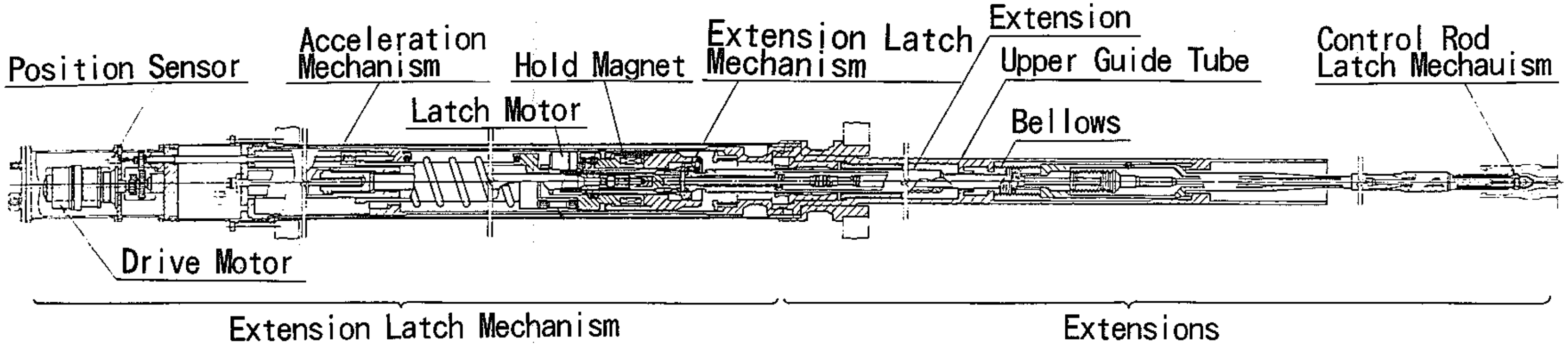


Fig. 6 Coarse Control Rod Drive Mechanism

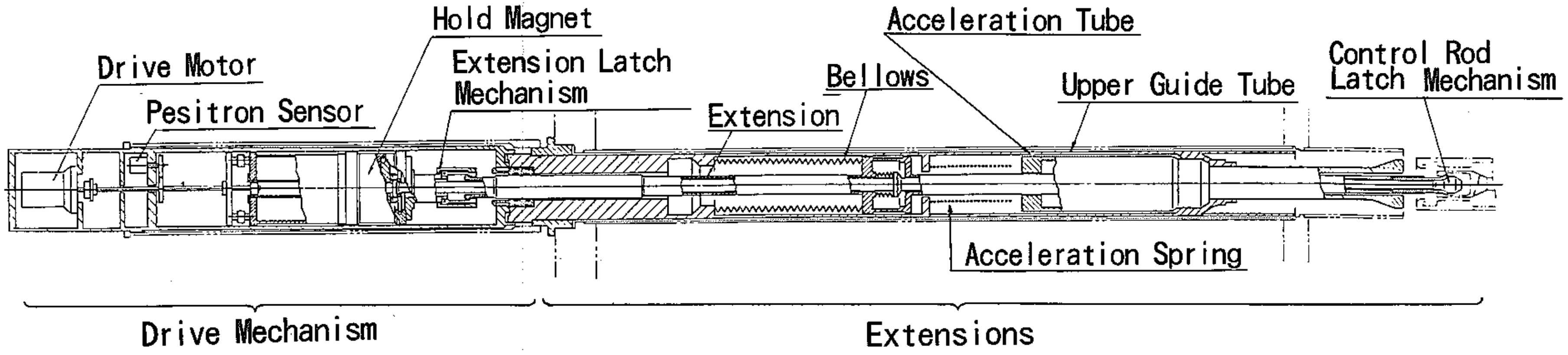


Fig. 7 Back Up Rod Drive Mechanism

