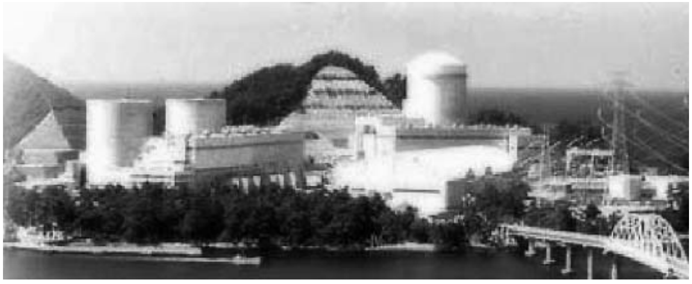

For the Long-Term Stable Supply of Electric Energy

–Yesterday, Today, and Tomorrow of Nuclear Power Generation–

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1. Introduction

More than thirty years have passed since nuclear power generation started on commercial basis in Japan. Beginning with introducing the technology from abroad, acquisition and improvements of the technology have been progressed in every field of design, manufacturing, construction, operation and maintenance through the diligent efforts of all of the relative people concerned. As a result, now the 52 light water reactor plants supply approximately one-third of the electric power of our country and play an important role as major electric power source.

For continuing to play the role successively, it is important that the light water reactor plants assure competitiveness against other electric power sources, such as combined cycle thermal power plants, maintaining the highest safety level. As one of specific efforts to attain this purpose, Mitsubishi Heavy Industries, Ltd (MHI) has been proceeding with the design of the new plants based upon the experience accumulated to date, meanwhile taking measures for maintaining the stable operation of the aged plants. Also MHI has been focusing to develop technology required and measures available for the effective use of equipments and plants.

In the mid- and long term planning, MHI is pursuing the development of advanced reactor, including realization of local distributed electric power sources as well as multi-purpose energy sources in order to meet the diversifying needs for future nuclear power plants. This paper presents an overview of the current activities of MHI in these area, including a brief history of introduction and acquisition of light water reactor technology (**Fig. 1**).

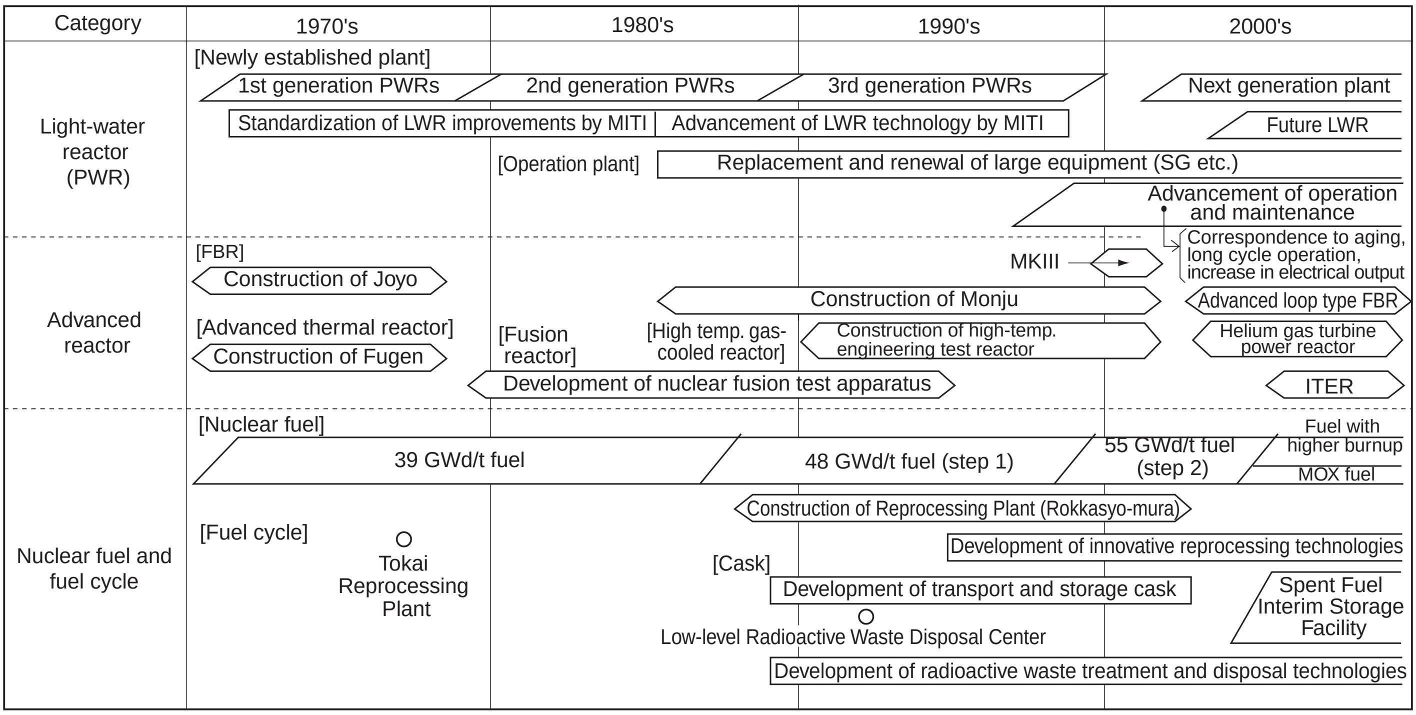

Fig. 1 Progress of nuclear energy systems of MHI

2. Yesterday-From introduction to taking root of light water reactor technology

2.1 Introduction of light water reactor technology

MHI entered into an agreement with Westinghouse Electric Company of the United States in 1959, and introduced technology on the pressurized water reactor (PWR) as the commercial nuclear power plant. Based upon those technology, MHI has been disseminating PWRs throughout Japan. MHI has thus far built total of 23 PWR plants over years, including Mihama Unit 1, which entered into commercial operation in 1970 and first supplied nuclear generated electric power to EXPO Osaka held in 1970, and Genkai Unit 4 , the most recent PWR plant which commenced commercial operation in 1997 (**Table 1**). These PWR plants can be classified into three generation groups, the first group started commercial operation in 1970's, the second in 1980's and the third in 1990's. The first generation group including nine units were imported plants or domestic plants constructed based on the imported technology. The second generation group includes seven units constructed based on MHI's own technology that were developed through the experience in construction and operation of the first group plants. The third generation group is consisted of seven units which have been further improved based on domestic technology.

