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STATUS OF DEVELOPMENT — AN INTEGRAL TYPE SMALL REACTOR MRX IN JAERI

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Abstract

JAERI is conducting a design study on an integral type small reactor MRX for the use of nuclear ships.

The basic concept of the reactor system is the integral type reactor with in-vessel steam generators and control rod drive systems, however, such new technologies as the water-filled containment, the passive decay heat removal system, the advanced automatic system, etc., are adopted to satisfy the essential requirements for the next generation ship reactors, i.e. compact, light, highly safe and easy operation.

Research and development (R&D) works have being progressed on the peculiar components, the advanced automatic operation systems and the safety systems. Feasibility study and the economical evaluation of nuclear merchant ships have also being performed.

The experiments and analysis of the safety carried out so far are proving that the passive safety features applied into the MRX are sufficient functions in the safety point of view.

The MRX is a typical small type reactor realizing the easy operation by simplifying the reactor systems adopting the passive safety systems, therefore, it has wide variety of use as energy supply systems.

This paper summarizes the present status on the design study of the MRX and the research and development activities as well as the some results of feasibility study.

1. INTRODUCTION

A small type reactor might be of great advantage to the energy supply for such the limited area as a ship, an island, a remote place, etc. Wide variety of energy usage, for examples, an nuclear propulsion, an electric power supply, a district heating, a sea-water desalination, etc., is considered.

Nuclear ships have outstanding advantages so as to enable long-period navigation with high power and long-period underwater navigation. It is therefore, thought that the nuclear ships will contribute largely to the advancement and diversification of marine transportation, scientific activities in the ocean, etc., in the future. Because of no production of such polluting materials as NOX, SOX and CO2 produced in the use of fossil fuel, the utilization of nuclear reactor into ships contributes to the global environmental protection.

At present nuclear ships are not expected to be applied immediately for practical use mainly from economic aspect. Looking into future, however, there is a lot of potentiality that the needs of nuclear ships would be actualized according to to the change in economic and social circumstances and owing to the increase of demands for their outstanding advantages.

The Japan Atomic Energy Research Institute (JAERI) is carrying out the design studies on advanced nuclear ship reactors of which features are compact in size, light in weight, highly safe and easy to operate. The Marine Reactor X (MRX) is aimed for the use of a bigger merchant ship or an ice-breaker.

In parallel with the design study, research and development works are being conducted to realize the systems in use and to prove the operational and safety functions of the systems.

2. CONCEPT OF ADVANCED MARINE REACTOR MRX [1]

2.1 Basic Concept

To put nuclear merchant ship into the commercial service, the improvement of economy is very essential as well as increasing reliability and operability of the reactor systems.

The improvement of economy should be emphasized in developing the reduction of construction and operation cost as follows;

-The construction cost of reactor systems can be reduced by means of making the reactor systems compact, light and simple. Adoption of passive safety systems contributes for the simplification of systems.

-The operation cost of reactor systems can be reduced by means of easy operation and maintenance and improving the reliability of both systems and components. Simplification of systems and the advanced automatic operating and supporting systems will be effective. Reduction of nuclear fuel cost is also essential.

-Simplification of plant systems increases the reliability so that reduction of malfunctions and defects of components is expected. Adoption of the advanced automatic operation and supporting system is also effective to prevent human errors.

In order to satisfy these requirements, following typical design features have been adopted (Fig.1).

- Integrated type PWR
- In-vessel type control drive mechanism
- Water-filled containment
- Passive decay heat removal systems
- Advanced automated control systems
- One-piece removal of the reactor systems

Fig.2 and Table 1 give a conceptual drawing and major design parameters of the MRX. A basic idea of engineered systems is shown in Fig. 3.

2.2 Description of Reactor and Primary Systems

(1) Integrated type PWR

Integrated type PWR could eliminate possibility of large scale pipe rupture accidents and then simplifies the safety systems. It also reduces the dimensions of reactor plant system. Because of compact dimensions of the integrated reactor system, it should remind the capability of maintenance and inspection of components. In the MRX, it is so designed that the reactor components and the primary coolant pumps can be removed remotely and the steam generator tubes can be inspected from out side of the reactor pressure vessel.

