Status report 95 - Integrated Modular Water Reactor (IMR)

Overview

Full name	Integrated Modular Water Reactor
Acronym	IMR
Reactor type	Integral Type Reactor
Coolant	Light Water
Moderator	Light water
Neutron spectrum	Thermal Neutrons
Thermal capacity	1000.00 MWth
Gross Electrical capacity	350.00 MWe
Design status	Conceptual Design completed
Designers	Mitsubishi
Last update	21-07-2011

Description

Introduction

The Integrated Modular Water Reactor (IMR) is a medium sized power reactor with a reference output of 1000 MW(th) (350 MW(e)) and an integral primary system reactor (IPSR) with potential deployment after 2020.
The IMR design goals are to attain economic competitiveness with other electric power sources including large-scale reactors, and attain a high degree of reliance on intrinsic safety features i.e., elimination of initiating events that might cause fuel failure, operator-free management of accidents, no need for external water and power during accidents, etc. To achieve these targets, IMR employs the hybrid heat transport system (HHTS), which is a natural circulation system under bubbly flow condition for primary heat transportation, and no penetrations in the primary cooling system by adopting the in-vessel control rod drive mechanism (CRDM). These design features allow the elimination of the emergency core cooling system (ECCS).

The main features of the IMR plant system are:

- No reactor coolant pumps, pressurizer and coolant pipes with large diameters,
- The small containment vessel (CV) is made possible by adopting the integrated primary system design and simplified systems,
- A simplified chemical and volume control system (CVCS) and waste disposal system (WDS) achieved by the boric-acid free design,
- No ECCS and containment cooling/spray system
- Simple support systems, such as the component cooling water system (CCWS), the essential service water system (ESWS) and the emergency AC power system. These are designed as non-safety grade systems, possible by use of a stand-alone diesel generator.

The IMR is primarily designed to generate electricity as a land-based power station module. The capacity of the power station can easily be increased and adjusted to the demand by constructing additional modules. Because of its modular characteristics, it is suitable for large-scale power stations consisting of several modules and also suitable for small distributed-power stations, especially when the capacity of grids is small. IMR also has the capability for district heating, seawater desalination, process steam production, and so forth. The IMR concept has a very small containment vessel (CV), as shown in Figure 1, and brings economic competitiveness with the large-scale LWRs.

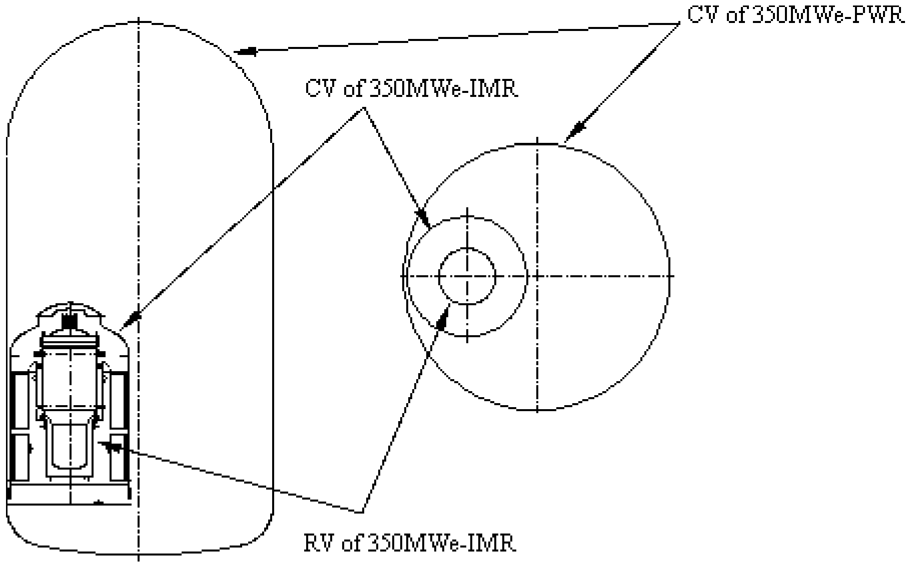

Fig.1. Comparison of CV size between a same power-scale IMR and PWR

IMR started its conceptual design study in 1999 at Mitsubishi Heavy Industries (MHI), reflecting changes in the business environment such as lower economic growth and electricity demand and deregulation of electricity markets in Japan. An industry-university group led by MHI, including Kyoto University, Central Research Institute of Electric Power Industries (CRIEPI), the Japan Atomic Power Company (JAPC), and MHI is currently developing related key technologies through two projects, funded by the Japan Ministry of Economy, Trade and Industry, from 2001 to 2004 and from 2005 to 2007. In the first project, the feasibility of the HHTS concept was tested through two series of experiments.

[1]-[7] They are;

- Phase1-1: air-water scale tests to confirm void distribution and void behaviour in the reactor,
- Phase1-2: high temperature natural circulation tests to study two-phase natural circulation in the reactor with the actual temperature, pressure, and axial dimensions of IMR.

In the second project, the thermal-hydraulic data under natural circulation conditions with bubbly flow for the HHTS design were obtained by four series of simulation tests using alternate fluids, sulfur hexafluoride (SF_6) gas and ethanol (C_2H_5OH), whose pairing has good agreements with steam-water under high pressure conditions around 8~15MPa on bubbly flow performances [8]-[10].

They simulate bubbly flow in;

- Phase2-1: single sub-channel geometry in the IMR fuel subassembly,
- Phase2-2: a multi-bundle geometry in the IMR core,
- Phase2-3: a core internal structure, like the CRDM support plates, in the riser,
- Phase2-4: a structure around the upper part of the riser, where gas separation occurs. The test facilities were built and operated at the MHI Takasago R&D centre.

Technologies of the in-vessel CRDM are based on marine reactor (MRX) development by Japan Atomic Energy Research Institute (JAERI) and MHI. [11]

After these conceptual design efforts, basic design and validation tests are required before making an application for IMR licensing.

Description of the nuclear systems

2.1. Main characteristics of the primary circuit

The cross-section of the IMR reactor is shown in Figure 2 and main characteristics of the primary circuit are summarized in Table 1.

