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Passive Safe Small Reactor for Distributed Energy Supply System Sited in Water Filled Pit at Seaside

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ABSTRACT

Japan Atomic Energy Research Institute has developed a Passive Safe Small Reactor for Distributed Energy Supply System (PSRD) concept. The PSRD is an integrated-type PWR with reactor thermal power of 100 to 300 MW aimed at supplying electricity, district heating, etc. In design of the PSRD, high priority is laid on enhancement of safety as well as improvement of economy. Safety is enhanced by the following means: i) Extreme reduction of pipes penetrating the reactor vessel, by limiting to only those of the steam, the feed water and the safety valves, ii) Adoption of the water filled containment and the passive safety systems with fluid driven by natural circulation force, and iii) Adoption of the in-vessel type control rod drive mechanism, accompanying a passive reactor shut-down device. For improvement of economy, simplification of the reactor system and long operation of the core over five years without refueling with low enriched UO2 fuel rods are achieved. To avoid releasing the radioactive materials to the circumstance even if a hypothetical accident, the containment is submerged in a pit filled with seawater at a seaside. Refueling or maintenance of the reactor can be conducted using an exclusive barge instead of the reactor building.

KEY WORDS: Passive safety system, Integral type PWR, Natural circulation and self-pressurization in the primary loop, Electricity and heat cogeneration, In-vessel type CRDM, Water filled containment, Water tight shell, Water filled pit.

INTRODUCTION

From the view point of addressing global warming and energy security, it is necessary to increase the utilization of nuclear energy for not only electricity generation by large scale nuclear power plants, but also usages such as heat supply to air conditioning, sea water desalination etc.

Japan Atomic Energy Research Institute (JAERI) completed the basic design of an advanced marine reactor for large ships, MRX [1] with a thermal power of 100 MW, which was evaluated in the report of the U.S. Department of Energy [2] - it surveyed the feasibility of deployment of small, modular nuclear reactors in remote communities that are deficient in transmission and distribution infrastructures - as the one of feasible reactors for deployment in remote areas in a decade. On the base of MRX design, JAERI has been developing concepts of PSRD (Passively Safe Small Reactor for Distributed Energy Supply System) that are used as energy supply sources for various utilizations such as small grid electricity generation, heat supply, and seawater desalination.

In this paper, concepts of PSRD system aimed at generating electricity by siting in a seaside pit, focusing on the core design optimized, a motor driven in-vessel type control rod drive mechanism, and the passive safety system are presented.

DESIGN STRATEGY

High priority in the design is laid on furthermore enhancement of safety as well as improvement of economy, since the reactor should be sited close to energy demand areas and with various types of siting. In the siting, it is taken account of no release of radioactive material to the circumstance outside the reactor plant even in case of a hypothetical accident. The reactor thermal power of the PSRD, 100 to 300 MWt, is determined by taking account of deployment not only in small islands in Japan, but also in a relative large one including Okinawa. For large demand of power, a lot of modular reactors can be used. To achieve enhancement of safety and improvement of economy, the reactor system is designed as follows:

1) to extremely reduce possibility of accident occurrence and to adopt the fully passive safety systems as possible.
2) to simplify the reactor system, since it contributes to enhancement of safety, but also improvement of economy through reducing costs of construction, operation and maintenance.
3) long-term operation reactor core with a low enrichment UO2 fuel without refueling or maintenance, which is important factor for economy improvement.

REACTOR SYSTEM

A cross section of the reactor pressure vessel (RPV) together with that of the containment vessel (CV) is shown in Fig. 1. Inside the RPV, the core locates in the lower part, the steam generators (SGs, two sets) in middle part, the control rod drive mechanisms (INV-CRDMs) in the upper part. Around the core, the radiation shield is provided outside the core barrel. There are neither the primary coolant pumps nor the pressurizer.

The SG is of the once-through, helical coil tube type. The primary cooling water flows outside the tubes, and the secondary water and the steam flow inside the tubes. The SGs are hung from the main flange of the RPV. In refueling, the center flange together with the INV-CRDMs after de-latching the control rods is removed.