TABLE 1. MRX BASIC DESIGN DESCRIPTION

Reactor type	: Integral PWR
Thermal power (MWt)	: 100
1. Core and reactivity control	
Fuel/moderator material	: UO_2/H_2O
Fuel inventory (tons of heavy metal)	: 6.326
Average core power density (kW/liter)	: 41
Average/maximum linear power (kW/m)	: 7.626/30
Average discharge burnup (MWd/t)	: 22,600
Enrichment (initial and reloaded)	: 4.3/2.5% (without/with Gd)
Life of fuel assembly (year)	: 8
Refueling frequency (year)	: 4
Fraction of core withdrawn (%)	: 52.6
Active core height (cm)	: 140
Equivalent core diameter (cm)	: 149.2
Number of fuel assemblies	: 19
Number of fuel rods per assembly	: 493
Rod array in assembly	: Triangle
Pitch of assemblies/fuel rods (mm)	: 326/13.9
Clad material	: Zircalloy 4
Clad thickness (mm)	: 0.57
Type of control rod	: Cluster
Number of rod clusters	: 13
Number of control rods per assembly	: 54
Neutron absorber material	: 90 % enriched B_4C
Additional shutdown system	: Boron injection
Burnable poison material	: Fuel rod with Gd_2O_3 and burnable poison rod of borosilicate glass
2. Reactor coolant system	
(1) Coolant	
Coolant medium and inventory	: H_2O (41 t)
Coolant mass flow through core (kg/s)	: 1,250
Cooling mode	: Forced
Operating coolant pressure(MPa)	: 12
Core inlet/outlet temperature(℃)	: 282.5/297.5
(2) Reactor pressure vessel	
Inside diameter/Overall length (m)	: 3.7/10.1
Average vessel thickness (mm)	: 150
Design Pressure (MPa)	: 13.7
(3) Steam generator	
Number of SG	: 1 (2 trains)
Type	: Once-through helical coil
Configuration	: Vertical
Tube material	: Incoloy 800
Heat transfer surface per SG (m^2)	: 754
Steam/feed water temperature (℃)	: 289/185
Steam/feed water pressure (MPa)	: 4/5.8
(4) Main coolant pumps	
Number of cooling pumps	: 2
Type	: Horizontal axial flow canned motor
Pump mass flow rate (kg/s)	: 640
Pump design rated head (m)	: 12
Pump nominal power (kW)	: 145
3. Containment	
Type	: Water filled (simple wall)
Inner diameter/height (m)	: 7.3/13
Design pressure (MPa)	: 4
Design temperature (℃)	: 200