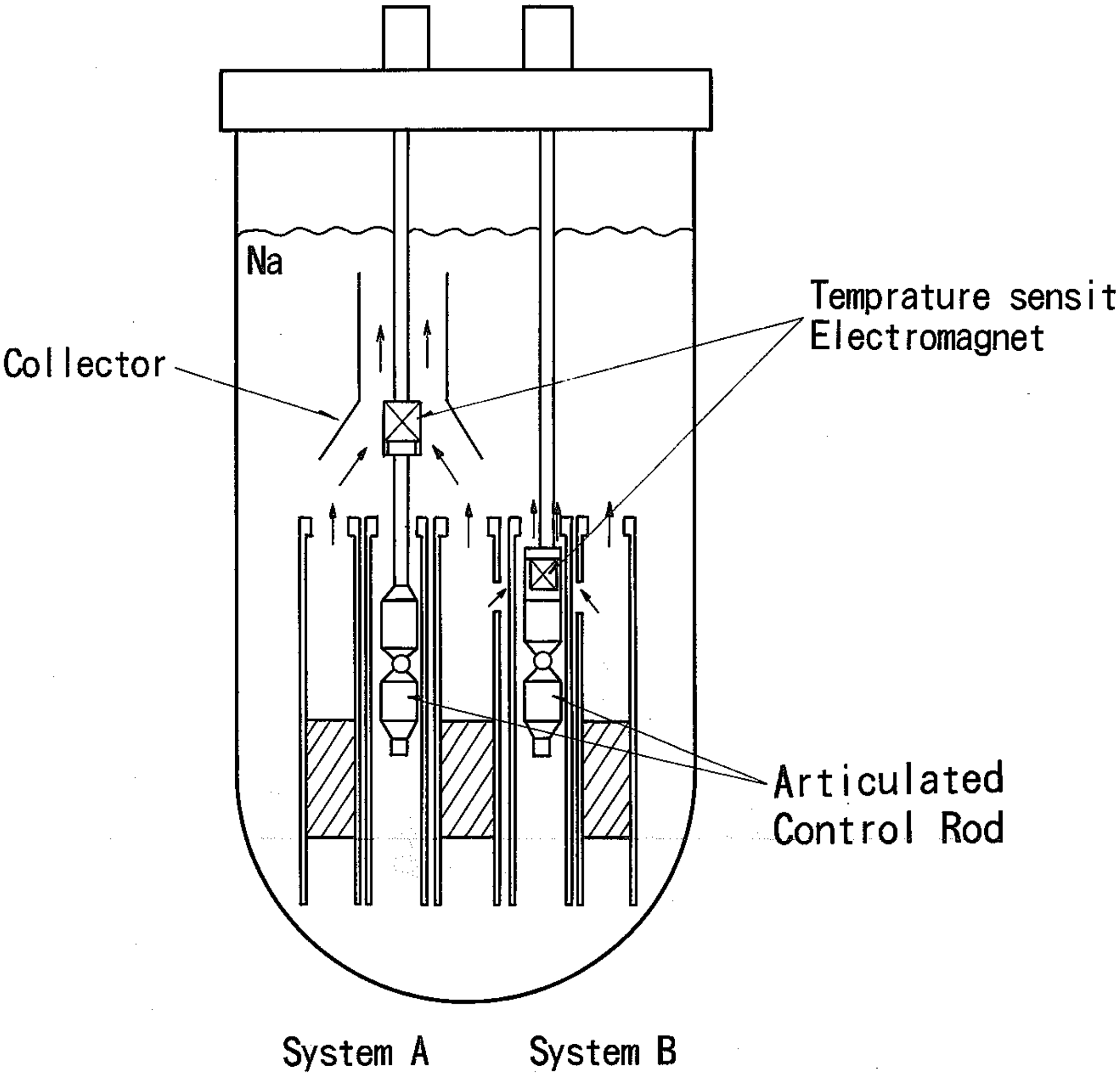


Fig. 8 Conceps of shutodown system ;provided for the test

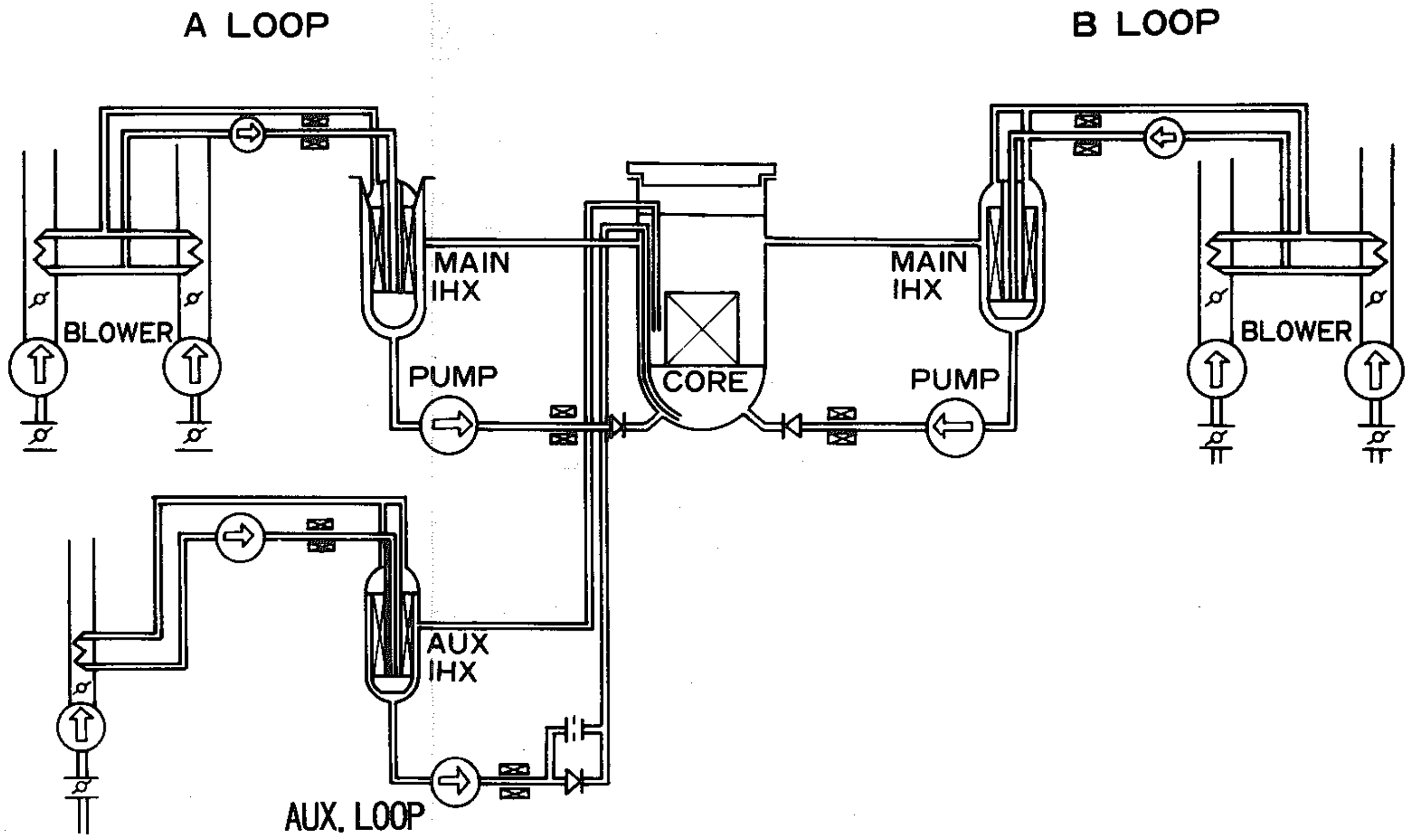


Fig. 9 HEAT TRANSPORT SYSTEM OF JOYO