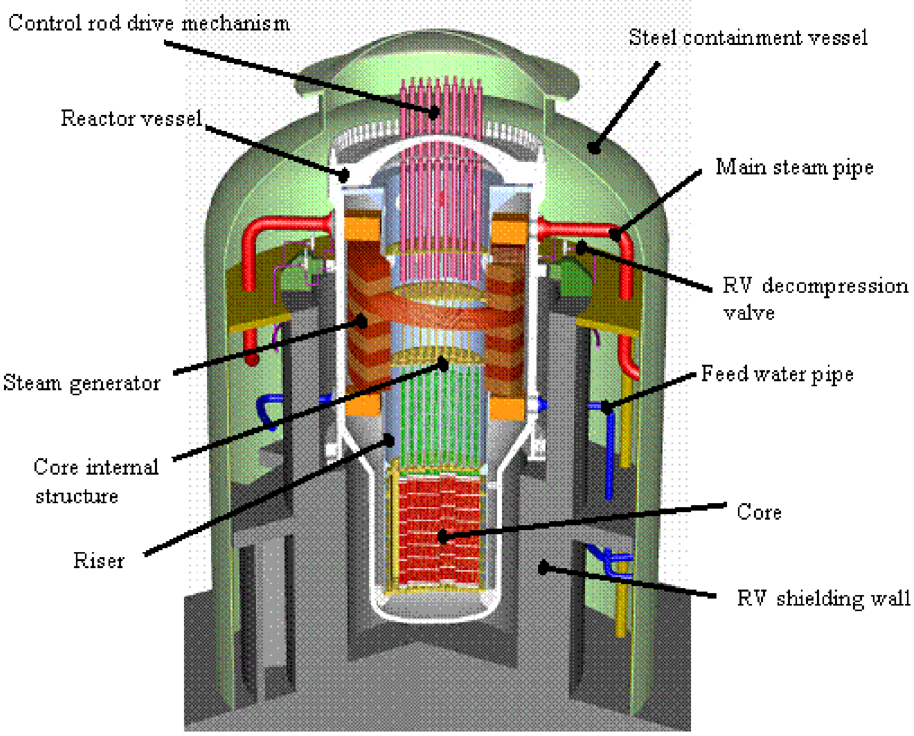

Fig.2. Cross section of IMR reactor

In the HHTS, IMR employs natural circulation and a self-pressurized primary coolant system, altogether resulting in a simple primary system design without reactor coolant pumps and pressurizer, it also reduces maintenance requirements. In addition, the use of the HHTS concept makes it possible to reduce the size of the RV. The HHTS is a kind of two-phase natural circulation system. The coolant starts boiling in the upper part of the core, and two-phase coolant keeps bubbly flow and flows up in the riser and is condensed and cooled by the SGs. This design approach increases coolant flow rate and thus reduces the required the RV height to transport the heat from the core. The IMR primary cooling system design under bubbly flow makes it easy to employ PWR design technologies.

Circulation Type	Natural circulation with bubbly flow
Coolant Material	Light Water
Core inlet/outlet temperature	303°C/345°C
Primary coolant flow rate	3120 kg/s
Reactor operating pressure	15.51 MPa (abs)

Core outlet average void fraction	17%

Table 1. Thermal-hydraulic characteristics

2.2. Reactor core and fuel design

A cross section of the IMR fuel assembly and a core map of IMR are given in Figures 3 and 4 respectively. Design specifications for the fuel and core are given in Table 2.

Items	Specifications
Fuel rod	
Outer diameter (mm)	9.0
Effective height (mm)	3650
Cladding material	Zr-Nb alloy
U-235 enrichment (weight %)	4.45 and 4.95 (avg. 4.80) for the reference core
Fuel assembly	
Rod arrangement	21×21
Rod pitch (mm)	12.6
Number of standard fuel rods	381 (32-rod including Gd)
Number of RCC thimbles	32
Number of burnable poison thimbles	24
Number of instrumentation thimbles	4
Core	
Number of fuel assemblies	97
Average linear heat rate (kW/m)	7.2
Average power density (kW/l)	40
Number of RCCs	72
Refueling interval (EFPM)	26
Refueling batch number	3

Table.2. Fuel and core design specifications

Basically, the fuel design of IMR is the same as with conventional PWRs. The reference IMR design study is done assuming the use of low-enriched uranium dioxide fuel (less than 5 weight % U-235). The IMR fuel assemblies use square type open lattices, like in conventional PWRs. The major differences are as follows;

a) Control rods, rod cluster control (RCC) type, perform the reactivity control, whose neutron absorber is 90 weight % enriched B4C, and the soluble acid boron system is used for the backup reactor shutdown to avoid corrosion of structural materials by boric acid ,

b) The hydrogen-to-uranium ratio (H/U) is set to 5, which are larger than in conventional PWRs, to reduce the pressure drop in the primary circuit,

c) The coolant boils in the upper part of the core and the core outlet void fraction is less than 20%, locally in the core less than 40%, to keep bubbly flow conditions,

d) To reduce axial power peaking caused by coolant boiling, the fuel consists of two parts, the upper part with higher enrichment and the lower part with lower enrichment. Additionally, hollow annular pellets are used in the upper part fuel to reduce axial differences of burn-up rate.

The refueling interval is 26 effective full power months (EFPMs). The power density is lower (about 1/2.5 of current PWRs) but the fuel lifetime is longer (6.5 years) than currrent PWRs, so that the averaged discharged burn-up is about 46GWd/t, which is approximately the same as current PWRs. The cladding material employs Zr-Nb alloy to obtain integrity under the 345^{o}C-temperature and long-lifetime conditions.

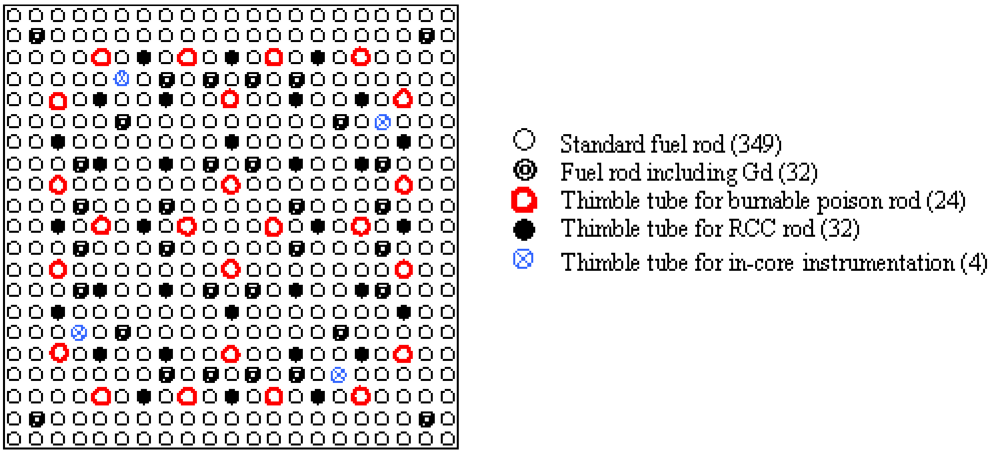

Fig.3. Cross section of fuel assembly

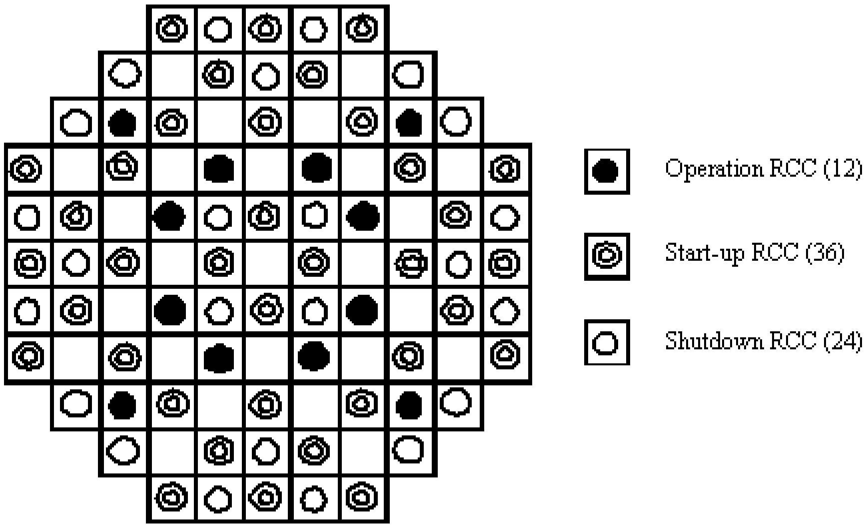

Fig.4. Core map (RCC arrangement)

The assembly size is determined to avoid re-critical in the one-assembly submergence accident in pure water with no RCCs and no burnable poison rods. The fuel materials are same to the current PWR. A spacer is a grid type and a simple plate type with no vanes to reduce pressure drop in the core.