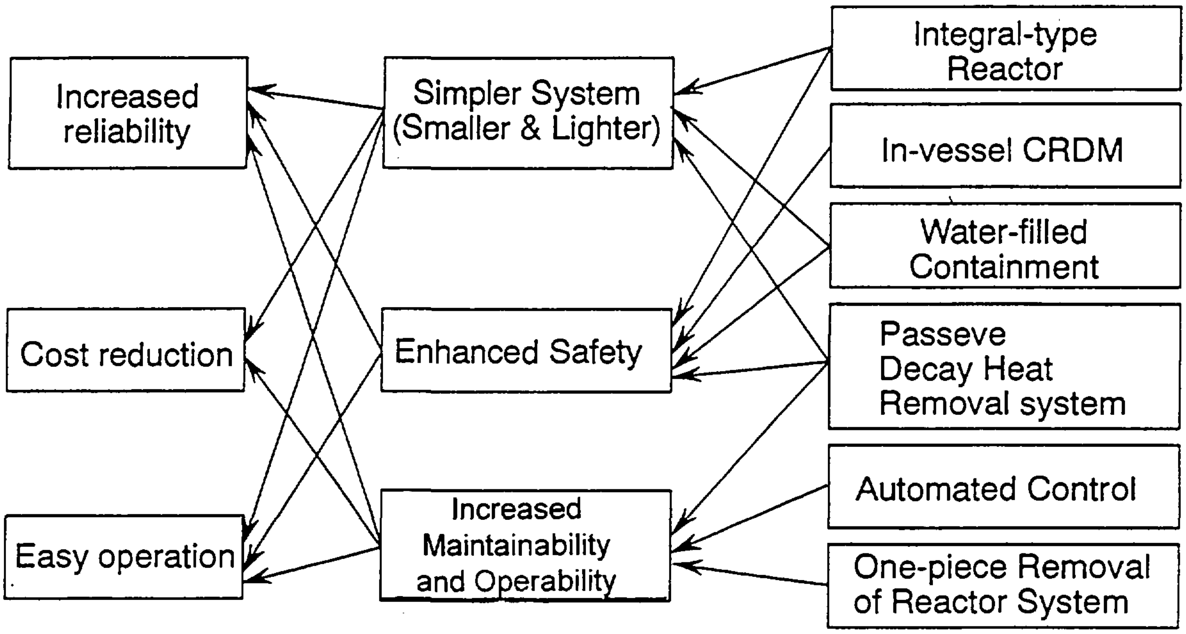


Fig.1 Requirements and New Technologies adopted in MRX

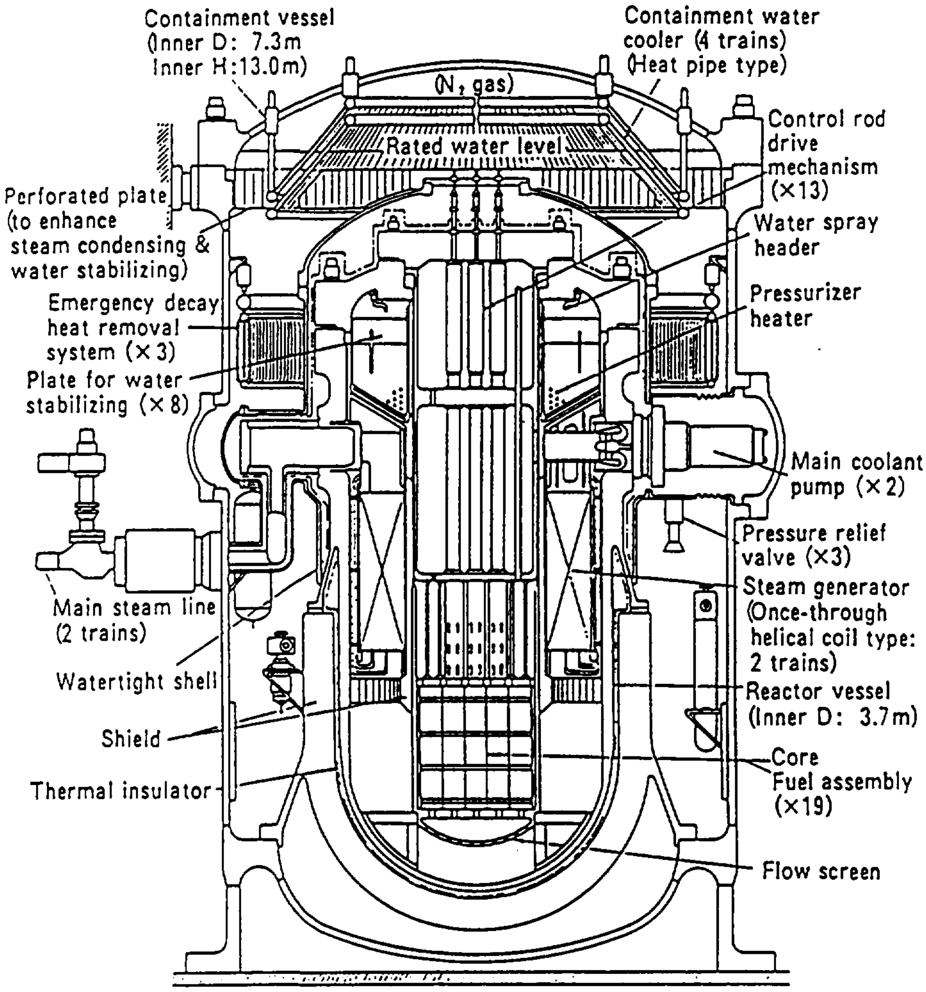


Fig.2 Conceptual Design of MRX

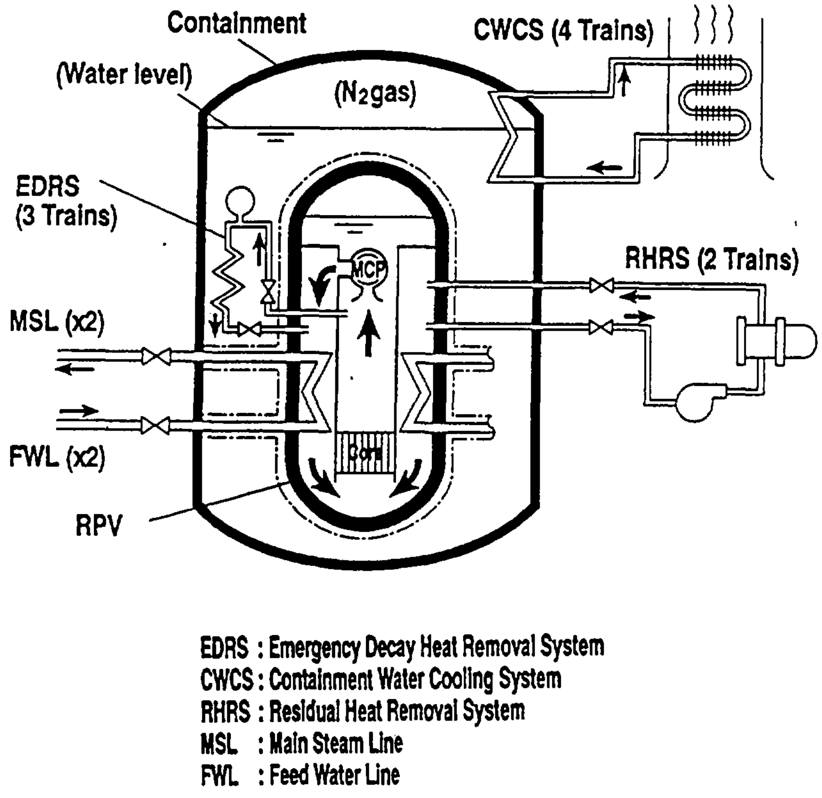


Fig.3 MRX Reactor Cooling Systems

(2) Reactor core and reactor pressure vessel

The core consists of 19 fuel assemblies and of 13 control rod clusters. Conventional PWR type fuel rod (9.5 mm O.D.) is employed. The reactor pressure vessel (RPV) of 6.8 m I.D. and 9.3 m H. is relatively larger in size. This provides a larger primary water inventory with increasing the distance between the reactor core and the RPV, and reduces the neutron fluence at the RPV. The average power density of 42 kW/l is sufficient low so as to have an enough margin for larger load change of the ship operation.