Ever since introducing the technology for the first generation plants such as Mihama Unit 1, MHI had promoted domestic production of equipment and improvement of the technology introduced in early stage in line with actual domestic conditions. During the ten years plus after nuclear power generation was put in use, MHI experienced such troubles as bowing of fuel rod, cross flow from core baffle plate clearance and degradation of steam generator (SG) tubes which resulted in decrease of plant availability. To overcome these problems, MHI made thorough investigation of the root causes, and took comprehensive measures such as improving the design of equipment in terms of materials and structures, improving operational controls, water quality control for example, as well as developing and adopting the improved inspection and corrective maintenance techniques.

Some measures taken by MHI against degradation to SG tubes are presented below as an example case for technical improvements.

The steam generator is a vertical U-tube heat-exchanger to transfer the heat generated in the reactor core to the secondary turbine-generator system, and formed of several thousands of the tubes. Since the introduction of the technology from Westinghouse, MHI had suffered from various types of degradation with tubes. Countermeasures against those troubles implemented by MHI were improvement of the water quality in the secondary system, structural modification of the

Table 1 Japanese PWR plants

Type	Plant Name	Electric Output (MWe)	Owners	Commercial Operation
2-loop PWR	Mihama No. 1*	340	The Kansai Electric Power Co., Inc.	Nov. 1970
	Mihama No. 2	500	The Kansai Electric Power Co., Inc.	July. 1972
	Genkai No. 1	559	Kyushu Electric Power Co., Inc.	Oct. 1975
	Ikata No. 1	566	Shikoku Electric Power Co., Inc.	Sep. 1977
	Genkai No. 2	559	Kyushu Electric Power Co., Inc.	March. 1981
	Ikata No. 2	566	Shikoku Electric Power Co., Inc.	March. 1982
	Tomari No. 1	579	Hokkaido Electric Power Co., Inc.	June. 1989
	Tomari No. 2	579	Hokkaido Electric Power Co., Inc.	April. 1991
3-loop PWR	Takahama No. 1*	826	The Kansai Electric Power Co., Inc.	Nov. 1974
	Takahama No. 2	826	The Kansai Electric Power Co., Inc.	Nov. 1975
	Mihama No. 3	826	The Kansai Electric Power Co., Inc.	Dec. 1976
	Kawauchi No. 1	890	Kyushu Electric Power Co., Inc.	July. 1984
	Takahama No. 3	870	The Kansai Electric Power Co., Inc.	Jan. 1985
	Takahama No. 4	870	The Kansai Electric Power Co., Inc.	June. 1985
	Kawauchi No. 2	890	Kyushu Electric Power Co., Inc.	Nov. 1985
	Ikata No. 3	890	Shikoku Electric Power Co., Inc.	Dec. 1994
4-loop PWR	Ohi No. 1*	1 175	The Kansai Electric Power Co., Inc.	March. 1979
	Ohi No. 2*	1 175	The Kansai Electric Power Co., Inc.	Dec. 1979
	Tsuruga No. 2	1 160	The Japan Atomic Power Company Co., Ltd.	Feb. 1987
	Ohi No. 3	1 180	The Kansai Electric Power Co., Inc.	Dec. 1991
	Ohi No. 4	1 180	The Kansai Electric Power Co., Inc.	Feb. 1993
	Genkai No. 3	1 180	Kyushu Electric Power Co., Inc.	March. 1994
	Genkai No. 4	1 180	Kyushu Electric Power Co., Inc.	July. 1997

*: Primary system: Westinghouse Electric Company,
Secondary system: MHI,
Others of primary and secondary systems: MHI

tube supports, use of the improved materials for tubes and improvement of tube manufacturing methods.

The purposes of the secondary system water quality control are to prevent the SG tubes from being corroded and the secondary system equipment from being age-degraded. The water quality control technology first introduced from the U.S, was phosphate (PO_4) treatment which was on the extension of conventional thermal power plants. However, this method caused a corrosive reduction of heat transfer tube wall thickness that resulted from a concentration of phosphate at narrow region (clevis) between the heat transfer tube and tube support plate. In order to prevent this problem, phosphate treatment method was replaced with the all volatile treatment (AVT) method which was expected to reduce the concentration at the clevis. After replacement, although a stress corrosion crack (SCC) was experienced due to the remaining phosphate at clevis, AVT method had successfully precluded the heat transfer tube degradation due to phosphate.

Because the tube supports structures is susceptible to the impurity condensation at clevis between tube and support plate, MHI determined to improve the shape of the hole on the support plate for reducing the enrichment of impurity. Based on the results of evaluations of various characteristic tests, MHI devised the shape of Broached Egg Crate (BEC) for holes which could reduce the clevis region and verified their concentration characteristics by tests. As a result, BEC holes were found effective for reducing the impurity enrichment to 1/100 or less compared to conventional round shaped holes. Accordingly this revised design was applied to Takahama Unit 3 and the subsequent plants as well as to the replacement steam generators. Another modification to steam generator is for the anti-vibration bars (AVB) which are inserted to suppress the vibration of U-bend portion of tubes for preventing from the fretting wear of tubes due to insufficient support. In this case, the numbers of supporting points were increased.

In order to increase the strength of the tube against SCC, research and development were carried out for changing the conventional materials into new ones. As a result, it was found that the resistance of Ni-Cr-Fe alloy to SCC in the high temperature and high pressurized water increases as the amount of Cr was increased. After TT alloy (thermal treated alloy) 690 containing 27 to 31% Cr and subjected to the special thermal treatment (aging treatment for approximately 15 hours under 700°C) after full solution treatment was verified to have excellent SCC resistance, it was adopted for Ohi Unit 3 and the subsequent plants as well as for the replacement steam generators.