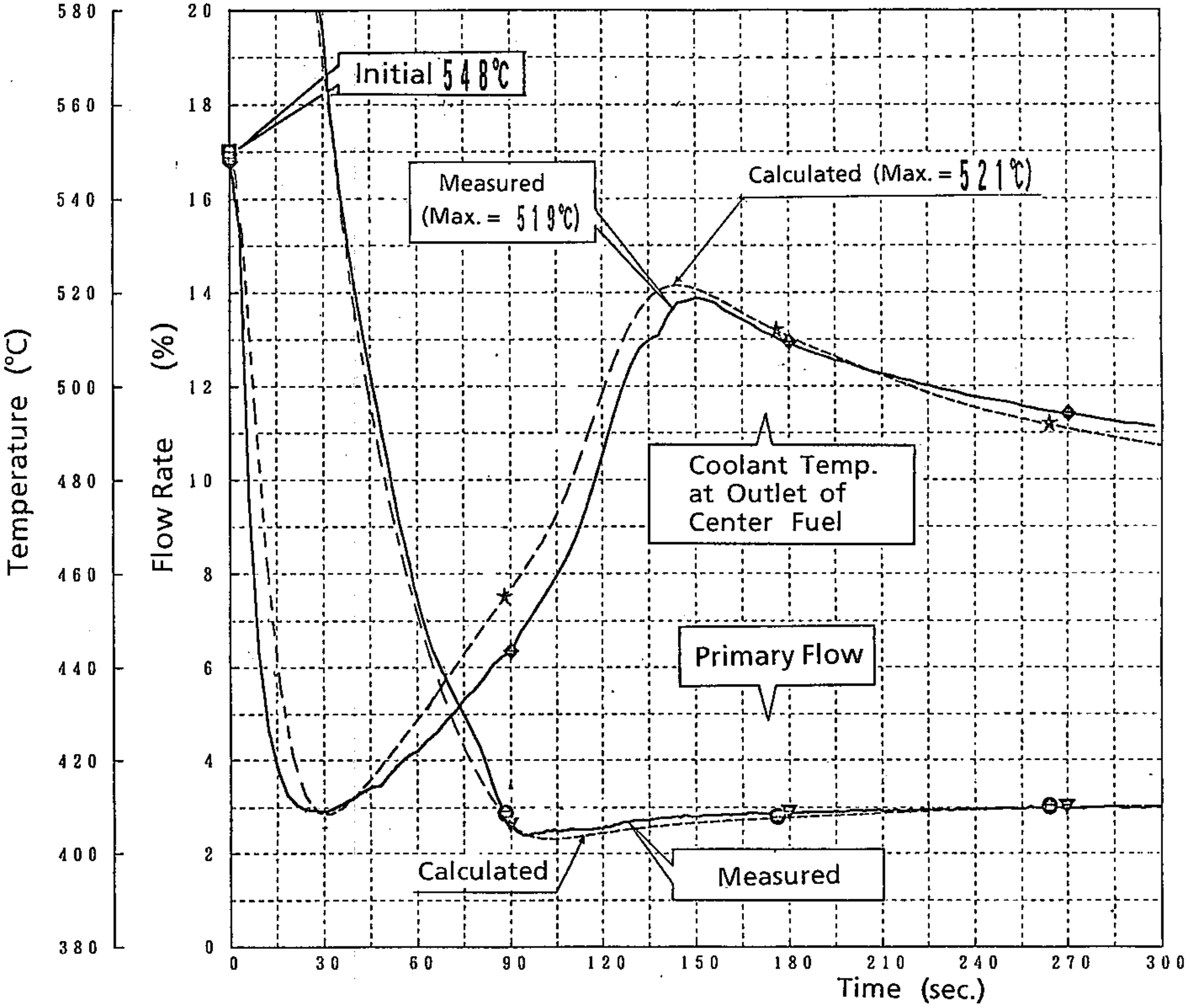


Fig. 10 Result of Natural Circulation Test of JOYO

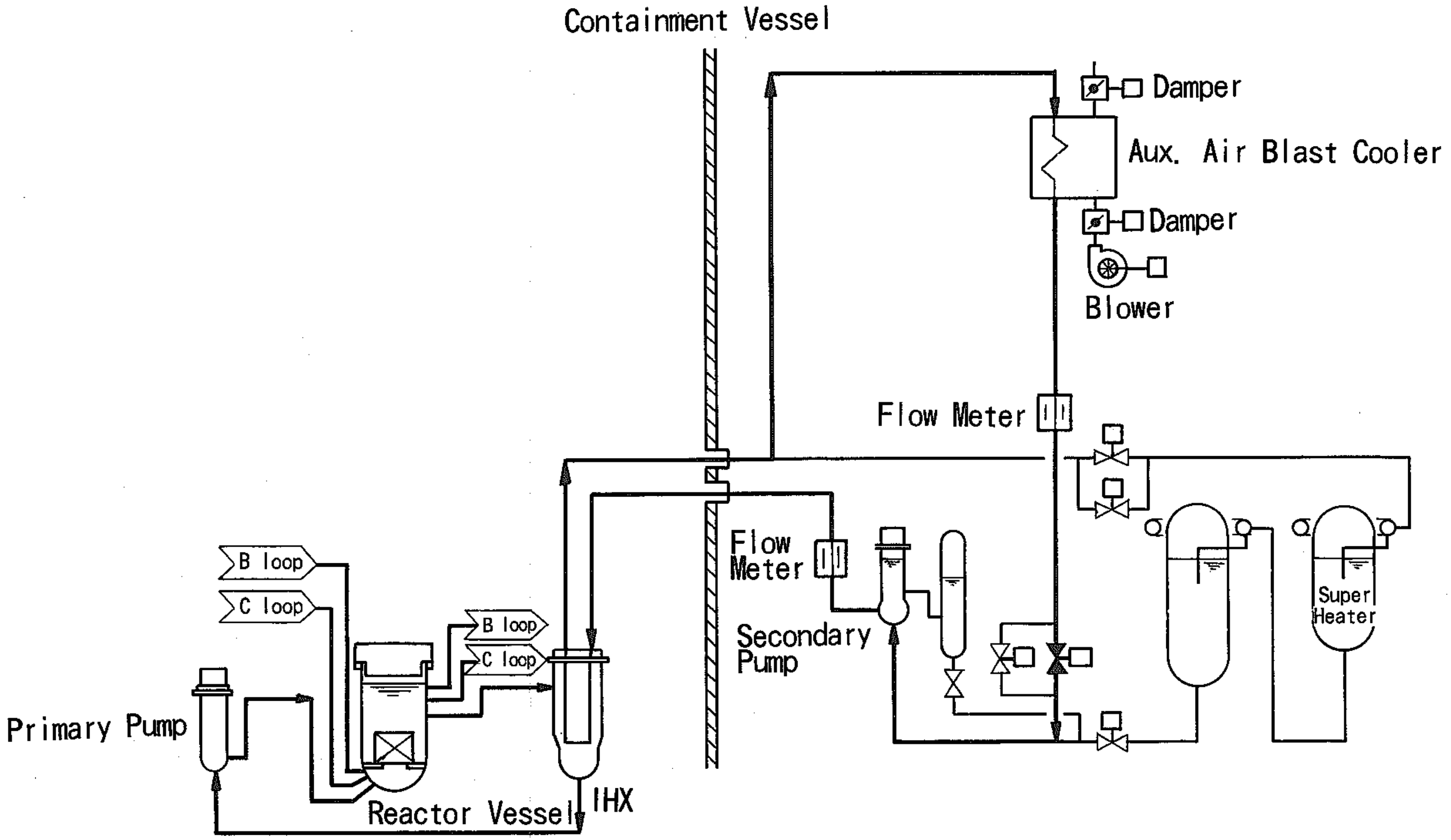


Fig. 11 Heat Transport System of Monju