(3) Control rod drive mechanism

In-vessel type control rod drive mechanisms (CRDMs) are placed in the upper region inside the RPV. Employment of the in-vessel type CRDM could eliminate the possibility of rod ejection accident and enable the reactor plant compact.

(4) Steam generator and primary circuit

Steam generator of once-through helical type is positioned in the RPV. Two trains are adopted for the main steam and feed water lines. The whole primary circuit is almost incorporated within the RPV. The pressurizer is installed in the upper part of the RPV. Two main coolant pumps are placed in the hot leg at the upper cylindrical region of the RPV as shown in Fig.2.

2.3 Engineered Safety Systems

(1) Water-filled containment

In the MRX, water injection systems are not provided for LOCAs and core flooding during LOCAs is maintained by the water-filled containment system which could maintain core flooding passively by limiting the blowdown of the primary coolant into the containment. The design pressure of the containment vessel is 4MPa to withstand a high pressure at LOCAs.

A compact reactor plant is realized by the water-filled containment because water in the containment acts as the radiation shield so that installation of concrete shield could be avoided.

(2) Emergency decay heat removal system(EDRS)

This system transfers decay heat of the core to the containment water at the event of isolation of reactor containment. It includes three trains and one of trains has ability to remove the core decay heat of 50%. Each train consists of a water reservoir tank, a cooler and two valves. In any case of accidents, coolant is circulated by natural convection.

(3) Containment water cooling system (CWCS)

This is a heat pipe system for a long term heat removal from the containment water to the atmosphere. For its working gas, anti-freezing gas such as R22 ($CHClF_2$) will be used taking into account of low temperature conditions in the ice-sea atmosphere.

2.4 Automatic Control System

It is very important to reduce the number of reactor operators in the economy and safety points of view. To reduce operator actions, highly automated control systems will be adopted and will cover whole operations, i.e., start-up check-out, start-up, power operation and shut-down in normal operations as well as safety actions during abnormal and accident conditions.

The system consists of control systems and diagnostic systems as shown in Fig. 4. Control systems generate control signals for control equipments, for examples, control rods, pressure control valve, flow control valve, etc., in accordance with the reference signals (demand signal) and each parameters. If difference in

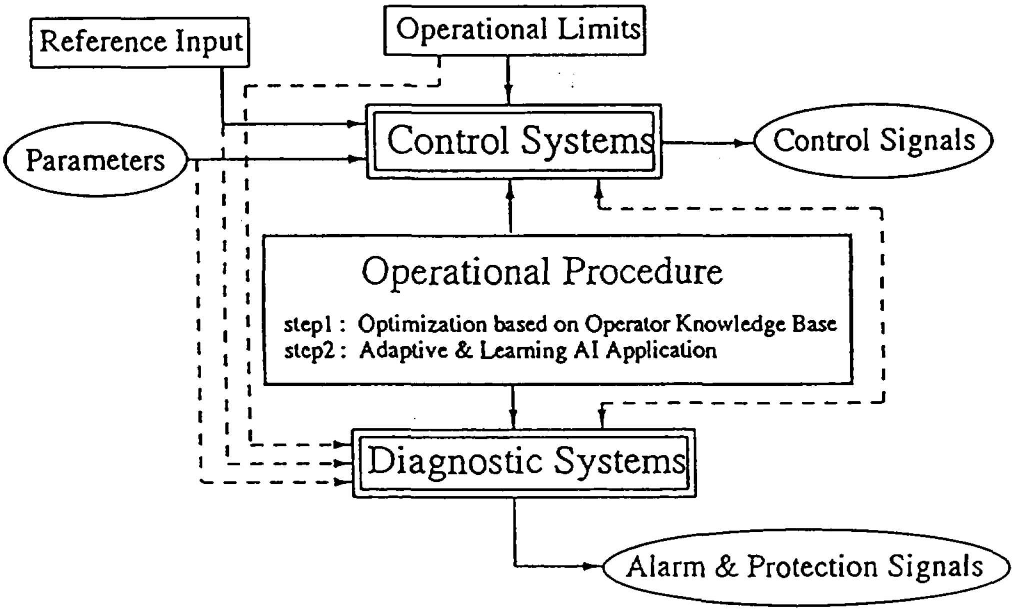


Fig.4 Advanced Automatic Control and Diagnostic Systems

each parameter is existed, control signals are generated by a given operational procedures to bring parameters to demand conditions. Giving demand signals as reference signals before starting operation, no operator actions would not be requested. To monitor the malfunction of systems and plant operating conditions, diagnostic systems are also provided.