As for manufacturing methods, stress corrosion cracking from outside of tube (secondary side) was experienced due to residual alkali which came to be concentrated at the clevis between tube and tube plate. To prevent this problem, a method of expanding the tube inner diameter along the entire length embedded in the tube plate by using a roller was adopted for eliminating the clevis. Associated with this problem, tube expansion by roller brought high residual stress inside the tube and stress corrosion crack occurred inside the tube (in the reactor coolant side). For resolving the problem, MHI determined to use the hydraulic pressure expansion method to restrain the residual stress (**Fig. 2**).

2.2 Establishment and expansion of the improved technology

In the second generation plants, many improvements were reflected based upon the experience obtained in the first generation. In addition, the modifications of inspection and maintenance procedures through the adoption of integrated reactor vessel head structures, the increase of space for maintenance and inspection and automated maintenance/inspection works resulted the reduction of occupational radiation exposure and shortening the periodical inspection duration. Equipments were also

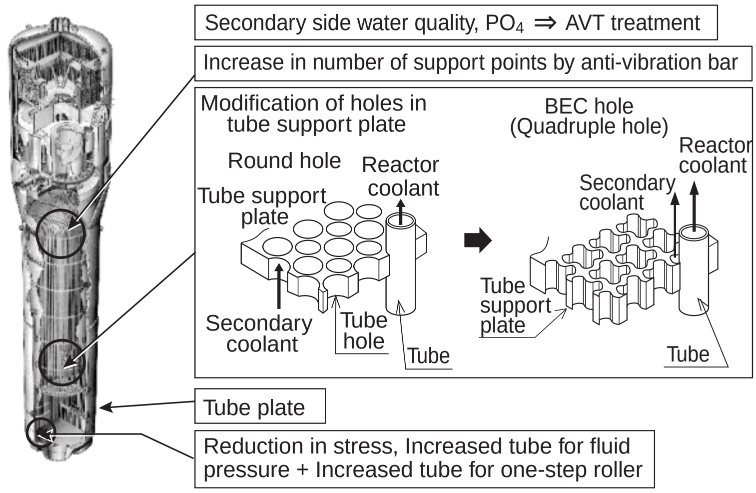

Fig. 2 Improvement of steam generator

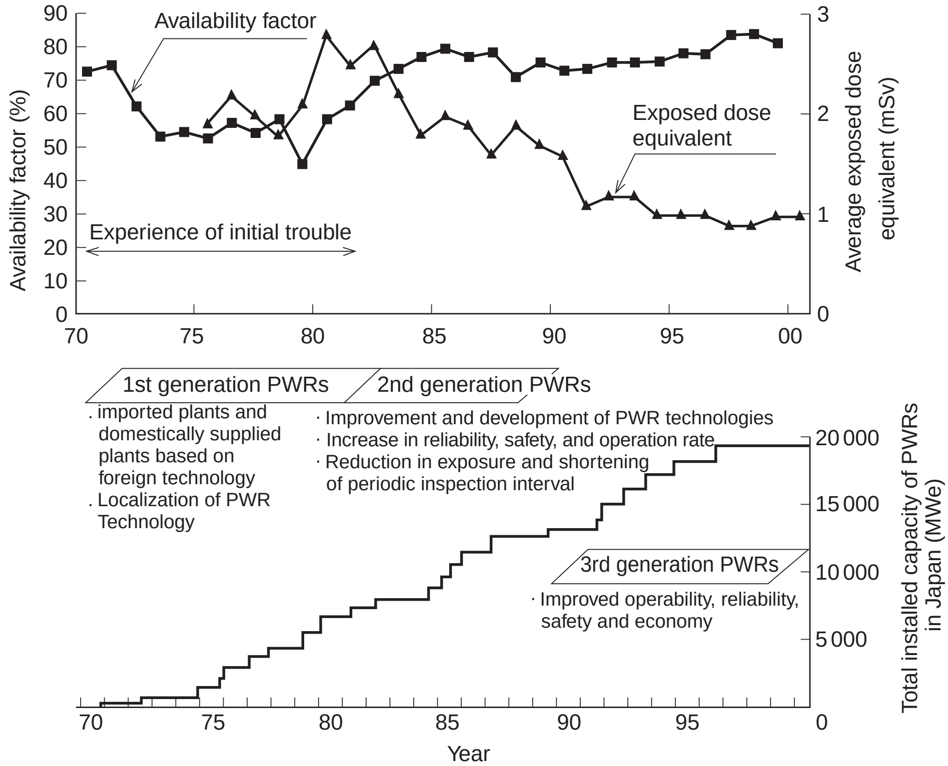

Fig. 3 Trend of operation rate and exposed dose to employees

simplified through the adoption of a super-sized moisture separator and heater with increased unit capacity. Plant reliability was also increased by application of an integrated low-pressure turbine rotor. Along with the reflection of utility's excellent maintenance and operating technique, they contributed to an increase of the plant availability remarkably (**Fig. 3**). In the third generation plants that followed the second generation plants, the matured Japanese version PWR plants realized further improvements in operability, economic efficiency and plant performance through the application of advanced technology such as digital controllers and advanced main control board, and optimization of the original system/equipment designs and plant layout designs which brought the simplification of systems and equipments and a reduction of equipment installation spaces in the buildings.

3. Today-Assuring the role of nuclear energy as a basic electrical power source

3.1 Development of APWR (Advanced PWR)

Today, from the viewpoint of assuring competitiveness with other electrical power sources, such as combined cycle thermal power plants, light water reactor plants must be able to provide with high performance, facilitated operation and maintenance, and increased economic efficiency as well as assured safety. In this regard, MHI has positively adopted numerous advanced technology in the design of the plants, advanced design techniques, such as three dimensional CAD methodology and streamlined construction methods in response to the utilities' needs. Tsuruga Unit 3 and 4, which are supposed to be the first APWR units developed as the third advanced standard design during the period from 1981 to 1985 under the intimate cooperation of government, utilities and manufacturers. Since 1986, various studies have been voluntarily continued for further advancement by the utilities and MHI. The aim of the plants, which provide the largest output in the world, is to realize significant increases in reliability, safety, operability and economic efficiency through introducing the sophisticated technology into the equipment and systems.