The primary cooling water flows up after passing through the core by single-phase natural circulation driving force, turns out the core barrel through the flow holes, which are positioned above the SGs, and flows down through the SGs. The water level will vary during the normal operation between the top and the bottom of the flow holes.

The volume control system and the purification system are not used during reactor power operation, in order to simplify the system and reduce possibility of a loss of coolant accident due to pipe rupture. These systems, however, will be used except for the reactor power operation, e.g., prior to open the RPV cover for refueling or prior to reactor startup after closing it. These lines of the system will be completely isolated during the reactor power operation. Pipes penetrating the RPV are limited to only the pipes of the steam, the feed water and the safety valves.

The inside of the containment is filled with water, i.e., water-filled containment. There is the nitrogen gas in the upper space and the fresh water below the gas inside the containment. The RPV and the emergency decay heat removal system (EDRS) are submerged in the water. The water-filled containment has a function of safety engineered system as well as one of enclosing the area for prevention of radioactive material release to surrounding. The water inside the containment has also a role of radiation shielding instead of the concrete shield. The outside of the containment is also filled with water -submerged in the seawater-.

A thermal insulation is necessary to prevent the heat loss from the RPV into the water. The RPV is covered by the thermal insulation of the stainless steel felt. A water-tight shell (WTS) keeps the thermal insulation from being wet by water. The heat loss from the RPV with this insulation is estimated less than 1% of the rated power.

Major parameters of the PSRD with thermal reactor powers of 300 MW are presented in the Table 1. The operation pressure and temperature in the primary loop of the PSRD are lower than those of existing large scale PWRs. One of main reasons is that even if these operation conditions are upgraded to those of the existing PWRs, the increase of the thermal efficiency is very small, but the thickness of the RPV and CV should be increased, resulting in high construction cost

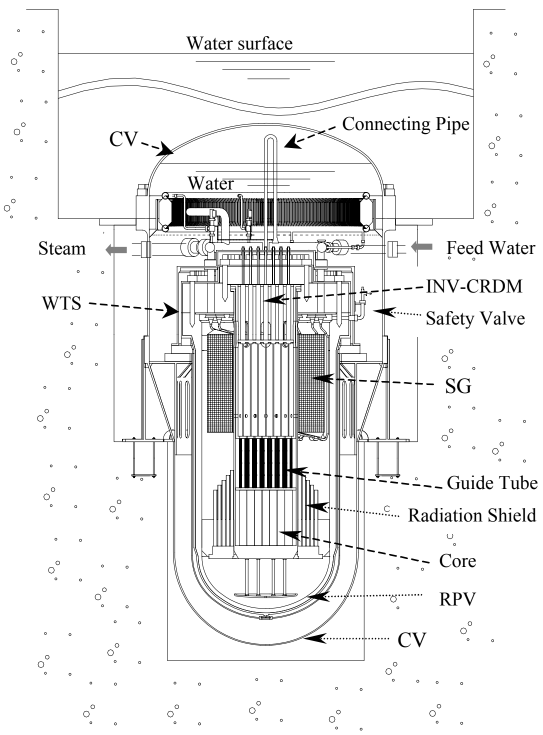

Fig. 1 Concept of PSRD

Table 1 Major parameters of PSRD design (300 MWt)

Reactor power (MWt)	300
Power plant output (MWe)	95
Type	Integral
Reactor coolant	
Operation press. (MPa)	10
Inlet/Outlet temp.	264.8/311
Flow rate (kg/s)	1200
Reactor core	
Equivalent dia./height (m)	2.20/2.25
Av. linear heat flux (kW/m)	7.3
U^{235} enrichment (Wt %)	4.7
Fuel inventory (t)	19.8
Fuel	
Outer diameter/pitch (mm)	9.5/13.9
Burnable poison	9%Gd_2O_3inUO_2
No. of fuel assembles	69
Control rod and CRDM	
Absorber	B_4C
No. of control rods	24 x 69
Steam generator	
Type	Once-through
Steam temp./press.(^oC /MPa)	301/4.0
Reactor vessel	
Inner dia./height(m)	6/14
Containment	
Type	Water-filled
Design press. (MPa)	2