Although concepts of the systems are similar as the conventional plant, adaptive and learning AI systems are being adopted.

2.5 Maintenance

For nuclear ships, it is very important to shorten the period of the maintenance and refueling from the economical point of view. From this standpoint, the design study of one-piece removal method is being carried out. This method is that the reactor containment is removed itself with the RPV and the auxiliary systems and then is transferred to the maintenance facilities as shown in Fig 5. After the removal, the new reactor containment of which maintenance is already completed is replaced.

It is thought that this method is promising because the integral type reactor is relatively small and light. The merits of this method are ;

(a) to shorten the period in the dock required for maintenance and refueling,
(b) to carry out the maintenance and refueling in the large space of land facilities safely,
(c) to reduce the cost of the maintenance and refueling by using them commonly,
(d) to re-use the reactor system after the ship's life, and
(e) to make the decommissioning of the ship easily.

2.6 Safety Evaluation

In the evaluation of safety characteristics of the MRX, analysis of LOCA, steam line break accident, feed-water line break accident, and total loss of electricity have been made.[2]

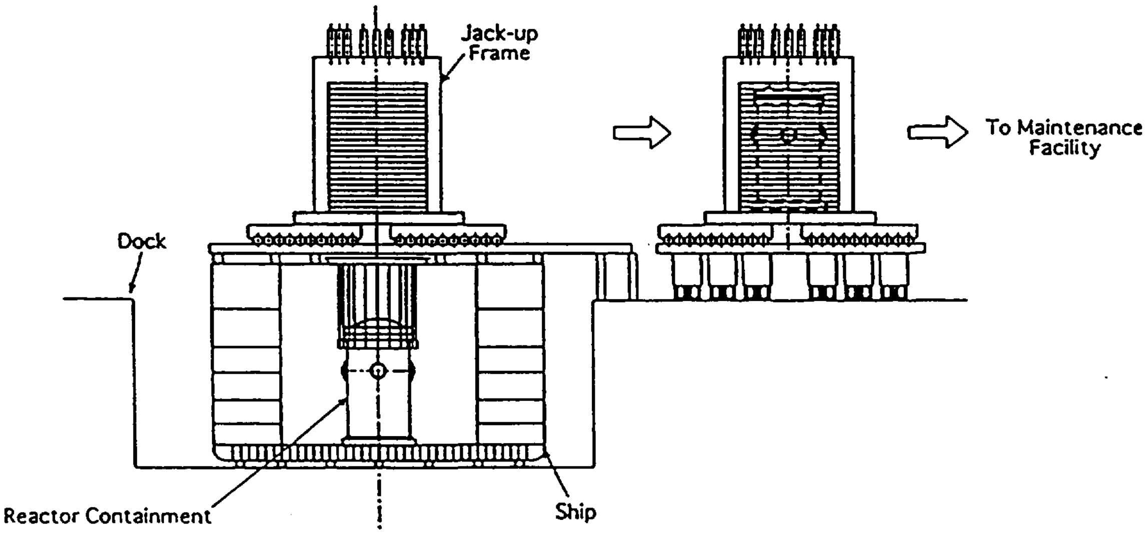


Fig.5 Concept of One-piece Removal of Reactor Containment

Fig. 6 shows a typical result of LOCAs obtained by the RELAP 5/Mod2 calculation assuming the double ended guillotine break of a 50 mm dia. pipe of the Residual Heat Removal System of which case is to be the most severe one in the design basis accidents of the MRX. The reactor goes shutdown at 119 seconds after the pipe break and the pressure in the containment reaches to the maximum at 1250 seconds after the break and then the escape of water from the RPV stops resulting that the drop of water level stops. The maximum pressure of the containment vessel during LOCA is 1.8 MPa which is lower than the design pressure of containment vessel (4 MPa). Water level in the RPV is higher (2m) than top of the core even in the ship inclines 30 degrees.

Through these analysis, it is being proved that the passive safety features applied into the MRX are sufficient functions in the safety point of view.

3. RESEARCH AND DEVELOPMENT PROGRAM

Research and development program on a nuclear ship has been proposed and being performed to solve technical subjects so that the nuclear ship will be put into commercial uses in the future.

The subjects are assorted into two groups, one is the research and development on the reactor system and the other is those on the nuclear ship systems. Because of importance to show the reliability of system, integral system tests using a large scale synthetic test rig is planned. A prototype integral test reactor program is also under discussion in JAERI.