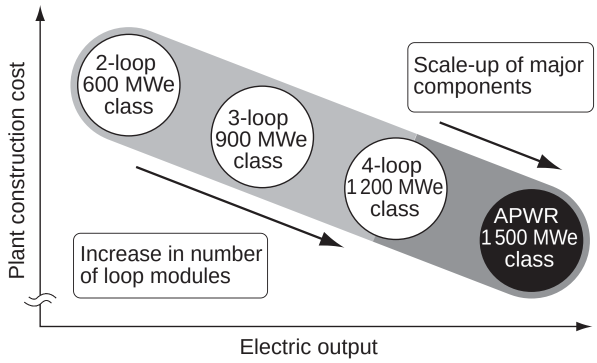

Fig. 4 Reactor model strategy

Although an APWR is of four loop plant, same as the conventional large PWR plant, power output can be increased to approximately 1 530 MWe by scale-up of major components (**Fig. 4**). The prime specifications of the APWR and conventional four loop plant are com-

Table 2 Main specifications of APWR plant

Item			Current 4-loop	APWR
Electric output (MWe)			1 180	1 530
NSSS power reactor system thermal output (MWe)			3 420	4 450
Reactor	Number of fuel assemblies		193	257
Reactor	Fuel rod lattice		17 x 17	17 x 17
Reactor	Active core length (m)		3.66	3.66
Reactor	Core loading (uranium weight) (t)		89	121
Reactor coolant system	Number of loops		4	4
Reactor coolant system	Reactor coolant flow (m^3/h/loops)		2.01×10^4	2.58×10^4
Reactor coolant system	Reactor coolant pressure (kg/cm^2a)		157	157
Reactor coolant system	Steam generator	Type	52F type	70F−1 type
Reactor coolant system	Steam generator	Number	4	4
Reactor coolant system	Steam generator	Steam pressure (kg/cm^2a)	62.5	62.5
Reactor coolant system	Reactor coolant pump	Type	93A-1 type	100A type
Reactor coolant system	Reactor coolant pump	Number	4	4
Reactor coolant system	Reactor coolant pump	Motor output (kW)	Approx. 4 480	Approx. 6 000
Turbine		Type	TC6F44 type	TC6F54 type
Turbine		Moisture separator & reheater	2-stage reheat	2-stage reheat
Generator		Capacity (MVA)	1 310	1 715

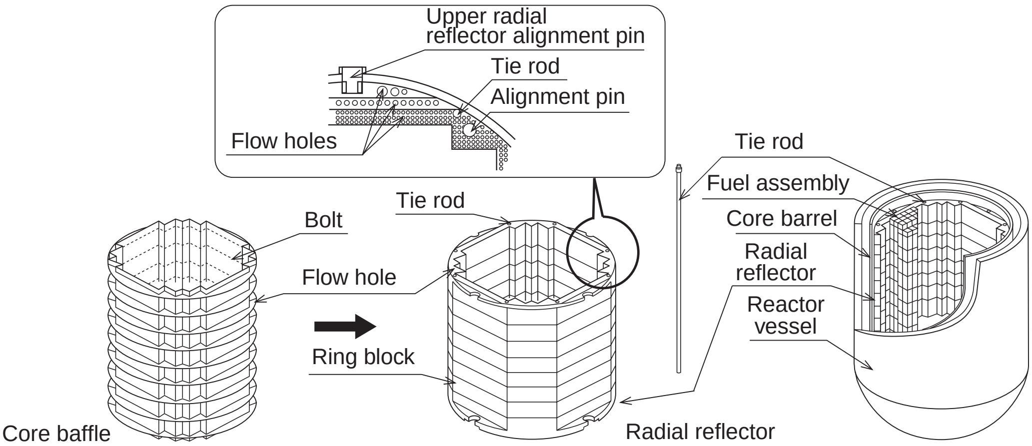

Fig. 5 Radial reflector

pared in **Table 2**. Major design features of APWR mainly consisting of advanced technology are presented below:

(1) Improvements in reliability

In order to increase the reliability of the APWR while assuring maintainability, improvements were made to the major components such as the core internals and the steam generators.

With regard to the core internals, instead of the core baffle formed with stainless steel plates assembled with a large number of bolts, it was decided to use the neutron reflector which is composed with eight stainless steel ring blocks stacked around the reactor core. Adoption of the neutron reflector led to a reduction of bolts used for assembling from some 2000 to about 50 and eliminated the welding lines (**Fig. 5**). In this way, the core internals were simplified and the neutron dose to the reactor vessel could be reduced to approximately one-third, thus the reliability of the reactor vessel was further improved.

A large-sized steam generator (Model 70F-1) was adopted in which the heat transfer area was increased from 5 000m^2 (conventional 4 loop plant) to approximately 6 500m^2 in accordance to reactor power increased. The diameter of the heat transfer tube, on the other hand, was decreased from the conventional 7/8 in. to 3/4 in. in order to suppress any increase of the shell. This is an example of applications of advanced technology to limit the increase of the equipment size followed with equipment capacity increase. The height of steam generator was limited by adopting the upgraded secondary separator with reduced numbers of separation stages. Through these