The RCCs are separated into three groups; an operation group (12 clusters), a start-up group (36 clusters) and a shutdown group (24 clusters). The operation RCCs govern reactivity changes with burn-up and power level, the start-up RCCs do reactivity changes with power level, and the shutdown RCCs do reactivity changes between the cold zero power state and the hot zero power state. Only 12 operation RCCs are inserted in the core during full power operation. Either of these groups can move the reactor from a hot full power to a hot shutdown state. The shutdown margins are more than 1%$\Delta\rho$ with the one-rod stuck condition and more than 5%$\Delta\rho$ with the all-RCC-in condition in the cold zero power state.
To reduce the burn-up reactivity swing and the required number of CRDMs, all fuel assemblies contain integrated Gd-fuel rods. Separate burnable absorber rods are also used to reduce the reactivity swing. The design gives a small reactivity swing as shown in Figure 5.

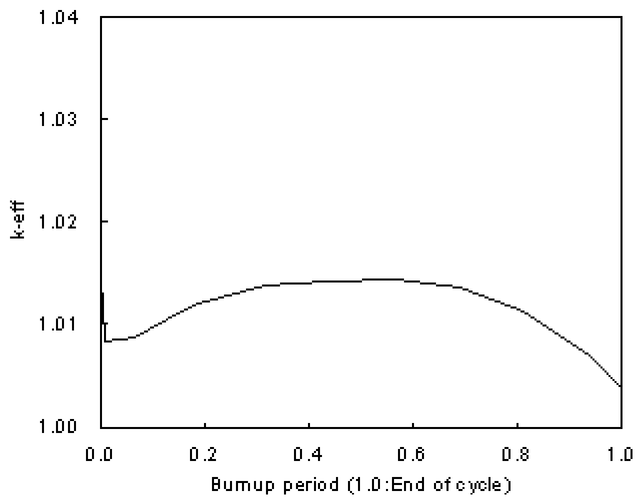

Fig.5. K_{eff} change with burn-up

2.3. Fuel handling and transfer systems

The fuel handling and fuel transfer systems consist mainly of the refueling crane, fuel transfer system, and spent fuel pit crane as in existing plants. Considering the recent need to reduce the periodical inspection time, many improvements including an increase in the speed of each system have been employed.

2.4. Primary circuit components

As shown in Figure 6, there are mainly 4 kinds of primary circuit component, control rod drive mechanisms (CRDMs) operating the RCCs, core internal structure supporting the RCCs, SGs removing heat from the core, and a riser generating natural circulation force.

The CRDM is located inside the RV and employs a reluctance motor and a separable ball-nut, which opens to scram (Figure 7). The CRDM is designed through experiments in the MRX development. The CRDM support structures are designed with simple and light configurations because the coolant velocity in the riser is about 0.6m/s and does not generate hydraulic vibration. All of the primary circuit components are easily dismounted and exchanged.

The SG is a large helical type with TT690-alloy tubes. The IMR has 4 SG units. The primary coolant flows over the outside surface of the SG tubes. Tube inspection is available from the secondary side of the SG. This design removes risks for stress corrosion cracking (SCC) and minimises a space for the SGs. The riser gives an enough difference of the coolant density between the core centre height and the SG centre height, which difference determines natural circulation force.

2.5. Auxiliary systems

The schematic diagram of IMR is in Figure 8. IMR has a chemical and volume control system, a residual heat removal system, component cooling systems, a sea water system, a spent fuel pit cooling and cleanup system, and a fuel handling system as reactor auxiliary systems. They are supporting systems required for the reactor operation and safety, and are designed by using the current PWR technologies, because the system configurations are similar to the PWRs, and limitations or requirements on the design are similar. [12]

The chemical and volume control system perform cleanup of the primary coolant and adjustment of water quality. In PWRs, the system controls concentrations of acid boron in the normal operation, but in the IMR, the system does not control that but only injects acid boron water into the primary system when the reactor shutdown by the control rod system fails. Therefore the system is simpler than a typical PWR system.