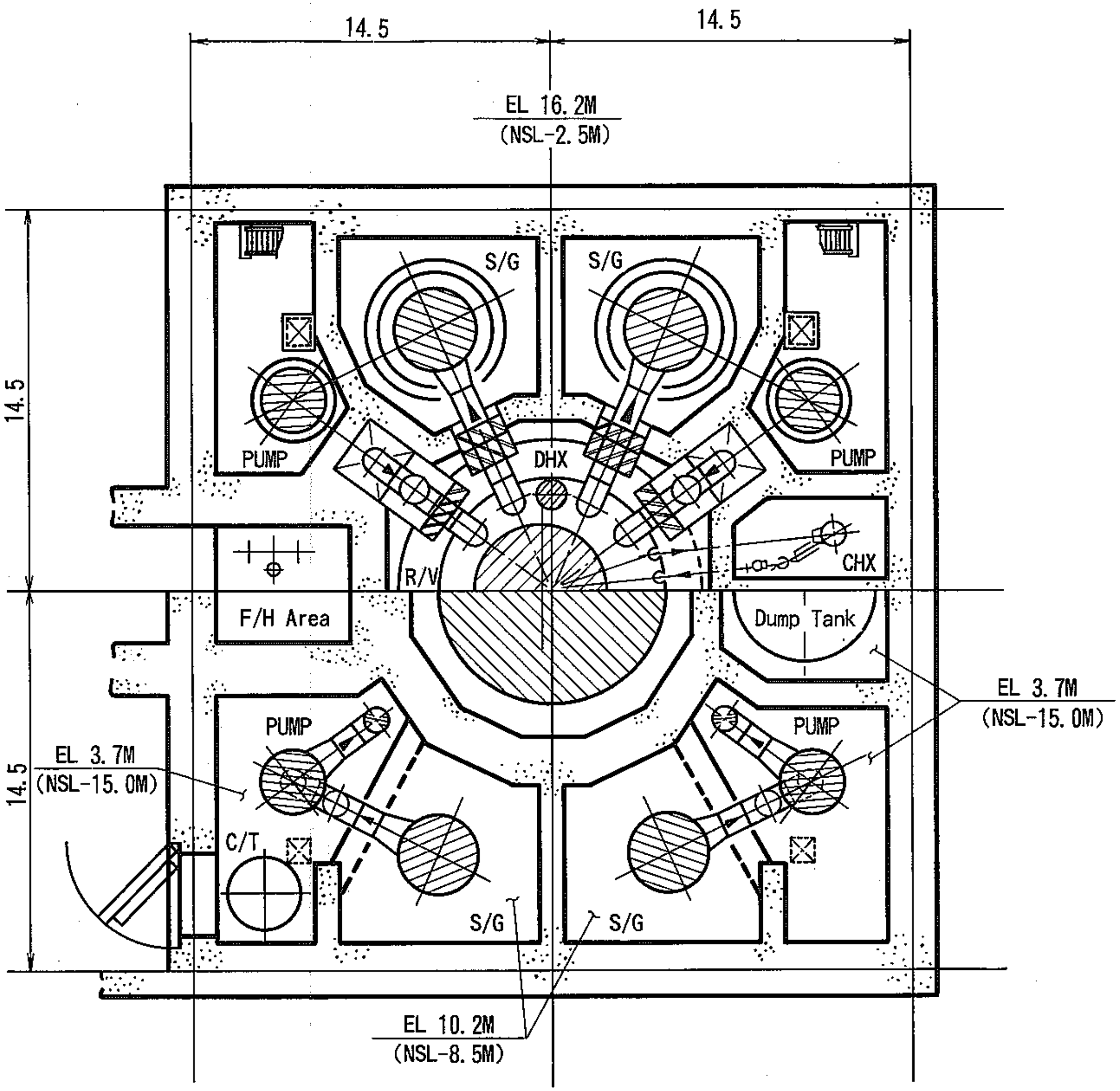


Fig. 12 Arrangement of Main Heat Transport System of Future LMFBR

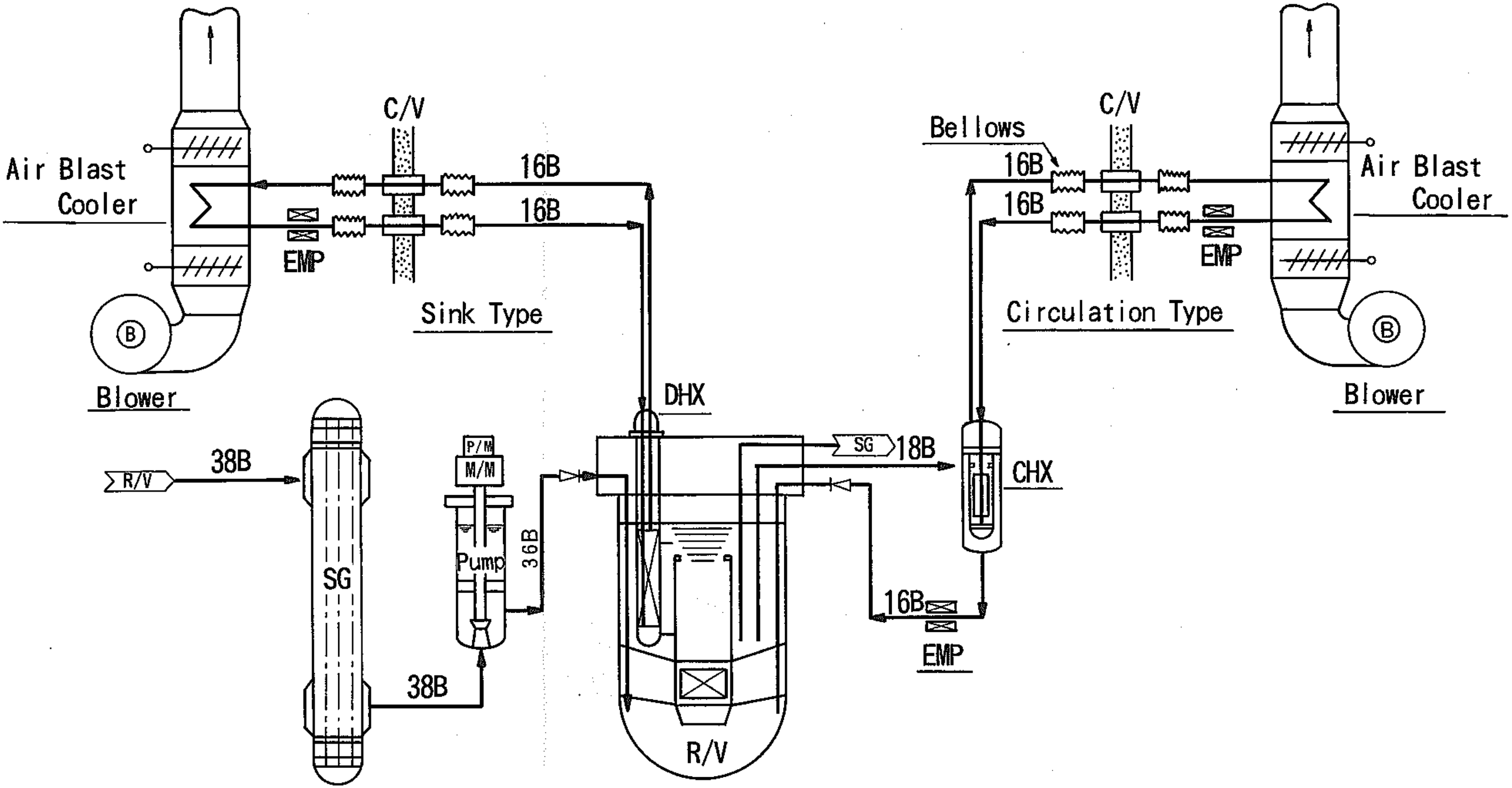


Fig. 13 Two Types of DRACS