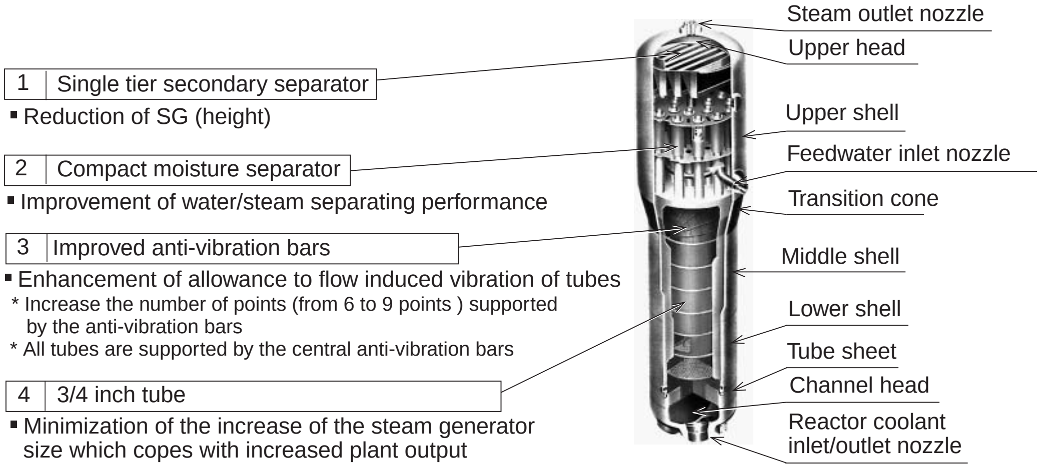

Fig.6 70F−1 type steam generator

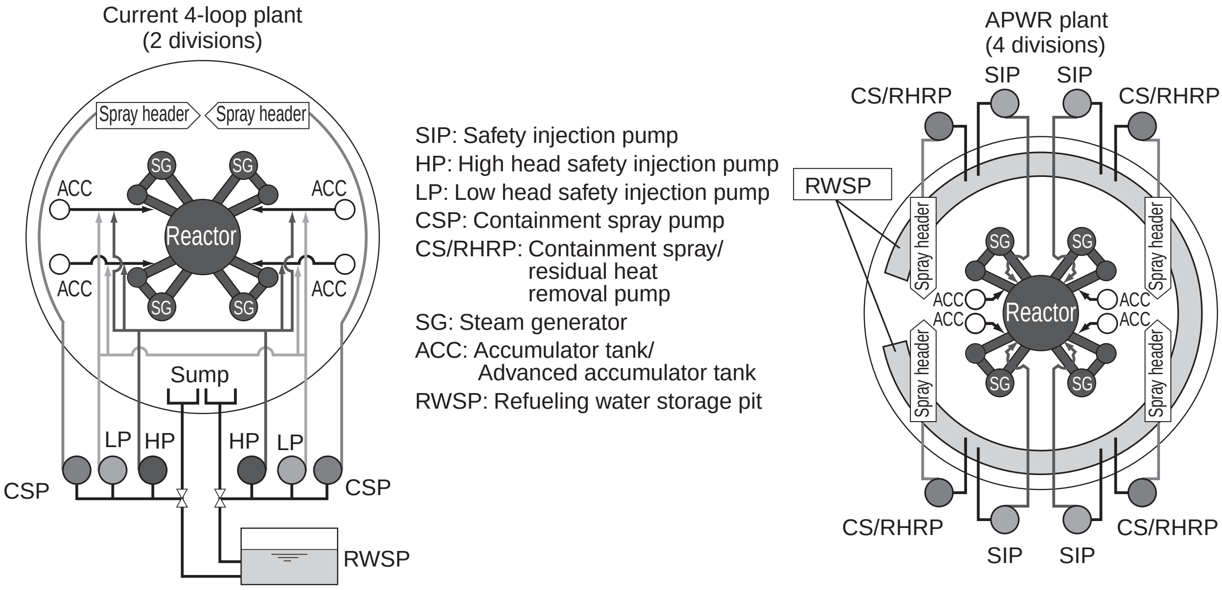

Fig. 7 Emergency core cooling system

modifications, the weight of steam generator was reduced by approximately 10% or more compared with conventional one with same capacity. In addition, the numbers of anti-vibration bars installed at the U-bend portion of the heat transfer tube bundle were increased, for improving the reliability, in order to increase the tube supporting points from 6 for the latest plants to 9 for APWR (**Fig. 6**).

(2) Enhancement in safety

For enhancing the safety features of APWR, the design of the emergency core cooling system was modified from the conventional 2 train configuration (2×100% capacity) to 4 train configuration (4×50% capacity) to increase the reliability of equipment operation during accident. By installing each channel near the associated loop, separation and independence of the safety-related equipments were reinforced and the pipe volume was reduced (**Fig. 7**).

In addition, the refueling storage pit previously installed outside containment was moved to the bottom floor inside containment to use as the water source for the emergency core cooling systems during loss of coolant accident (LOCA). Thus, the coolant injected into the core during accident can be collected in this pit for using as a water source again, and switching operation of water source can be eliminated for enhancing the safety.

High performance accumulator tanks were applied as an advanced technology to the emergency core cooling system. This accumulator tank is equipped with a device which can switch, without any external power, between large injection flow required in the early stage of LOCA and low flow in the latter stage. As a result, the conventional low pressure injection pump for low flow injection could be

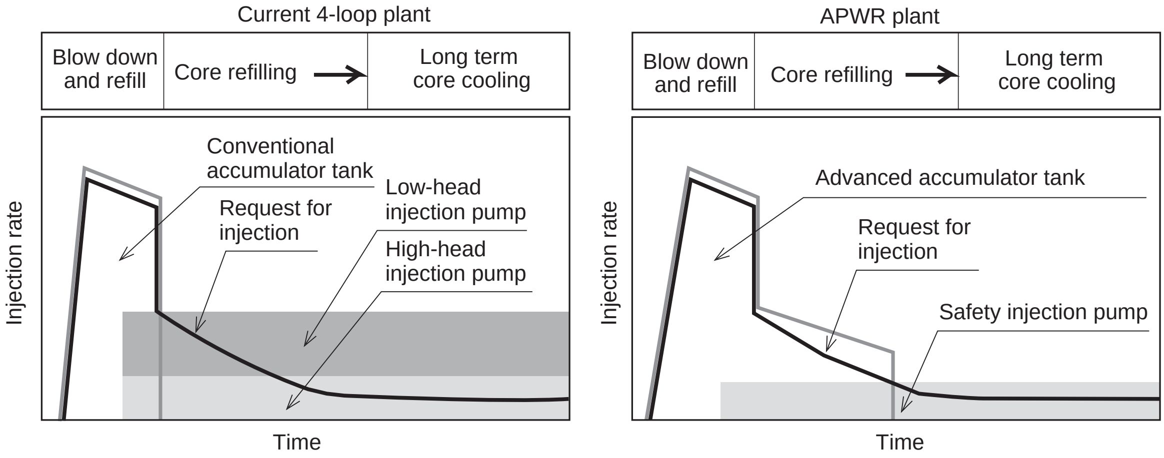

Fig. 9 Characteristics of core injection at loss-of-coolant accident (LOCA)