Core Design

The core of PSRD has been designed so as to achieve long life operation over five years without refueling or shuffling for enhancement of economic competitiveness. Design conditions are set up as follows. i) Low enriched UO2 of which 235U enrichment is to be less than 5% on the base of a framework in the current regulations of Japan. ii) The chemical shim for the power control in the normal operation and the boron injection for reactor shutdown in an emergency are not to be used in order to simplify the system and reduce the pipes penetrating the RPV wall. iii) The excessive reactivity at EOL is to be larger than 2% for immediately re-startup operation. iv) The reactivity shutdown margin at condition of a cold state is to be larger than 1%.

In the present design, the fuel assembly is based on that of current PWRs, of 17×17 type of fuel assembly with Zircaloy-4 cladding UO2 pellets. Fuel pin pitch (13.9mm) of the PSRD core, however, is wider than that (12.6mm) of the current PWRs to ensure efficient burn-up by greater moderation.

An issue concerning the high burn-up of core is how to suppress a rather large reactivity at the BOL. To comply with this, the PSRD adopts the fuel rods doped with Gd2O3 as well as the control rods that can be inserted in all fuel assemblies. The control rod clusters are divided with two groups: the reactivity control and shutdown group, and the back up shutdown group.

Detail of the 100MWt core was already reported [3]. The nuclear characteristics were evaluated by core analyses with SRAC95 developed by JAERI [4], which contains the ASMBURN modular for assembly calculation and the COREBN module for core burn-up calculation. Cross sectional views of the core with 300MWt are shown in Fig. 2. The core consists of all the same type of fuel assembly, where the fuel rods, the fuel rods doped with Gd2O3 and the thimble tubes are distributed.

Burn-up characteristics of the core are shown in Fig. 3 for a condition of continuous full power operation. The 300 MWt core attains the burn-up of over five years with a margin. The fuel rods doped with Gd2O3 is revealed effective for suppressing a large excess reactivity at the BOL.

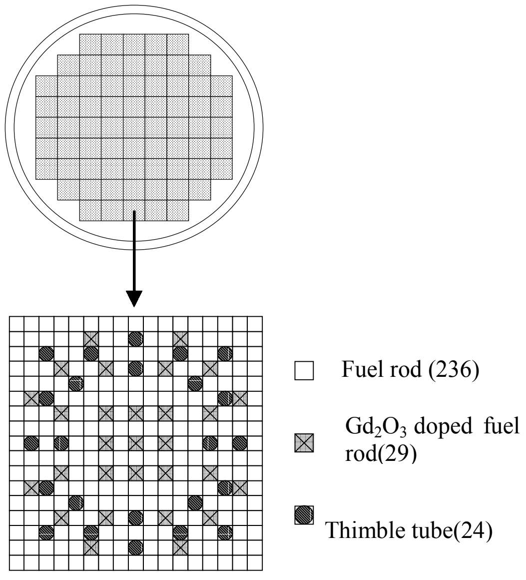

Fig. 2 Cross-section of 300 MWt Reactor Core

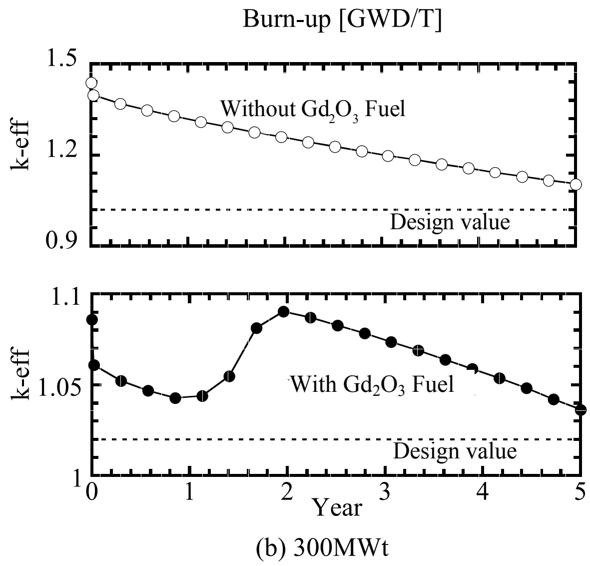

Fig. 3 Burn-up of 300 MWt Reactor Core
•(Upper figure; Without Gd_2O_3 fuel,
Lowe figure; With Gd_2O_3 fuel)