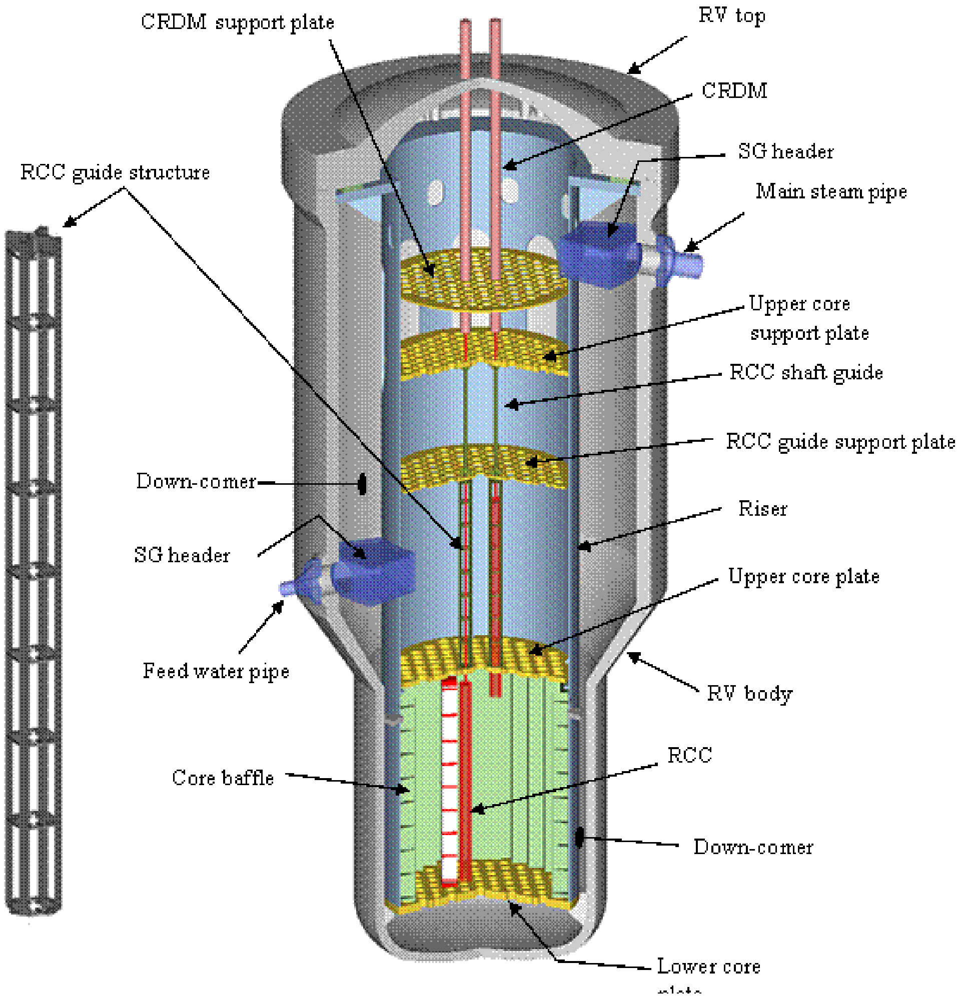

Fig.6. Outline of primary circuit components

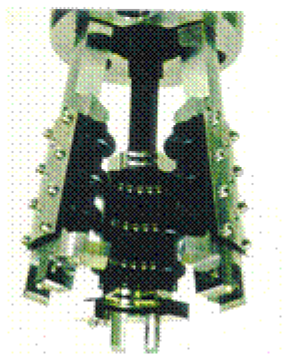

Fig.7. Separable ball-nut produced experimentally

The residual heat removal system removes the decay heat through the SGs and the residual heat removal cooler connected with the main steam and feed water lines.

The component cooling systems cools components of the IMR system, and the sea water system supplies sea water for the component cooling systems.

The spent fuel pit cooling and cleanup system removes the decay heat from the spent fuel and cleans up the pit water..

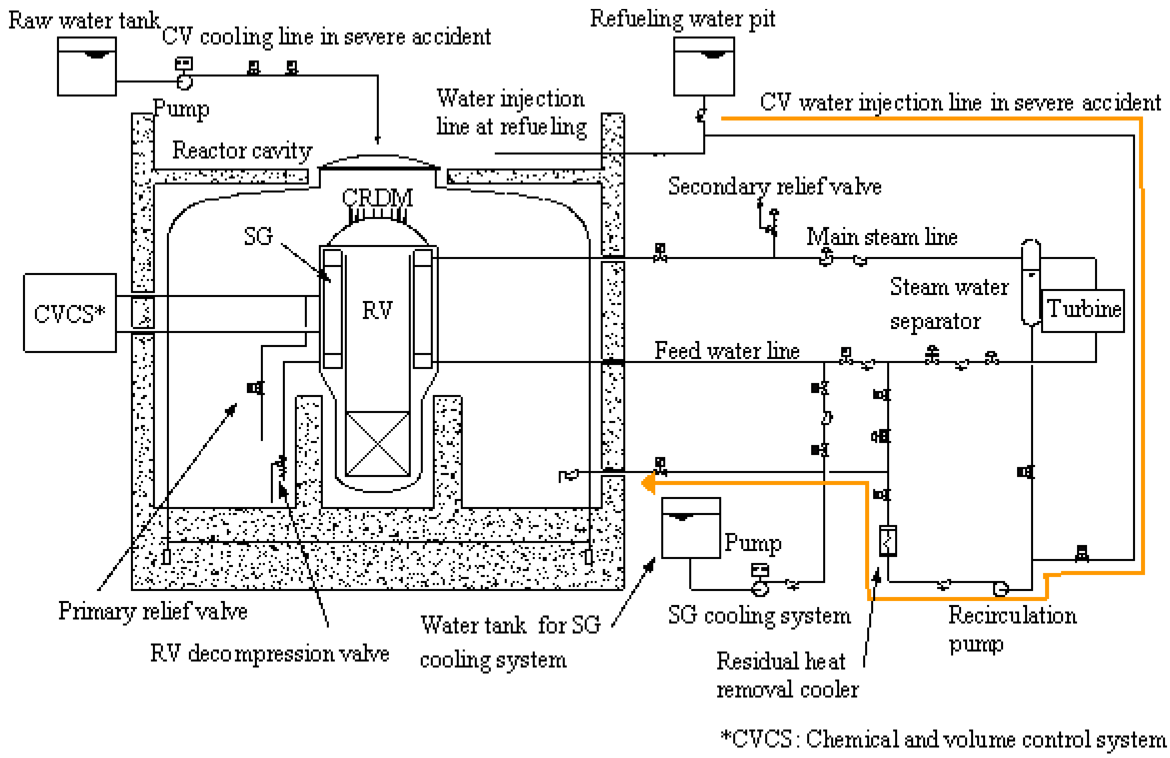

Fig.8. Schematic diagram of IMR

2.6. Operating characteristics

The reactor control system is designed so that it can follow the following load change without causing a reactor trip.

- a 10% step load change
- a 5% per min ramp load change
- 100% load reduction

2.7. Outline of fuel cycle options

Basically, the fuel cycle option of IMR is the same as with the conventional LWRs. The reference IMR design study has been done assuming the use of low-enriched uranium dioxide fuel (less than 5.0 weight % U-235). Using partially or fully loading MOX fuel will be acceptable. Additionally, the properties of the spent fuel of IMR are similar to the conventional LWRs, it can be reprocessed at existing reprocessing plants. The MOX fuel reprocessed by innovative methods with low decontamination factors, such as the pyrometallurgical process, will also be applicable, if it is acceptable for LWRs.

3.1. Safety concept and design philosophy

The basic principles of IMR safety design are as follows:

- By design, eliminate initiating events that might cause fuel failure,
- During accidents, require no operator actions or external support such as water, power, etc.
- The RV integrity will be retained by core cooling through the RV wall, even if severe accidents occur.
- The CV integrity will be maintained by submerging the CV head in water for refueling, even if severe accidents occur.

By adopting the integrated primary system design and the HHTS without reactor coolant pumps and main coolant pipelines, the possibility of accidents that may cause fuel failure, such as a large-break loss of coolant accident (LOCA), control rod ejection (R/E), loss-of-flow (LOF) and locked rotor (L/R), is essentially eliminated. During the normal operation, the water level in the reactor vessel is controlled by injection from the charging pumps. However, since the diameter of the pipes connected to the primary system (reactor vessel) is less than 10 mm, water level can be maintained to submerge the top of the core without any injection.1) Four Independent Safety Trains, both Mechanical and Electrical.

3.2. Provision for simplicity and robustness of the design

The ECCS and CSS installed in conventional PWRs are eliminated. The residual heat removal system (RHRS), CCWS, ESWS, emergency AC power system, and heating, ventilating, and air conditioning (HVAC) system of the main control room are designed as non-safety grade, because of using the stand-alone power generator devices.

3.3. Structure of the defence-in-depth

IMR will be designed, manufactured, constructed, and operated with the same quality, reliability, and safety margins, including negative reactivity feedback characteristics, and based on the same philosophy as the conventional LWRs. Additionally, as the design basis, IMR eliminates causes of initiating events which might result in fuel failure such as, LOCA, R/E, LOF, and L/R, by employing integrated primary system design, the HHTS and in-vessel CRDM.