R & D time table is shown in Fig. 7.

3.1 Research and Development of Reactor Systems

(1) Experimental study on thermal-hydraulics

Since such new and unique technologies as the integral type reactor concept, passive safety systems, etc., are being adopted, overall thermal-hydraulic characteristics of reactor systems are studied through the following experiments:

(i) Small scale thermal hydraulic test

To study the thermal-hydraulic behavior in the water-filled containment during the LOCAs, the Small Scale Test Rig (volume ratio: about 1/300 of MRX) has been fabricated and fundamental experiments are in progress.[3] In the experiments, following behaviors are evaluated.

- thermal and hydraulic responses in both the reactor vessel and the water-filled containment under LOCAs
- evaluation of mechanical loads generated by LOCAs
- capability of natural circulation and passive decay heat removal

(ii) Large scale synthetic test

To confirm the function of the safety features such as an integral type PWR with a water filled containment and passive safety systems, installation of Large Scale Synthetic Test Rig is planned. The conceptual view of the rig is shown in Fig. 8. Thermal power of the test section is 5 MWt (about 1/20 of the MRX), however, the height of the rig is same as that of the MRX because it is most important to simulate accurately the natural circulation condition. To obtain the behavior under the ship motions, inclinations and vibration, tests on a boat, where the test rig is loaded on a boat, is planned.

These experimental results will be very useful for understanding the phenomena related to the passive safety systems and for verification of the system.

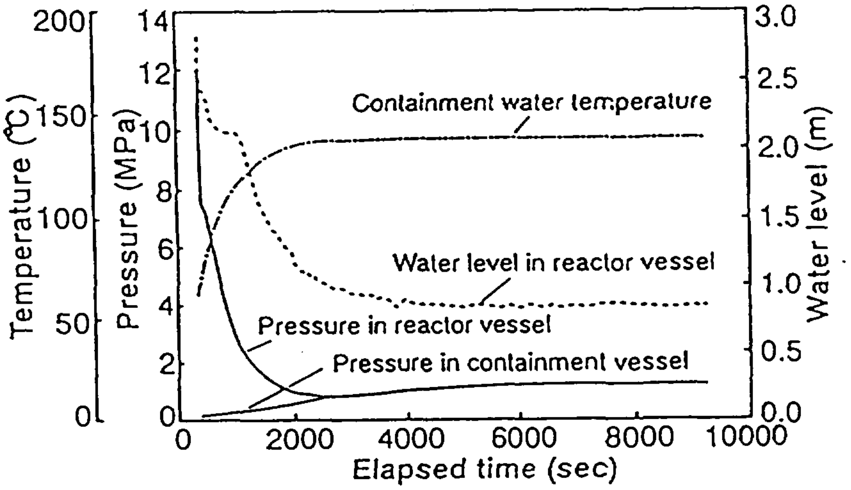


Fig.6 Typical Transient of LOCA in MRX
(Double ended guillotine break of 50mm dia. pipe)