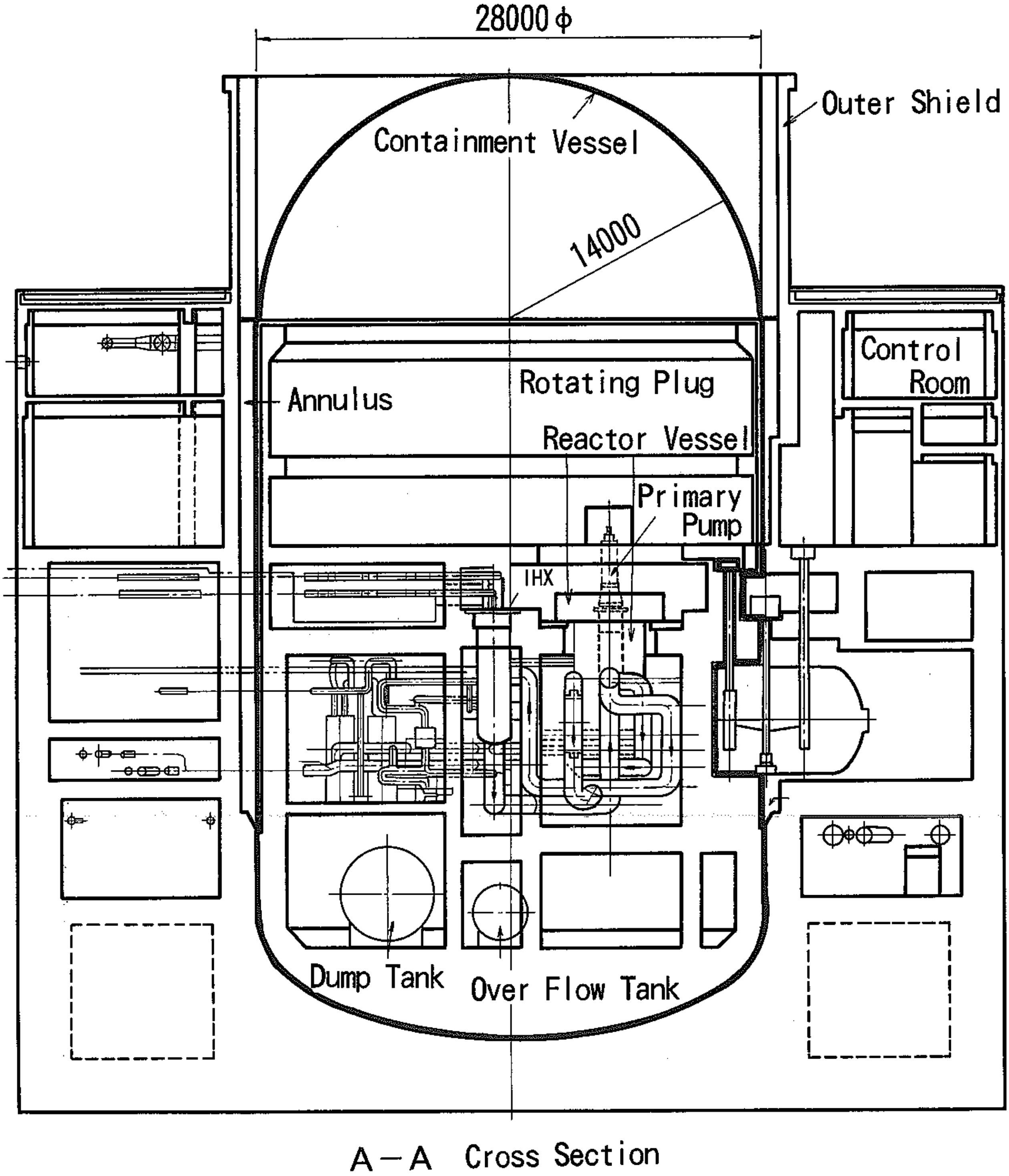


Fig. 14 Containment System of Joyo

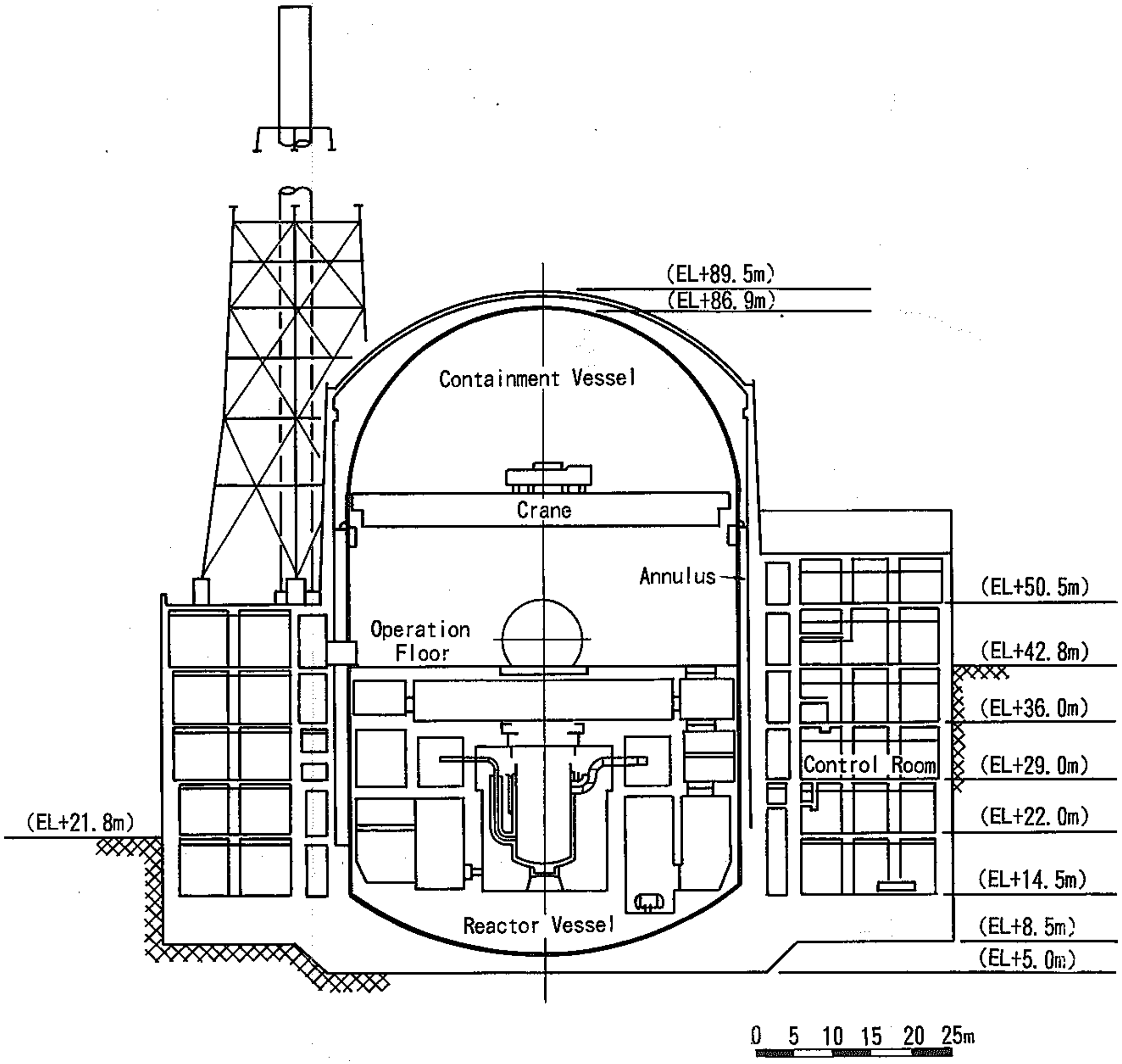


Fig. 15 Containment System of Monju