In case of design basis accidents, IMR detects abnormal condition and trips the control rods. Since IMR has no soluble boron system as a chemical shim, control rod worth is enough to maintain cold shutdown conditions. Additionally, in case of a trip failure, stand-by shutdown systems inject borated water to shutdown the reactor. Residual heat is removed by the SG cooling system, placed for each SG feedwater line, when IMR incurs loss of external energizer or loss of cooling function through the SGs, like accidents with SG tube rupture or main feed water line rupture, and so on. When accidents, the separetion valves on the damaged SG line are closed and the SG cooling system supplies water from the water tank to non-dameged SGs without operator action and external supports and keeps core conditions within the safety criteria.

IMR design could remarkably decrease the possibility of radiological release. In addition, the CV would work as a barrier even if a large radiological release from the RV is hypothesized.

3.4. Active and passive systems and inherent safety features

The active and passive safety systems and inherent safety features are summarized in Table 3.

Category	System	Note
Passive system	Primary shutdown system (Control rods)	Rod insertion by gravity Enough reactivity worth to move the reactor from power operation to a cold shut-down
	Backup shutdown system (Boric acid injection system)	Boron injection by accumulated pressure
	Emergency DC Power System (Batteries)	Batteries are required at the early stage of accidents to operate plant protection system
Active system	SG cooling system	Pumps with the stand-alone diesel generators
Inherent safety features	Integrated primary system	Eliminates large-break LOCA by design
	HHTS	Eliminates LOF, L/R by design
	In-vessel CRDM	Eliminates R/E by design

Table 3. Safety features and systems

3.5. Design basis accidents and beyond design basis accidents

Figure 9 shows heat removal paths on normal operation, design basis accidents and severe accidents.

Design basis accidents (DBAs) are supposed to cause no fuel failure with the functions of reactor shutdown and residual heat removal being carried out by the SGs cooling system.

In case of beyond-design-basis accidents (BDBA) such that the SGs cooling system is not available, normal cooling systems, such as the component cooling water system (CCWS), residual heat removal system (RHRS), etc. are used if possible. In case normal cooling systems are unavailable, the RV integrity is retained by core cooling through the RV wall, and submerging the CV head, using the water for refueling, retains the CV integrity. When decay heat removal through the SGs is not applicable, water leaking out of the RV will fall to the bottom of the RV cavity. Since decay heat can be removed through the RV wall, molten core debris could be retained inside the RV. In addition, decay heat in the CV could be removed through the CV head, which will be immersed in water supplied from the raw water tank by the operators, to keep the pressure in the CV lower than the design limitation. In the severe accidents, the RV decompression valve and the primary relief valve operate to reduce the pressure in the RV when accidents raise the primary pressure. The CV water injection line from the refueling water pit is also used to make a heat sink in the CV at the severe accidents.

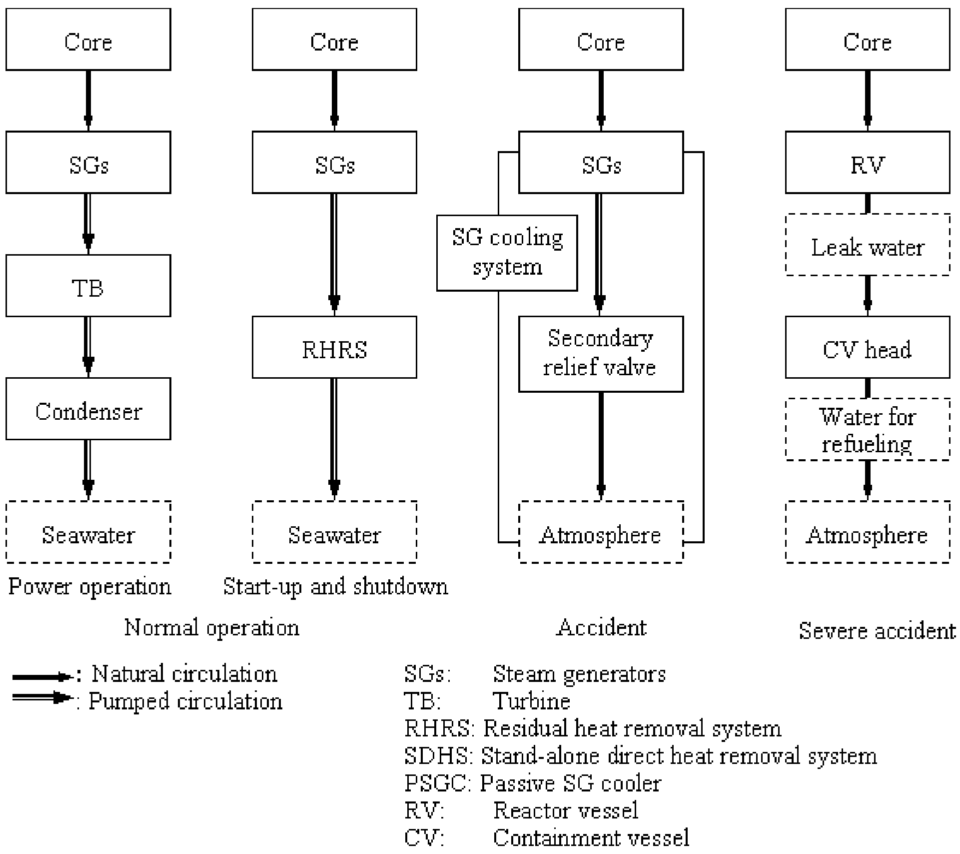

Fig.9. Heat removal paths on normal operation, accident and severe accident

3.6. Provisions for safety under seismic conditions

IMR is designed for seismic conditions of Japan, an earthquake country. The analysis with a typical and conservative seismic swing (S1:180gal, S2:308gal x 1.8), used in the current PWR design in Japan, shows the IMR plant integrity is kept. It is possible to also install seismic isolation devices in case of a site with severe seismic conditions.

Proliferation resistance

Design concepts for proliferation resistance are employing fuel materials with low risks to convert to weapons-usable materials, and giving low opportunities for diversion of fuel materials by outsiders. As ways to attain the concepts, IAEA recommends that employment of low enriched UO2 fuel and long refueling intervals.
IMR is an LWR with moderation ratios similar to conventional LWRs, so that properties of fresh and spent fuel are also similar to fresh and spent fuel of LWRs. Therefore, proliferation resistance is expected to be similar to conventional LWRs, i.e., the initial enrichment required is less than 5 weight % and spent fuel is hard to convert to the weapons-usable materials. The low power density core of IMR enables extending the refueling interval to more than two years.

Safety and security (physical protection)

The physical protection for IMR is planned to adopt same methods with the current PWR one because access routes

to the reactor building, the fuel handling systems and radioactive waste handling/storage systems are similar to the PWRs [12].
In particular, IMR employs designs as follows;

- the reactor, auxiliary and turbine buildings are placed in the protected area,
- the buildings are robust against natural hazards and attacks by outsiders,
- new and spent fuel assemblies are stored in controlled areas in the reactor building,
- each of the doorways to controlled areas in the buildings has a security gate and is kept tabs on.

Description of turbine-generator systems

IMR adopts a conventional turbine-generator system used in the current PWR [12]. Figure 10 shows a typical turbine system.