INV-CRDM

The control rod drive mechanism adopted in the PSRD is driven by an electric motor, and set inside the RPV (INV-CRDM). The INV-CRDM can eliminate a possibility of a rod ejection accident, contribute to compactness of both the RPV and the CV, and to simplicity of the reactor system. The INV-CRDM, therefore, is a key technology for an integral type reactor. The electric motor driving type of INV-CRDM developed by JAERI has a fine controllability in control rod position. It provides neither pipes penetrating the RPV nor a complicated control system that are provided in the hydraulic driving type of INV-CRDM [5].

The whole structure of the INV-CRDM is shown in Fig. 4. It consists a driving motor, a latch magnet, separator ball nuts, a driving shaft, a ball bearing and other components. Details are described in a reference [6]. These

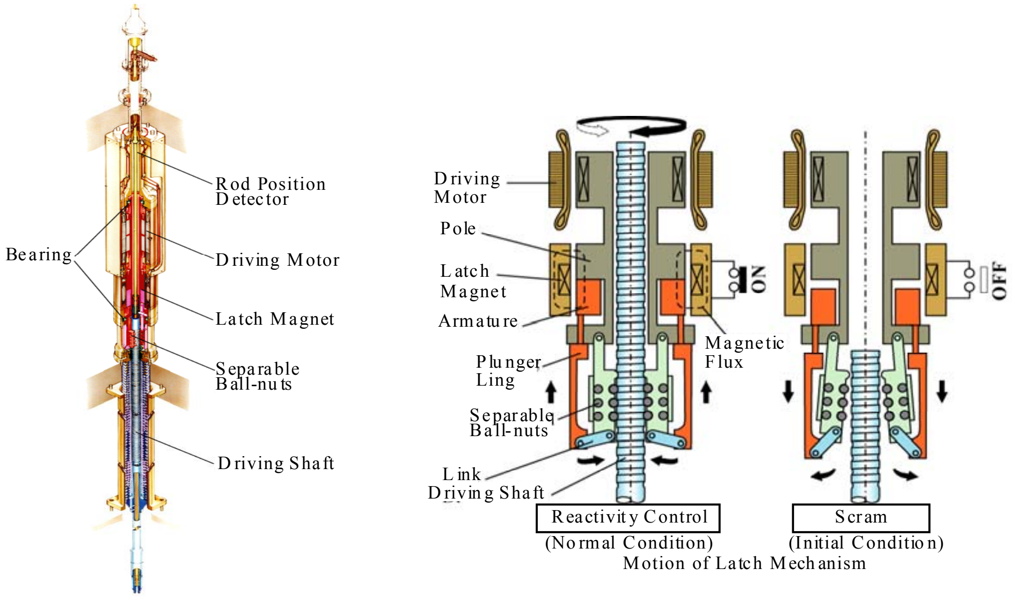

Fig. 4 Concept of INV-CRDM

components work in a fluid of the primary loop, the condition of which is very severe work, that is, at high temperature water (583K, 12MPa) or high temperature steam (for 583K, 10MPa).

De-latching the driving shaft connecting the control rod by the INV-CRDM can scram the reactor after receiving a scram signal: This is the active reactor shut-down. The reactor can be also shutdown passively by inserting the control rod into the core for response to core temperature rise. The device set at the driving shaft below the CRDM consists of a permanent magnet and a magnet control plate that has a characteristic of the saturated magnetic flux depending on the temperature; its flux decreases very much at high temperature. When the core outlet flow of very high temperature passes through the device, the magnet contacting force decreases due to drop in the saturated magnetic flux of the magnet control plate, and the control rod cluster separates from the driving shaft by gravity force. De-tail description is presented in reference [7].