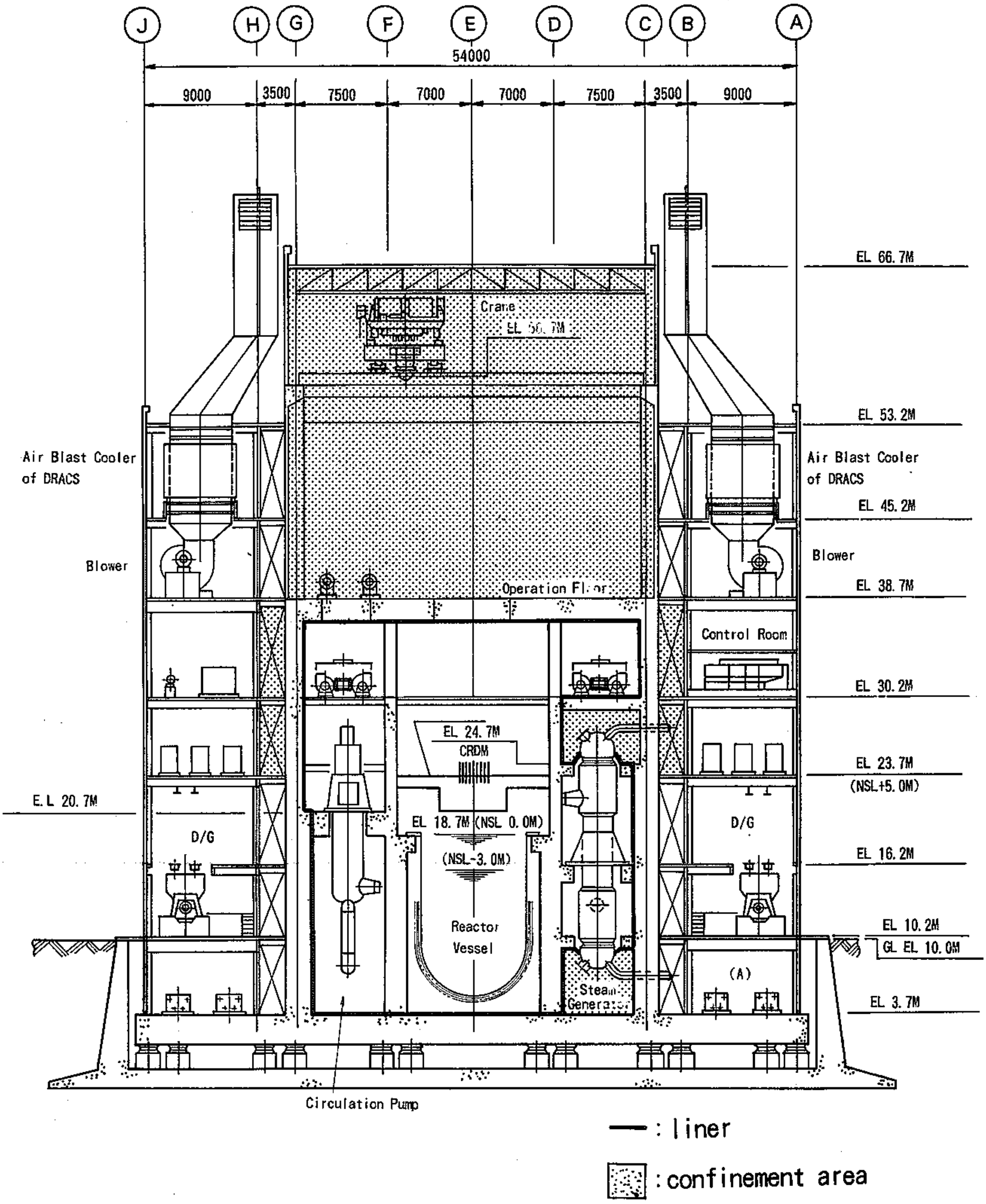


Fig. 16 Containment System of Future Plant

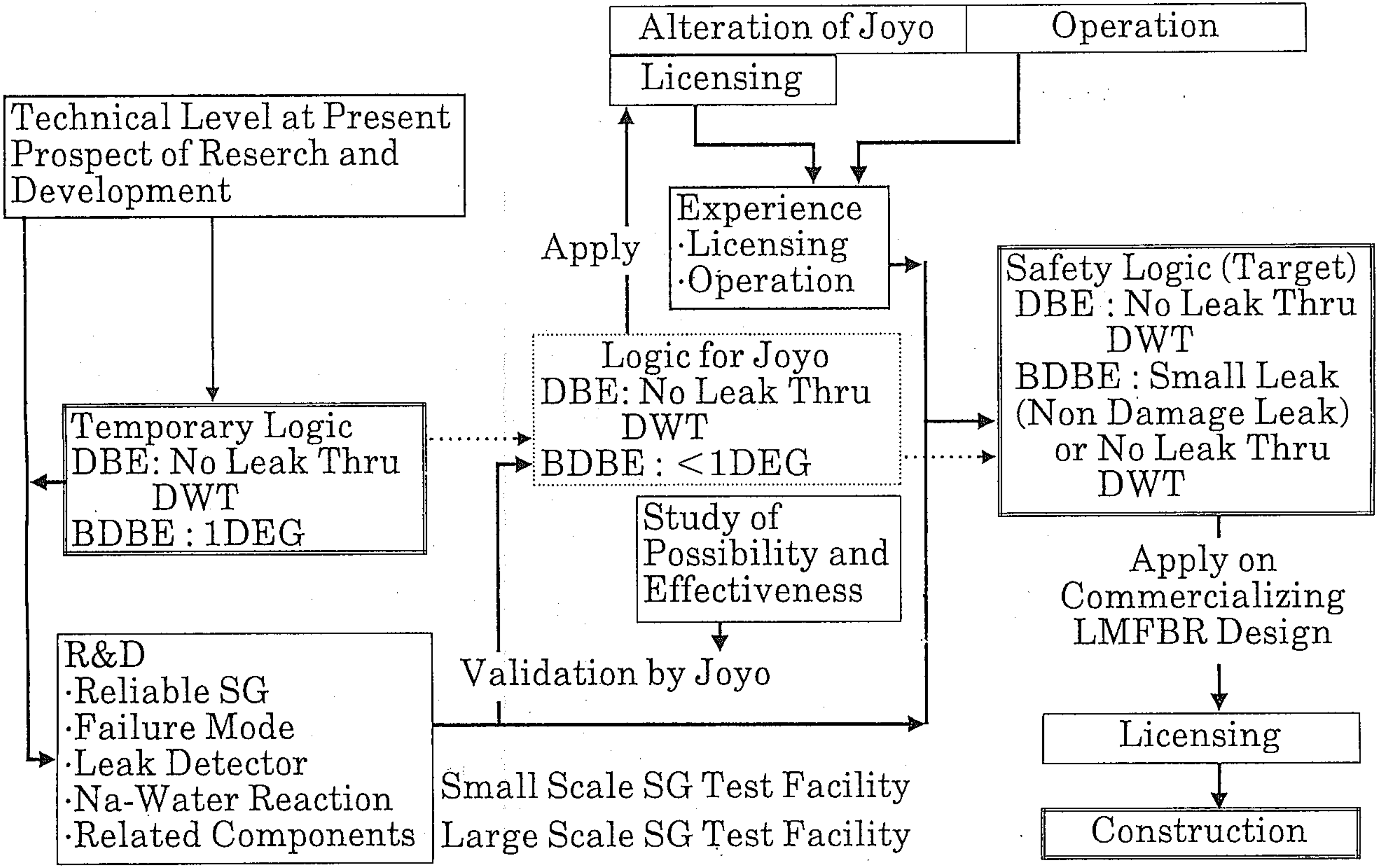


Fig. 17 Development Flow of LMFBR without SHTS (Tentative)