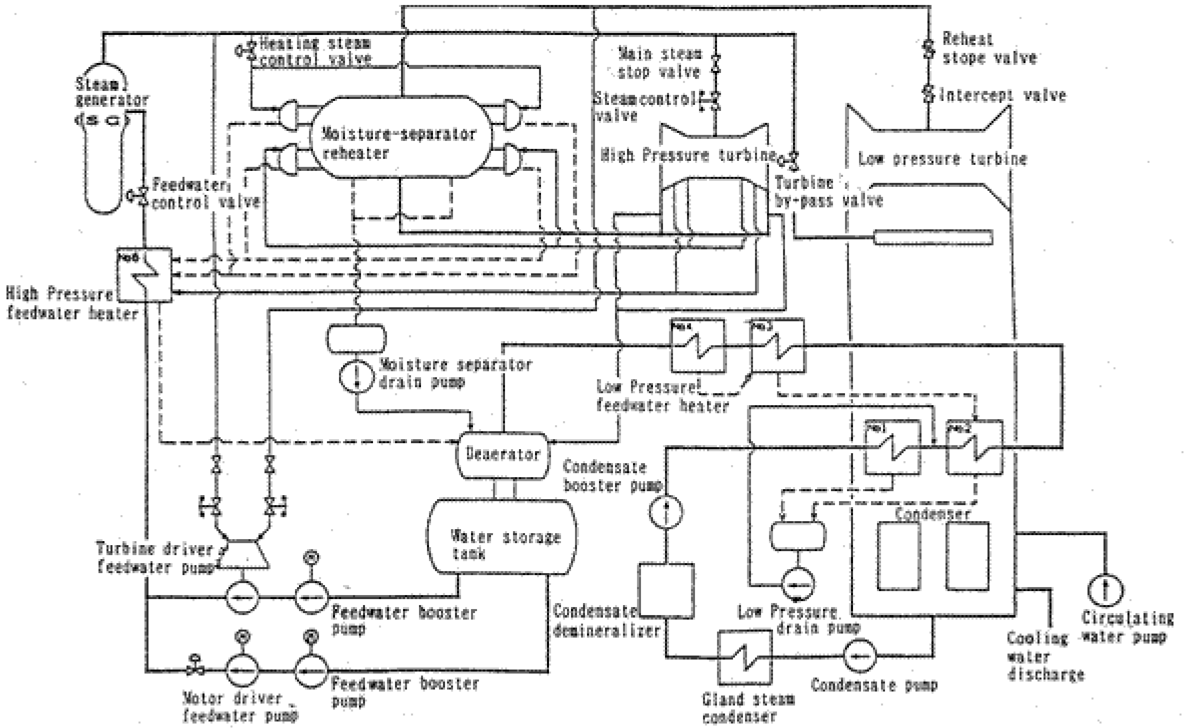

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Fig.10. Typical turbine system employed the current PWR in Japan [12]

The turbine system converts thermal energy of steam to rotational energy, and electrical energy through a generator. The system mainly consists of a turbine itself, a main steam system and a condensate feed-water system.

The SGs supply super-heated steam with 5.0 MPa of pressure and 296 oC of temperature. The turbine is a TC2F48 type with a high pressure turbine and a low pressure one, and has a power generation efficiency of 35%. A drive shaft of the turbine is connected a generator shaft and rotates a rotor of the generator, and generate electric power.
The main steam system, placed between the SGs and the main steam stop valves, transports steam to the turbine.
The condensate feed-water system has two sections. One is a condensate section from the condensers, placed a downstream of the low pressure turbine, to the deaerator tank, and completely condenses the secondary coolant to water. The other is a feed-water supply section from the deaerator tank to the SGs, and supplies 220 oC water to the SGs.

7.1. In-core neutron instrumentation

The low power density performance of IMR brings low fuel temperatures and does not require observations for linear heat rates. But from a viewpoint of departure from nucleate boiling (DNB), it is necessary to observe horizontal power distributions integrated axially. A fixed in-core detector (FID) including 3-5 self-powered neutron detectors (SPDs) is adopted in an in-core instrumentation system. The FID is used as an on-line detector. One FID is inserted per four fuel subassemblies except fuel assemblies placed the outer layer of the core, where assembly power is low enough to avoid DNB.

7.2. Out-core neutron instrumentation

Because the FID is used by inserting into the fuel assembly and has low sensitivities for neutron flux, the FID is not useful under operations with low power and refueling conditions. IMR adopts an out-core neutron instrumentation system, source range monitor and wide range monitor, which used in the current PWRs.

7.3. Control rod position indicator (RPI)

The power distribution observation with the FIDs gives rough data. On the contrary, changes of control rod positions with burn-up are small. Those require observing control rod positions with high accuracies. IMR adopt an indicator with a magnetostrictive wire. The indicator is placed in every CRDM and observes accuracies within ±10mm for 3.65 m of a control rod stroke.

7.4. Void fraction monitor

The outlet temperature of the primary coolant is the saturated temperature. To clarify core cooling conditions, IMR requires measuring inlet coolant temperature, primary pressure (or outlet coolant temperature), and average void fraction in the riser or primary coolant mass-flow rate. IMR adopts measuring average void fraction in the riser with void sensors, which has good integrity under hot temperature conditions.

7.5. Reactor control system

Figure 11 shows a plant control diagram of IMR.
When the power of the secondary system, i.e., steam generator heat removal, increases, the reactor core inlet coolant temperature decreases, then positive reactivity is added and the core power increases. On the contrary, when the steam generator heat removal decreases, negative reactivity is added and the core power decreases. Thus, the core power has the character to change automatically following the secondary system power rate. The secondary system power is adjusted by feed-water flow rate. Although the core power automatically follows the secondary system to some extent, the transitional power mismatch between primary and secondary systems appears as change of reactor pressure. Change of reactor pressure leads to change of the void fraction in the riser region, changing the void reactivity and natural circulation flow rate. Therefore, for stable operation, it is important to maintain reactor pressure near the target pressure. The control rods finely control the core power, so that the reactor pressure is maintained near the target pressure.
Principally, the plant power is controlled by two kinds of control devices, the feed-water control valve and the control rod.

RELAP5 analyses show the plant control system gives stabilities similar to the current PWRs.

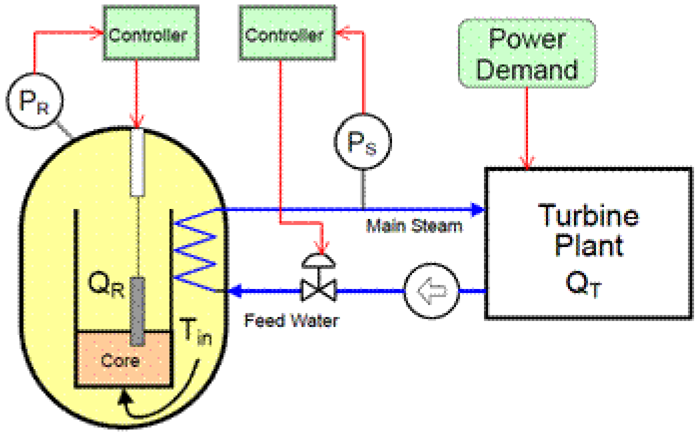

Fig.11. Plant Control Diagram

7.6. Other electrical and I&C systems

About other electrical and I&C systems, IMR adopts newest technologies used in the PWRs. [12]

Spent fuel and waste management

Managements for new and spent fuel assemblies and radioactive wastes on IMR are planned to basically adopt the same managements of the current PWR because materials of the fuel assembly, discharged burn-up, radioactivity of wastes are similar to those of conventional PWRs[12].