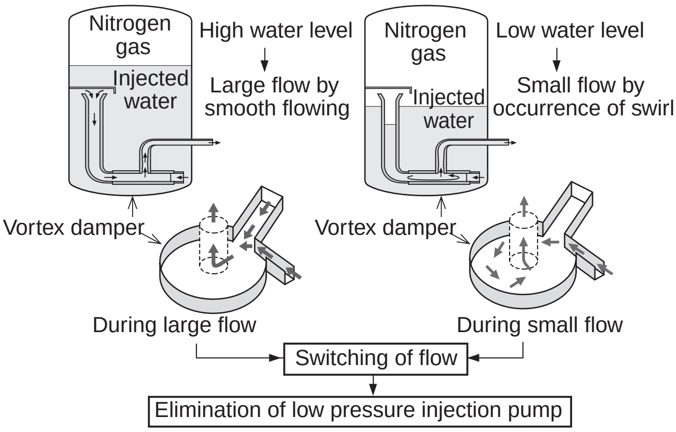

Fig. 8 Mechanism of advanced accumulator

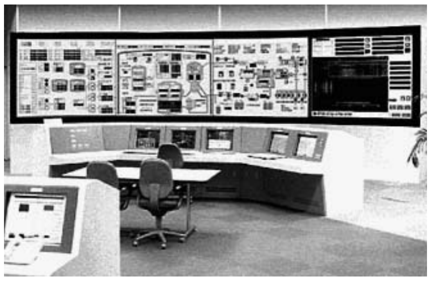

Fig. 10 Operator console, large display panel and shift supervisor console

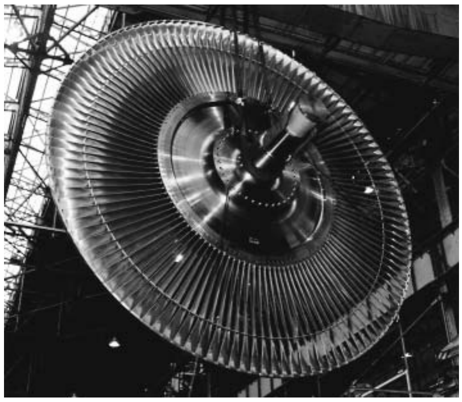

Fig. 11 Final-stage 54 inch blade of low-pressure turbine

eliminated (**Fig. 8** and **9**).

(3) Improvement of plant operability

The advanced main control board was designed to incorporate the operation system utilizing the compact consoles equipped with flat and touch-type computer displays. Additionally system monitoring and operations are integrated with each other by collectively displaying the monitoring information on the operation screen to allow easier operational control. The digital control/protection systems were adopted to facilitate the maintenance works using the self-diagnosis and auto-test equipments, as well as the advanced annunciator system which can identify the criticality and priority of the alarms was introduced to support the operator's activities. By introduction of those improved equipments and systems, the plant can be maneuvered by just one operator during normal and accident conditions. A large display has been placed in the main control room to indicate the status and parameters of the major systems so that all personnel, operators and shift supervisor, can easily identify the status of the entire plant for monitoring and operation. These design improvements will bring significant contribution to enhancement of the plant operability (**Fig. 10**).

(4) Large capacity, high performance turbine

Since an advancement of turbine performance will contribute greatly to higher plant economic efficiency, the steam turbine used for APWR was designed to attain the higher efficiency and increase the capacity in compliance with the reactor power increased as well as the reliability of large rotary machine by introducing the advanced technology. High performance blades designed using the complete three dimensional flow analyses were adopted for higher efficiency. A group of 54 in. blades was adopted as the final stage blades of the low pressure turbine (**Fig. 11**) so as to maximize the output under large steam flow conditions due to increased capacity. Accompanying to adoption of a large sized low pressure turbine, the bearings which

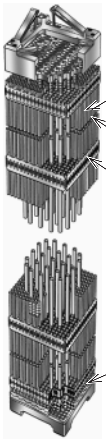

Fig. 12 Main features of step 2 fuel (55 GWd/t fuel)


Fig. 13 Steam generator replacement


Fig. 14 Reactor vessel head replacement (before shipment)

were originally supported from the turbine casing were changed to be supported directly on the base in order to increase the supporting rigidity of bearings so as to enhance the reliability against vibration.

3.2 Improvement and development of nuclear fuel

Since MHI manufactured nuclear fuel assemblies for Mihama Unit 1 in 1970, MHI has manufactured approximately 15 000 PWR fuel assemblies as of Dec. 2002. During the last eleven years, the fuel has had excellent operating experiences without any leakage.

In order to reduce the fuel cycle cost, the burn-up of the fuel was increased from 39 GWd/t to 48 GWd/t (step-1) following extension of core cycle length. At the same time, various design improvements were made with the aim of increasing reliability. At present time, the development of 55 GWd/t fuel has been completed as step-2 fuel, and the safety reviews by the utilities are on the way for commercial use.

The distinctive features of the step-2 fuel are use of corrosion-resistive cladding to meet the higher burn-up and high-density pellet to increase the amount of uranium loaded for further reduction of the numbers of the replaced fuel assemblies. Zircaloy, which has lower neutron absorption characteristics, was adopted as grid material in the fuel assembly design in place of the conventional Inconel. As a result, the reactivity of the core can be maintained longer compared to the Inconel used fuel with the same uranium enrichment, thus operation cycle duration can be extended. In order to reduce fuel leakage due to foreign materials (debris) in the primary coolant, the design of fuel was changed to apply the newly developed debris filter in the lower section of the fuel (**Fig. 12**).

MHI is striving for development of high burn-up fuel aiming further reduction of fuel cycle cost and increase of the reliability.