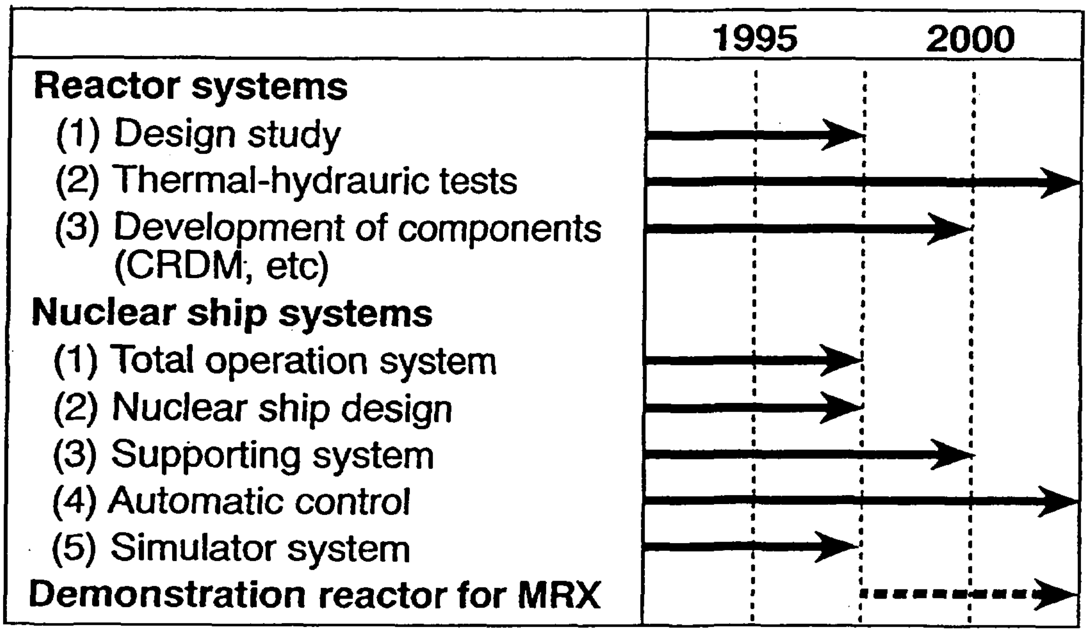
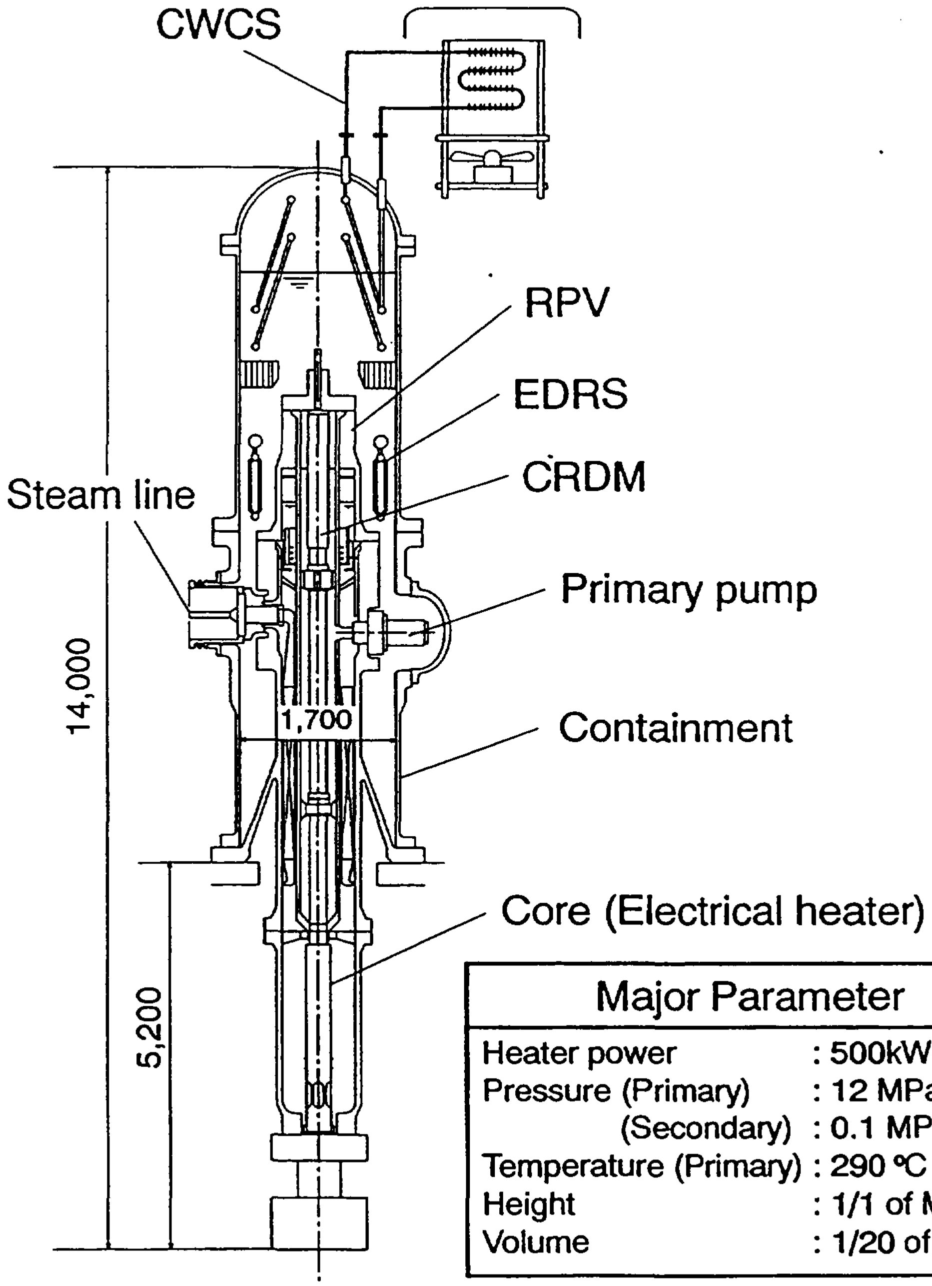


Fig.7 R&D Schedule on Advanced Nuclear Ship in JAERI



Major Parameter	
Heater power	: 500kW (5MW)
Pressure (Primary)	: 12 MPa
(Secondary)	: 0.1 MPa
Temperature (Primary)	: 290 °C
Height	: 1/1 of MRX
Volume	: 1/20 of MRX

Fig.8 Conceptual View of Large Scale Synthetic Test Rig

(2) Development of components

(i) In-vessel type control rod drive mechanism (CRDM)

In order to avoid a control rod ejection accident and to make the reactor system compact, the in-vessel type CRDM which is operable at the PWR operation conditions is applied. High temperature and pressure water-proof components such as a motor, a latch magnet, etc., have been developed.[4] Function and reliability tests using the full mock-up CRDM is being planned.