New fuel assemblies are stored in a dry storage area near the spent fuel pit, and are transported into the spent fuel pit before loading into the RV. After the reactor is shut down and the primary pressure boundary is opened, all fuel assemblies are removed from the RV into the spent fuel pit in the reactor building by using a fuel handling machines and cranes. The spent fuel assemblies are taken up burnable poison rod and control rod clusters, and stored and cooled in the pit for a planned period more than six months, generally. The control rod cluster is re-taken in the new fuel assemblies and the burnable poison clusters are stored as radioactive wastes. Before transportation to the spent fuel pit, the all fuel assemblies taken up from the RV are inspected, in the inspection pit, whether there are damages or not. If a fuel assembly has damages, the assembly is enclosed into a damaged-fuel-can in the inspection pit and transported to the spent fuel pit. PWR uses borated water in the spent fuel pit, but IMR uses pure water to avoid acid boron mixing into the primary coolant.

The radioactive wastes are solid, liquid and gaseous types, and are stored after proper and safe treatments for planned periods. For the gaseous wastes, there are a nitrogen waste gas treatment system and hydrogen waste gas treatment system remove radioactive noble gases such as krypton and xenon, originated from degassing the primary coolant in the CVCS. For the liquid wastes, a liquid waste treatment system is used to reuse, store and discharge the liquid wastes containing fission products and radioactive corrosion products, originated from drains of equipments. For the solid wastes, a solid waste treatment system is used to store materials such as evaporator concentrates, generated by the CVCS and the liquid waste treatment system, spent radioactive resins, spent radioactive filters, and so on.

Plant layout

The perspective view of the IMR reactor building is shown in Figure 12. The plant layout of IMR is shown in

Figure 13, which is optimized to satisfy various needs, such as safety, radiation, etc, with the same philosophy as applied to conventional PWRs. The important point of the IMR plant layout is the downsizing of building volumes to reduce construction costs. For this, IMR adopts a small steel CV, 14.8 m of the diameter and 22.8 m of the height, and a small reactor building, including the CV and a fuel handling building. The CV design limitations are same with the Japan PWRs.

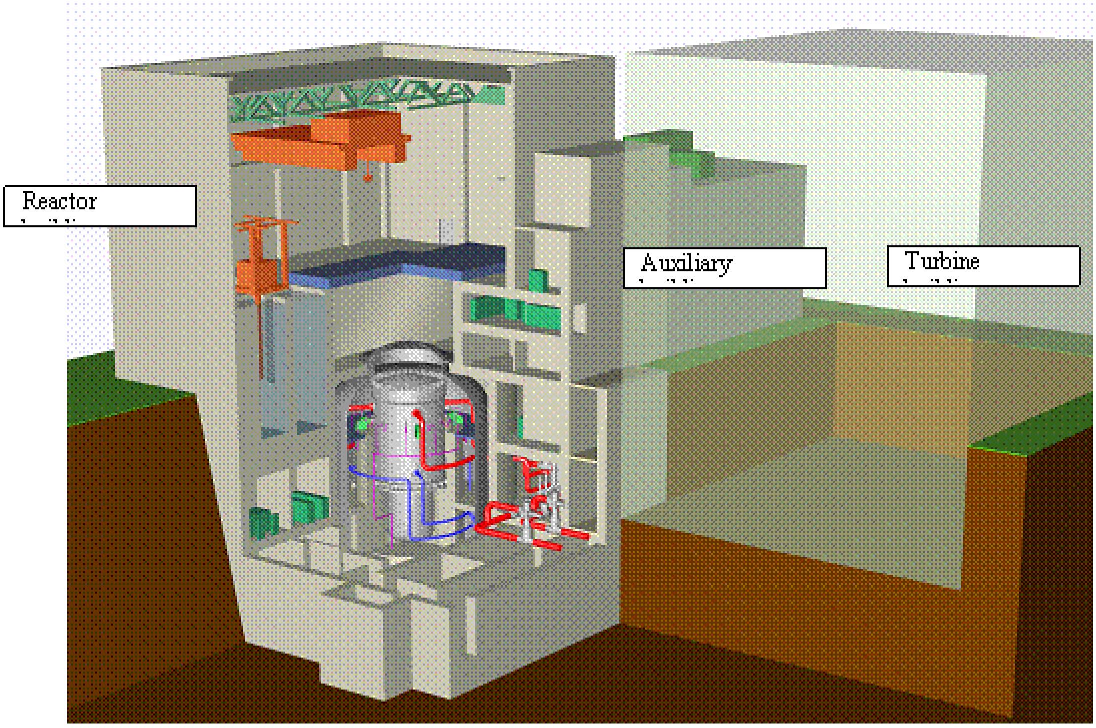

Fig.12. Perspective view of the IMR reactor building

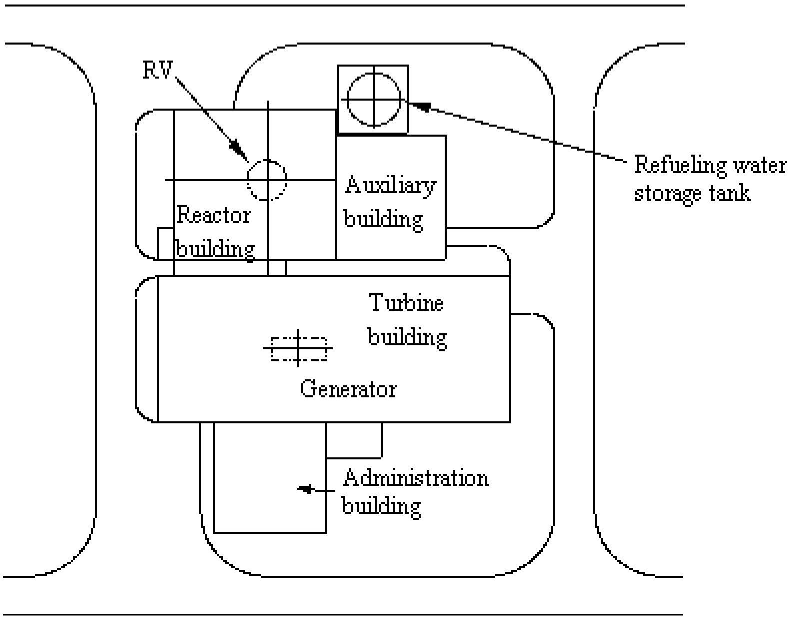

Fig.13. IMR plant layout

The reactor, the auxiliary and turbine buildings have sizes of 34.0mL x 36.6mW x 47.6mH, 28.0mL x 24.5mW x 23.0mH and 28.0mL x 24.5mW x 23.0mH respectively. The whole surface area of the IMR plant site is 4900 m2.