The design developments of Mixed Oxide (MOX) fuel have already been completed in line of the national recycle policy, and the MOX fuel is now ready for operation in the core with the burn-up up to 45 GWd/t. On the other hand, careful investigation of the fuel manufacturing plant and coordination of the specifications required for the quality control to assure that the MOX fuel has a quality equivalent to that of domestic uranium have been made for the case when MOX fuel may be manufactured in the large-scale MOX manufacturing plant in France and/or in United Kingdom. At the same time, preparatory works for licensing the fuel manufacturing plant are under progress from the standpoints of the quality assurance.

3.3 Activities for stable operation of existing plants

Commercial operations of Mihama Unit 1 (PWR) and Tsuruga Unit 1 (BWR) commenced in 1970. There has been an increase of the numbers of aged plants which have been operated for more than twenty years. In order to reduce the power generation cost through their lives, it is important to operate these plants by using the existing equipments as effectively as possible while maintaining the stable operation. In order to meet those requirements, extension of the operating period and increase of generated power in the possible range are considered. A brief summary of the technical developments for these purposes is presented below:

(1) Measures for the aged plants

In order to extend the plant life maintaining safety and reliability, preventive maintenance must be carried out regularly and thoroughly so as to prevent the occurrence of failures or troubles. From the viewpoint of preventive maintenance, MHI has replaced the steam generators and the reactor vessel upper heads based upon the experience in oversea plants, and also plans to replace the core internals of aged plants in the future (**Fig. 13** and **14**).

Also MHI is actively addressing the development of inspection technology to detect any indications as early as possible that could lead to failures or troubles. Notable examples include the intelligent Eddy Current Test (ECT) equipment that allows accurate and

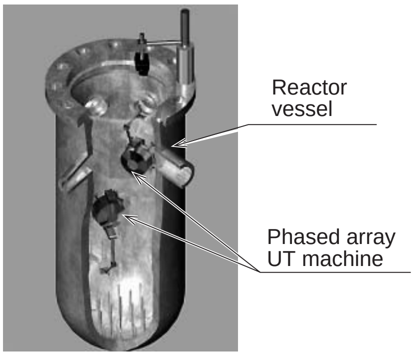

Fig. 15 Application of phased array UT into reactor vessel

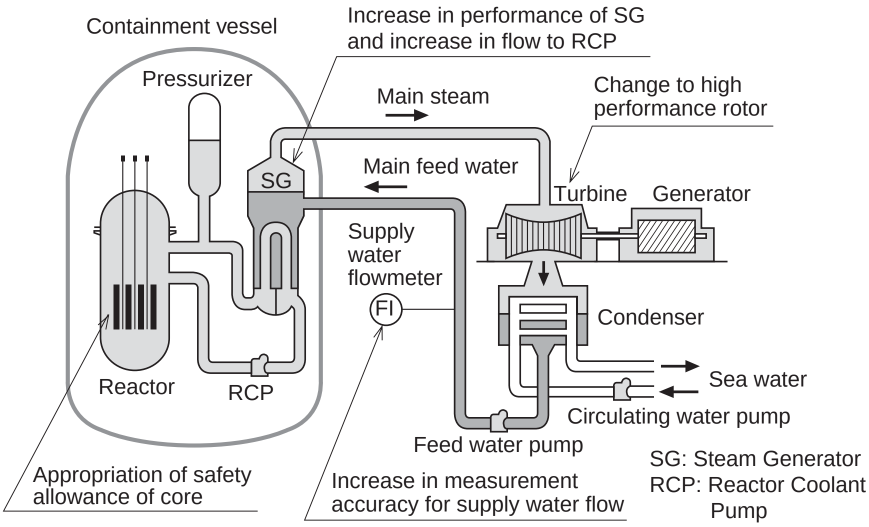

Fig. 16 Method for increasing electrical output

high speed inspection of steam generator heat transfer tubes and phased array Ultrasonic Test (UT) equipment (**Fig. 15**) that is capable of shortening flaw detection time for equipments such as the reactor vessel and reducing the undetectable region. The studies are currently underway on the feasibility of practical use of these equipments.

In addition, MHI is positively addressing the development of evaluation methods for the occurrence and progress of stress corrosion cracks in Ni-based alloys in the primary coolant and advanced crack growth analysis methods that can take into account the residual stresses. Each plant is being evaluated in turn and confirmed the operability for sixty years without any problem through the adoption of suitable measures including the development and application of the techniques mentioned above.

(2) Long cycle operation

The longest operating cycle permitted in Japan until now is thirteen months, however the review of extension of the operating cycle has started and is expected to realize in the near future. In the U.S., most nuclear power plants have already been approved to operate for eighteen months or more and are now implementing. In Japan, specific studies are now underway for extension of the operating cycle as an effective measure to increase the plant availability.

To realize long cycle operation, the plant must be evaluated and verified from the viewpoints of the fuel performance, the reliability of plant facilities and the overall plant safety. With regard to the fuel performances, the development of the high burn-up fuel has already been completed, and every effort toward practical use is now promoted. The evaluation of the effects on the reactor core design and the safety analysis, and the countermeasures to the evaluation results are now under consideration. As to the reliability of facilities, the integrity evaluation of equipments, which are maintained during periodical inspection, has been performed, partly under way, and verified the fundamental applicability to long cycle operation. In order to evaluate the effects of long cycle operation on plant safety, the incremental of the risk has been assessed through the application of probabilistic safety analysis (PRA) approach, and various measures for improving the facilities and operation are now under investigation.

(3)Increase of electrical output

For operating plants, the license amendment for increasing the electrical output by making changes of the plant equipment or optimization of the safety margin are frequently applied aiming at the improvement of economical efficiency in the U.S. and Western Europe. As an engineering measure to increase the electrical output without changing the reactor thermal output, consideration can be given to improving the thermal efficiency by replacement of the existing equipments, such as replacement with large capacity and high performance steam generators and high efficiency turbines. Equipment replacement works, such as change to advanced turbine, are already performed in Japan for better performances. Also, increasing the thermal output of the reactor by optimizing the design margin and/or equipment margin necessary for maintaining the integrity can be effective engineering measures. MHI is proceeding with technical studies into those measures, including the verification and evaluation of the safety and integrity of the plants, referring to the experience in the U.S. and Western Europe. The increase of electrical output of 15 to 20% at most, depending on the number of loops, is expected through the combination of the above measures taken (**Fig. 16**).