(ii) Water-proof components and insulator

Components in the containment are submerged in water, therefore development of water-proof components and thermal insulator is requested. Easy maintenance is also essential. Conceptual design is under way.

3.2 Research and Development on Nuclear Ship Systems

In order to put nuclear ships into the commercial use, it is indispensable to realize an economical, safe and reliable reactor system. In addition, such supplementary items as international agreement on safety, sea rescue, preparation of maintenance yards, etc., should be solved.

Following activities are being progressed.

(i) Conceptual design of nuclear ships and supporting system

In order to determine the design conditions of reactors and to study total operation systems, conceptual design of many kinds of nuclear ships such as a general cargo ship, a container ship, an ice breaker, a deep-sea submersible, etc., are being performed.

(ii) Evaluation of economy

Cost evaluations not only on a rector system but also on a ship system is being made to clarify the most cost sensitive items. A typical result of cost evaluation for RFR (Required Freight Rate: operation cost to transport one container) of an 6,000 TEU container ship is given in Fig. 9 and Fig. 10.

(iii) Development of nuclear ship simulator

The nuclear ship simulator NESSY (Nuclear Ship Engineering Simulation System) has been developed in JAERI and used for the simulation of the nuclear ship "Mutsu" so far.[5] It can simulate both behaviors of the reactor system and the ship motions. Mutual interactions such as changes of the reactor power, the steam generator water level, etc., due to the ship motions by wave or maneuvering can be analyzed.

The accuracy of the system has been verified with the operation data of the "Mutsu" and it is proved that this system is very useful to analyze the plant behaviors in normal and accident conditions.[6] Modifications of models and parameters are being made for the MRX reactors.

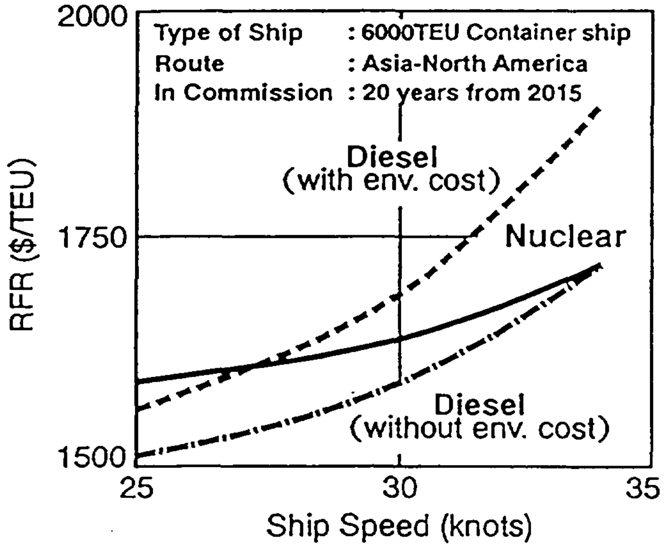


Fig.9 RFR as a function of ship speed

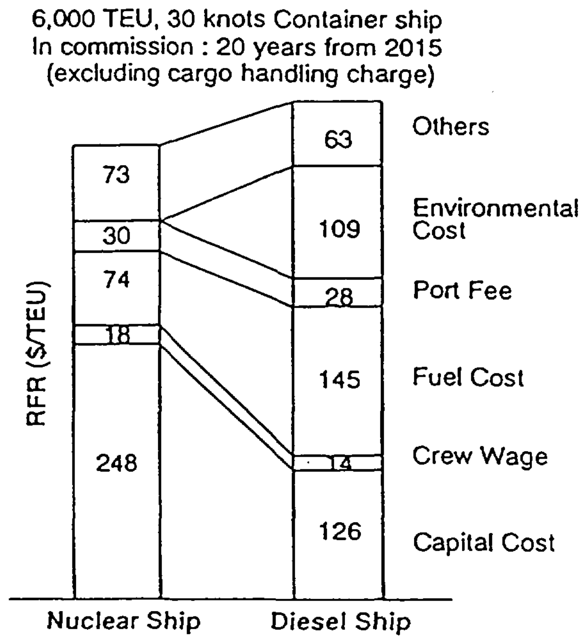


Fig.10 Comparison of RFR

4. Conclusion

A concept of the advanced nuclear ship reactors MRX has been established. The reactor systems adopt the passive safety systems. The safety capability of the reactor system has been proved by analyses. In addition to the design study, extensive research and development activities are being performed and these activities can contribute largely for the realization of the nuclear ships in the commercial use in future.

Considering that the MRX are small size reactors with highly safe capability and a transferable ones, they have wide variety of use as the energy supply system.

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