Engineered Safety System

The engineered safety system of the PSRD, the passive safety system, consists of the water-filled containment, the EDRS with hydraulic force valves and the SGs, as shown in Fig. 5. The main functions of this system are to maintain core flooding in cases of accidents including a LOCA and to remove the core decay heat.

Core flooding can be maintained passively by pressure balance of the containment and RPV in an early transient period of a LOCA, and with help of EDRS in a later transient period. Thus, the core flooding in a LOCA can be attained passively without ECC pumps or an accumulator.

Decay heat can be removed with the EDRS as follows. When an accident e.g., a LOCA happens, the reactor will be shut-downed, the feed water pumps stop and the isolation valves for steam and feed water lines close. Hydraulic force valves, force of which are supplied through pipes from the feed water pump outlets, open passively due to pump stop, to flow the fluid in the EDRS to the SGs. The core decay heat is transferred to water of the containment through the SG and EDRS, by natural circulation heat transfer mode. Heat is transferred from water inside the containment to that outside it through the wall.

The pressure increase of the containment in case of a LOCA can be suppressed by steam condensation phenomenon in the water-filled containment. The design pressure of the containment, therefore, can be greatly lowered. The pressure increase and the water level of the core in case of a LOCA depend on the initial water level or the gas volume of the containment. The relationships between the initial water level of containment and the balance pressure, etc., were studied experimentally [8]. In the basic design of the MRX with the thermal power of 100MW, the above-mentioned performance of the water filled containment was analytically confirmed.

The water tight shell (WTS) has a U-bent pipe connecting to the water inside the containment. The pipe has a very small hole at the top of U-bent, which allows to breathe between the space inside the WTS and the upper gas space of the containment according to temperature change due to the states of reactor operations such as the full power, or the cold shut-down. This pipe allows the design pressure of WTS to be very low.

The PSRD can adopt optionally the system of RPV outer-cooling type of In-vessel Retention (IVR) for case of a severe core damage accident or core melt. This is that when the temperature of the RPV wall rises to a certain value due to a severe accident, thermal expansion of the arrow that is attached to the bottom of the wall will break a part of the WTS and introduce the containment water into the space between the RPV and the WTS for outer-cooling of the RPV as shown in Fig. 5.