Plant performance

The thermal and electrical powers of IMR are 1000MWt and 350MWe. IMR is capable of both base-load operations and load-follow operations including daily load follow, where, for example, the electrical power changes from 100%-power to 50%-power for three hours, because IMR has same plant responses with PWR on the transient performances.
A design basis lifetime for main structures is 60 years. The capacity of the power station can easily be increased and adjusted to the demand by constructing additional modules. IMR also has high capabilities for district heating, seawater desalination, process steam production and so on because IMR can supply 296 oC steam without radioactive materials.
The IMR design operation schedule, which is determined considering the current Japanese regulation, is a regular maintenance with refueling (25 days), the first full power operation (13 EFPMs), a regular maintenance without refueling (13 days) and the second full power operation (13 EFPMs) before the regular maintenance with refueling. The total regular maintenance period is within 40 days per 26-EFPM operation, resulting in a predicted load factor of 95%. If the regulation accepts, it is possible to operate 26-EFPM with the 25-day regular maintenance, which would provide a load factor of 97%.
A construction period from the first concrete to the commercial operation start is about 24 months with the current tools and technologies. In the construction, the RV installed the SGs is transported to the site, and other elements manufactured in the maker factories are placed by field election works on the site. It is possible to shorten the period by employing assembling-unit construction methods.
The capital costs per MW(e) are expected to be similar to the large-scaled PWRs. The low total capital cost is attained by the small plant size, small site construction labour due to the short construction period. The low cost feature is favourable to reduce risks and burdens of the investment. The O&M costs are also reduced by less operating manpower through the reactor being capable of self-adjustment to the load, by less maintenance due to simplification and elimination of the certain equipment items such as reactor coolant pumps and safety systems and due to the two-year long operation cycle, and less amount of solid, liquid and gaseous wastes from the equipments and systems due to the boron-free design. The radiation exposure of workers is reduced by less equipment in the primary cooling

system and by less area facing the primary coolant due to the integrated RV, which limits the boundary of the primary circulation.
The simple and essentially safety features also help gain public acceptance around the site.

Development status of technologies relevant to the NPP

The major enabling technologies are as follows.

1. Stability at the plant start-up; Coupling analysis of nuclear physics and thermal hydraulics are developed but there are few validation data for the IMR start-up conditions. Validation data should be obtained through simulation tests.
2. Fuel cladding durability; More data are required to validate the integrity of fuel cladding under boiling conditions in neutron irradiation field.
3. Integrated RV; There are no manufacturing issues but some plant facilities may need to expand their capacity.
4. In-vessel CRDM and RPI; The technologies of in-vessel CRDM and RPI in IMR are based on design experiences of the next-generation marine reactor MRX developed by JAERI and MHI. The basic feasibility was tested but in addition to the development programme, more data are required to confirm the durability of motors, bearings, and ball-nuts under the IMR high temperature operating condition. Specifically, high temperature RPI testing under the IMR design conditions is necessary. Methods of the CRDM and RPI maintenance should be also improved.
5. In-vessel SG; Thermal-hydraulic data are needed to valid heat removal performances under natural circulation condition with bubbly flow. The SG tube is planned to be inspected from the secondary side of the SG, and inspection devices should be improved.

Deployment status and planned schedule

IMR is an IPSR categorized under international near term deployment (INTD) in the Generation IV International Forum. The Japan Ministry of Economy, Trade and Industry supported its conceptual design study and feasibility testing of key technologies from 2001 to 2007 [1]-[10].
Currently, the development team consists of Kyoto University, Central Research Institute of Electric Power Industries (CRIEPI), the Japan Atomic Power Company (JAPC), and Mitsubishi Heavy Industries (MHI).
IMR is now at the conceptual design stage. Validation testing, R&D for components and design methods, and basic design development are required before licensing. The time required for development and deployment of IMR depends on the financial situation and the extent of construction requirements. The target year to start licensing is 2020 at the earliest.

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Technical data

General plant data

Reactor thermal output	1000 MWth
Power plant output, gross	350 MWe
Power plant efficiency, net	35 %
Mode of operation	Baseload and Load follow
Plant design life	60 Years
Plant availability target >	95 %
Seismic design, SSE	Equivalent to that of PWRs in Japan
Primary coolant material	Light Water
Secondary coolant material	Light Water
Moderator material	Light water
Thermodynamic cycle	Rankine
Type of cycle	Indirect

Safety goals

Core damage frequency <	2.9E-7 /Reactor-Year
Operator Action Time	24 Hours

Nuclear steam supply system

Steam flow rate at nominal conditions	515 Kg/s
Steam pressure	5.6 MPa(a)

Feedwater flow rate at nominal conditions	220 Kg/s
Feedwater temperature	296 °C

Reactor coolant system

Primary coolant flow rate	3120 Kg/s
Reactor operating pressure	15.51 MPa(a)
Core coolant inlet temperature	303 °C
Core coolant outlet temperature	345 °C
Mean temperature rise across core	42 °C

Reactor core

Active core height	3.65 m
Equivalent core diameter	2.95 m
Average linear heat rate	7.2 KW/m
Average fuel power density	19.3 KW/KgU
Average core power density	40 MW/m^3
Fuel material	$UO2$
Cladding material	Zr-Nb
Outer diameter of fuel rods	9.0 mm
Rod array of a fuel assembly	Square
Number of fuel assemblies	97
Enrichment of reload fuel at equilibrium core	4.80 Weight %
Fuel cycle length	26 Months
Average discharge burnup of fuel	46 MWd/Kg
Burnable absorber (strategy/material)	Gd2O3 in fuel - Natural boron in Pyrex rod
Control rod absorber material	B4C with 90wt%-10B
Soluble neutron absorber	Boric asid with 90wt%-10B

Reactor pressure vessel

Inner diameter of cylindrical shell	6000 mm
Wall thickness of cylindrical shell	275 mm
Design pressure	17.26 MPa(a)
Design temperature	345 °C
Total height, inside	16800 mm

Transport weight	874 t

Fuel channel

Pressure Tube material	Zr 2.5wt% Nb alloy

Steam generator or Heat Exchanger

Type	Large helical
Number	4
Total tube outside surface area	6770 m^2
Number of heat exchanger tubes	5120
Tube outside diameter	11.2 mm
Tube material	TT690 alloy

Primary containment

Type	Steel
Overall form (spherical/cylindrical)	Cylindrical
Dimensions - diameter	14.8 m
Dimensions - height	22.8 m
Design pressure	0.492 MPa
Design temperature	144 °C
Design leakage rate	0.1 Volume % /day

Residual heat removal systems

Active/passive systems	Active

Safety injection systems

Active/passive systems	Passive

Turbine

Type of turbines	TC2F48
Number of turbine sections per unit (e.g. HP/MP/LP)	1/0/1
Turbine speed	3000 rpm

HP turbine inlet pressure	5.0 MPa(a)
HP turbine inlet temperature	296 °C

Generator

Type	Turbine generator
Rated power	390 MVA
Active power	350 MW
Voltage	6.9 kV
Frequency	3000 Hz

Condenser

Type	Sea water cooling
Condenser pressure	98 kPa

Feedwater pumps

Type	Booster pump
Number	2
Head at rated conditions	90 m
Flow at rated conditions	0.72 m^3/s