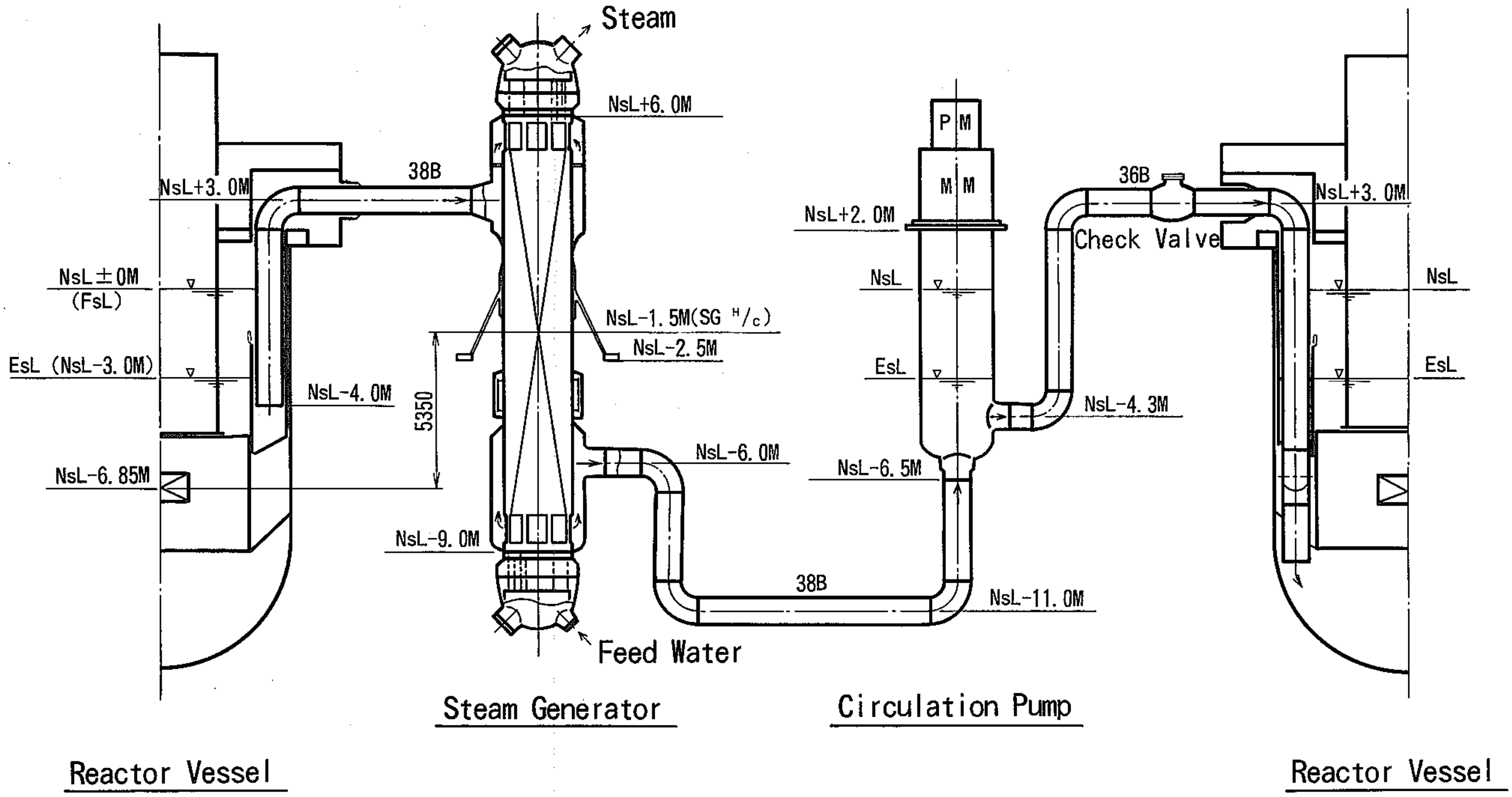


Fig. 18 Main Heat Transport System of Future LMFBR

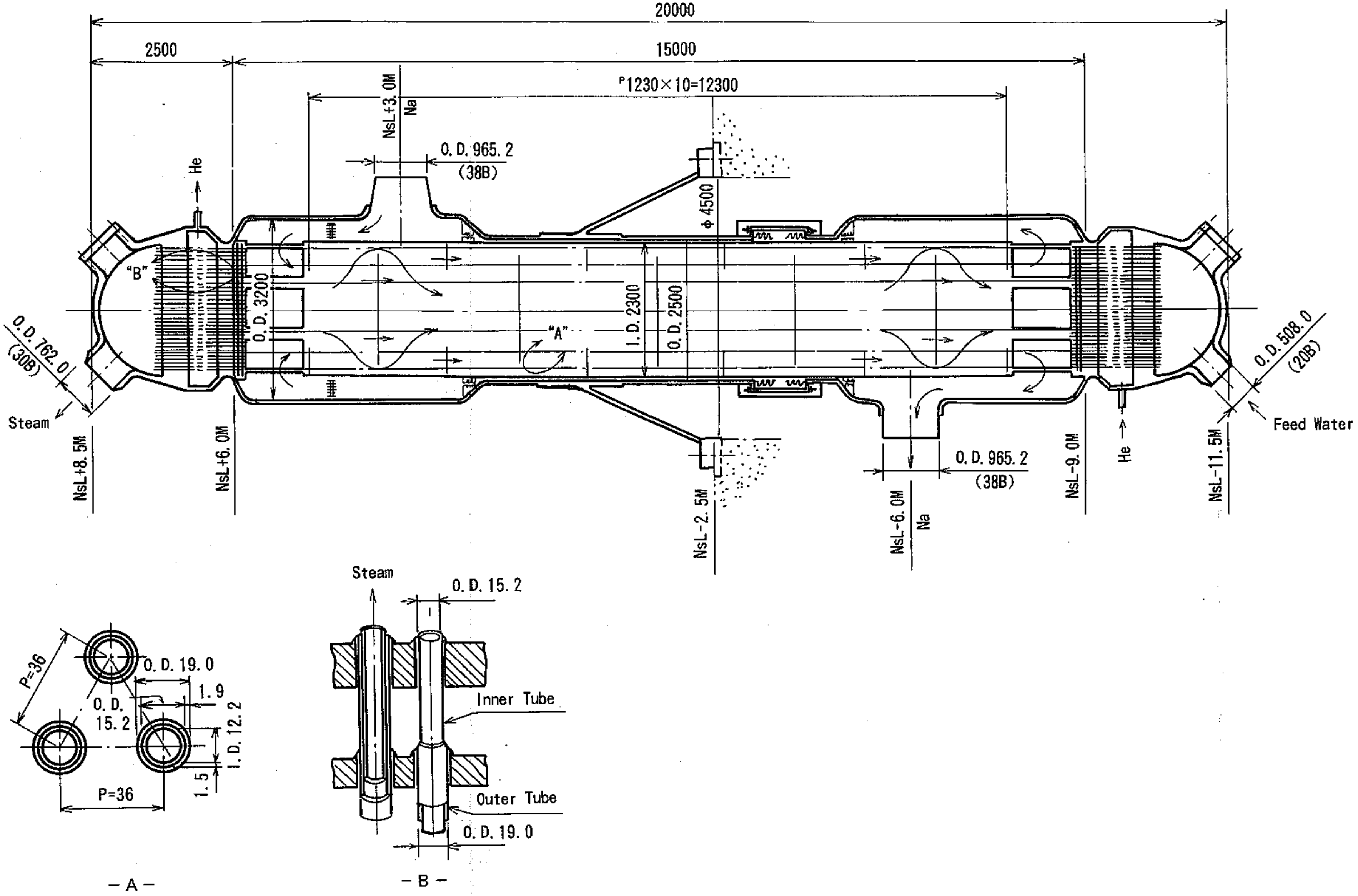
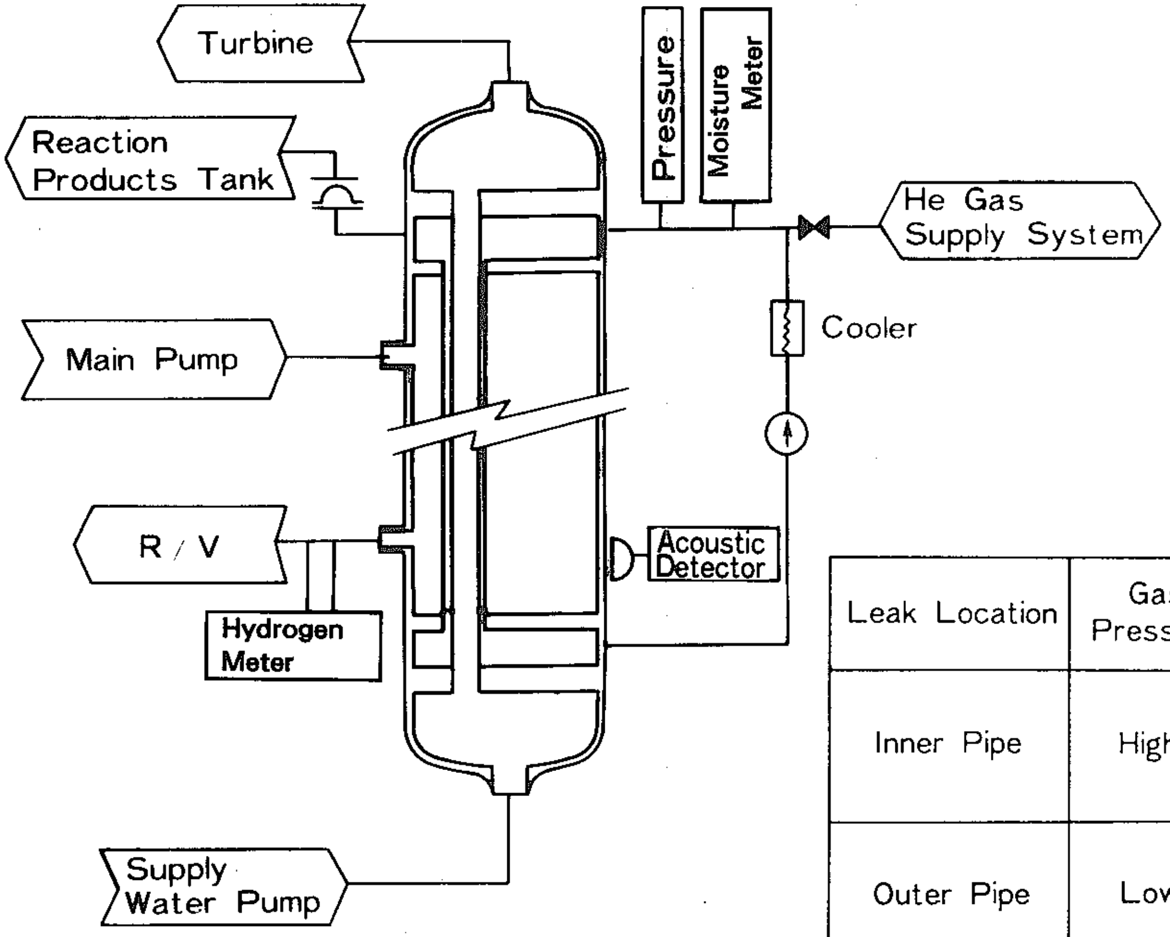


Fig. 19 Conceptual Design of Double Walled Tube Type SG



Leak Location	Gas Pressure	Moisture Meter	Hydrogen Meter	Acoustic Detector
Inner Pipe	High	High	—	—
Outer Pipe	Low	—	Hydrogen Concentration High	Acoustic

Fig. 20 Outline of Leak Detection System Concept