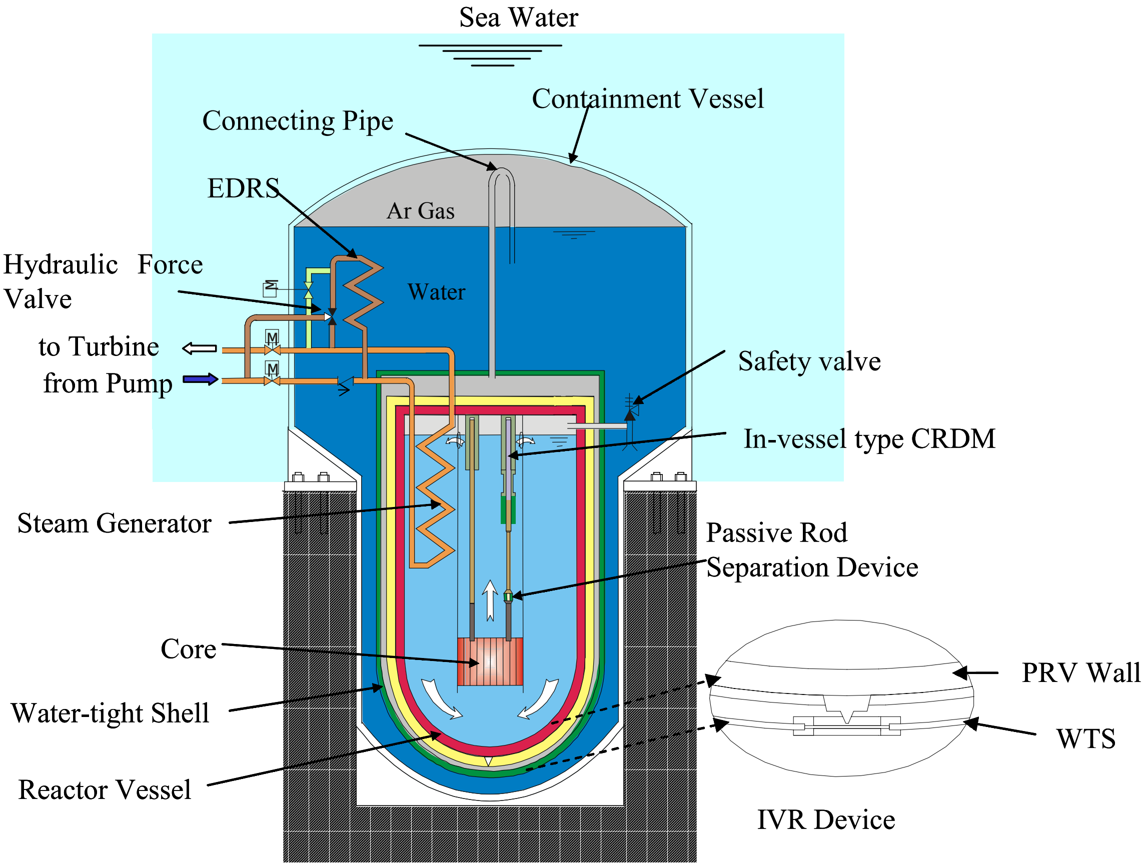

Fig. 5 Engineered Safety System

REACTOR SITING IN WATER FILLED PIT AT SEASIDE

Concept of Reactor Siting in Water Filled Pit

Various siting are possible for small reactors. JAERI has been studying concepts of nuclear barge [9], deep underground siting for supplying district heat at a city [10], and a seaside pit siting besides a normal on-ground siting, for the PSRD. Idea and concept of seaside pit siting is as follows.

In the safety evaluation concerning the reactor site, amount of radioactive material released to the circumstance should be estimated on the base of the accumulated inventory of its material inside the fuel rods that is released in the containment and leak rate of the containment by assuming a hypothetical accident. The leak rate is given as function of pressure difference between the inside and the outside of the containment during transient of an accident. This leak rate can be reduced by decreasing the pressure difference. If the outside pressure of the containment is higher than the inside pressure of it, leakage cannot happen to occur. The situation can be realized by submerging the containment in the deep water, that is, with help of high water pressure.

A reactor siting using water filled pit at a seaside is shown in Fig. 6. The PSRD module reactors are set inside pits made in the bedrock at a seaside and submerged in seawater, that is, the outside of the containment vessel is filled with seawater. Water depth of about 50 to 100m will enable the radioactive material to be confined in the containment for almost transient of hypothetical accident. The pit, of reinforced concrete, can be constructed by a Pneumatic caisson method, which is used in popular for basic construction such as bridges or tunnels. The seawater will be taken through the pipe and flow out to the waterway after circulating inside the pit by natural circulation force. This means that unlimited cooling water as the final heat sink can be provided.

Main issues to be clarified in practical use are i) corrosion of containment vessel with seawater, ii) earth quake resistance, iii) economic feasibility including pit construction cost, iv) operational procedure including refueling or maintenance. Concerning corrosion, its rate are in general very low at deep seawater over 10m. Lining of titanium alloy is used in practice for undersea structures, and is said effective over 100 years. On the earthquake, pit itself can provide enough strength and a rigid betrock will support it. Preferably the pit in a bedrock will has advantages of being strong against earthquake and crash of a flying object. Pit construction cost is not so high in a preliminary cost estimation, and it will be lowered by rationalization under construction of the site.

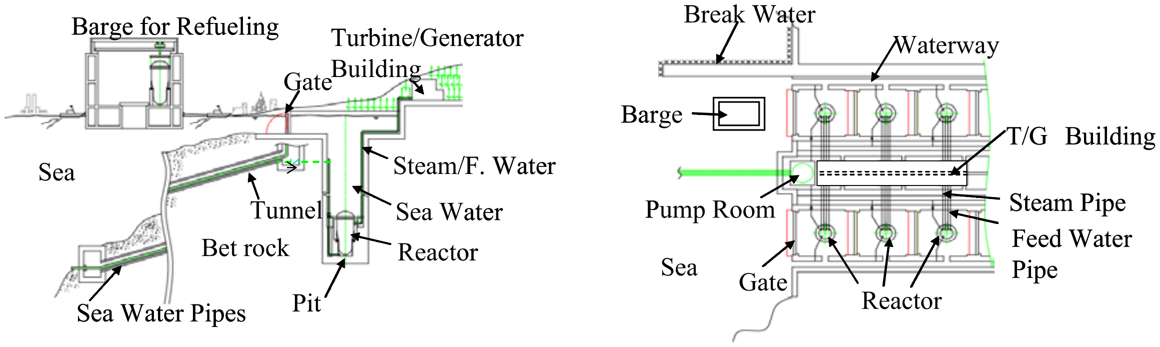

Fig.6 Reactor Siting in Seaside Pit

Operation and Refueling Procedure

The modular reactors are controlled at a control station center. Number of the reactors can be decided according to demand. Optimization of reactor operation can produce economical competitiveness for the system. A detail discussion on operation will be presented in other report. The basic procedure of refueling is as follow.

An exclusive barge instead of the reactor building is used for refueling or periodical maintenance of reactors. The barge is drawn to the place on the pit as shown in Fig. 7. Seawater in the pit is pumped out. The cover of containment is removed by using a crane and is placed on a bet of the barge. After removing the cover of reactor vessel together with the core internal and the INV-CRDMs, the fuel exchange facility is set on the containment. Spent fuels are withdrawn and set in the fuel cask. The spent fuels can be optionally stored inside the fuel storage coffin in the pit. New fuels carried are set in the reactor. The refueling procedure is desirable to be done by the all remote control system.

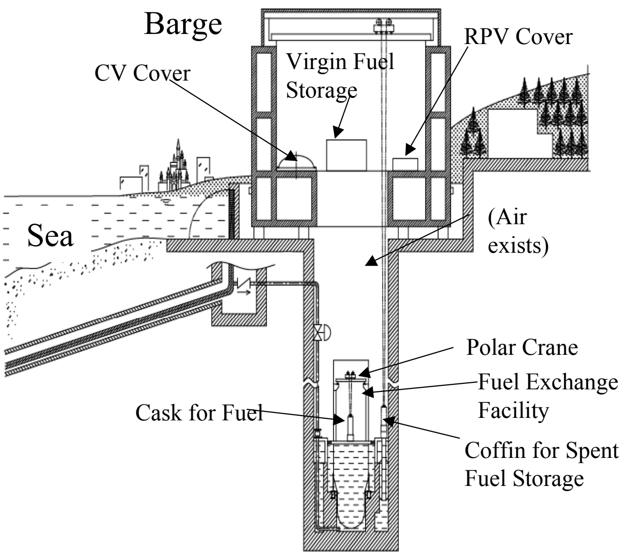

Fig. 7 Concept of Refueling

CONCLUSION

A highly passive compact reactor, PSRD with thermal power of 100 or 300MW, aimed at supplying energy for electricity, district heating etc., has been designed on the base of the advanced marine reactor MRX. The reactor is very simplified integral type one with natural circulation and self-pressurization ways in the primary loop, and its system adopts some innovative technologies. The pipes penetrating the reactor pressure vessel wall are limited to those of the steam line, the feed water line and the safety valve, in order to reduce a possibility of LOCA occurrence and simply the system.

A neutron analysis has confirmed that the core assures a long life operation of over five years with 100% load factor by using low enriched UO2 fuel rods without refueling or fuel shuffling. The INV-CRDM, a key technology of an integral reactor, can operate at high temperature water or steam. The engineered safety system adopted in the PSRD is simple, of fully passive one. The reactor siting in the water filled pit at a seaside is one of feasible options, which allows the radioactive material to be confined in the containment even if a hypothetical accident occurred, although some issues to be clarified for practical use exist.

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