4. Tomorrow-Aiming at long-term stable supply of energy

From the viewpoint of finding suitable solutions to environmental problems and attaining independence and long term security of energy supply, nuclear power generation is believed to continue to play an important role as ever in Japan which has virtually poor natural energy resources.

Accordingly, light water reactor plants will be required to increase economic efficiency while assuring sufficient safety through the introduction of new concepts. In addition to light water reactors, it is expected that medium or small size reactors will come to be realized as a locally distributed power source which would allow the risk of new installation to be reduced. There will also be increased demands for multi-purpose reactors in the future that operate at high temperature. In addition, there will also be a need to develop the nuclear fuel cycle based on the fast breeder reactor in order to enhance the long-term utilization of uranium resources.

These trends have already begun. At the generation IV international forum (GIF) on the generation IV nuclear systems held under the initiatives of the U.S. and participated by many countries including Japan, numerous proposals have been presented to realize the introduction of new types of innovative reactors by 2030 as a target date. Proposals contained the new type of reactors which would increase economic efficiency and safety, reduce the radioactive waste, prevent nuclear proliferation, use uranium in ever more effective ways,

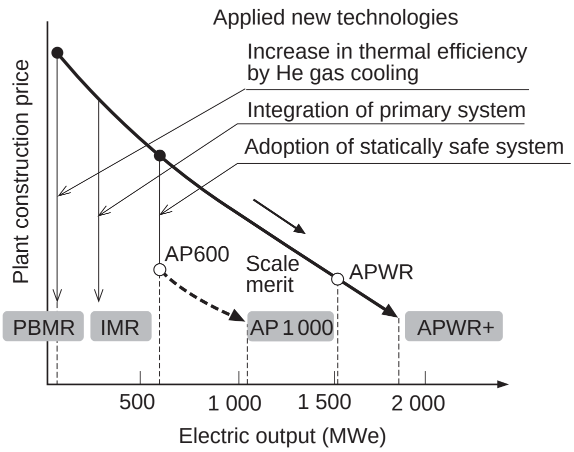

Fig. 17 Concept of increase in economic efficiency of future reactor

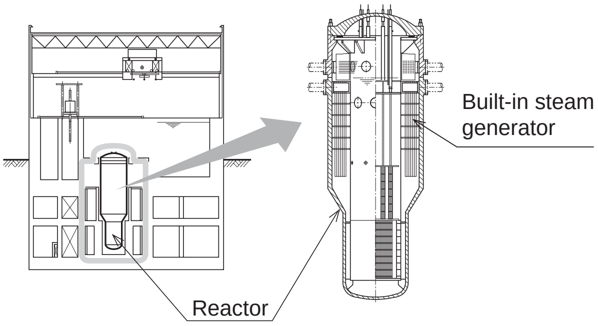

Fig. 18 Integrated modular water reactor (IMR)

and apply nuclear energy to various uses other than power generation. Six concepts were selected at the forum: Gas-Cooled Fast Reactor, Lead-Cooled Fast Reactor, Molten Salt Reactor, Sodium-Cooled Fast Reactor, Supercritical Water-Cooled Reactor and Very High- Temperature Reactor. In Japan, innovative reactor designs were also studied by the Atomic Energy Commission under the Long-term Nuclear Energy Plan of 2000.

Taking these efforts in Japan and overseas into account, MHI is actively working to develop the new APWR+ plant concept to meet the future needs for large capacity power production and the small integrated module reactor IMR (Integrated Modular Water Reactor) which can respond flexibly to power demands. MHI has also participated in a number of development projects and initiatives in cooperation with other major power producers around the world. These include the simplified AP1000 plant being developed under the initiatives of Westinghouse, the high temperature He gas-cooled small reactor PBMR (Pebble Bed Modular Reactor) being developed by PBMR Ltd. of South Africa and the high temperature gas-cooled reactor capable of being available for multi purposes such as hydrogen production. As overview of the basic philosophy for realizing an increase of economic efficiency for each concept is schematically shown in **Fig. 1 7**. A summary of the concept of plant are also presented below:

(1) APWR+

The reconstruction of the existing nuclear power plants will be demanded in the near future. MHI basically believes that large capacity plants can respond to these demands from the viewpoints of utilizing the construction site more effectively and reducing the overall construction costs. MHI is developing APWR+ as a promising concept for accommodating these needs. APWR+ is a 4 loop plant designed based upon the APWR in which electrical output can be increased to approximately 1 750 MWe by incorporating the longer fuel and increased capacity of major equipments. The safety systems as well as the electrical systems are of four channel configuration so that maintenance at power can be performed. In this concept, higher economic efficiency is attained by enhancing the safety and pursuing the merits of large scale production.

(2) Small Integrated Modular Reactor: IMR

If a nuclear power plant suitable for small distributed power source which is located in close proximity to the service area and requires no provision of the specific installations such as transmission lines, etc. and can be compatible with both the safety and the economy could be realized, a new nuclear energy market could be developed in the future. And if such a reactor could be of modular type, it could be able to respond flexibly to the electrical power demands and the site conditions. From the above viewpoint, MHI is developing the small integrated modular reactor (IMR) as a concept to meet these needs (**Fig. 18**).

The IMR is a plant with electrical output of 300 MWe in which the steam generator is integrated into the reactor vessel and the reactor is cooled by natural circulation of the primary coolant. Anticipated accidents can be limited by eliminating the primary coolant pipings. It will bring the enhanced safety as well as the improved economy. This reactor concept and compatibility with the safety are now under verification in the public research sponsored by the Ministry of Economy, Trade and Industry (METI). Since a small reactor thus standardized can be completely prefabricated in a factory and shipped by barge, a remarkable reduction of the construction duration and improvement of the economic efficiency can be expected to attain in combination with offshore siting. In addition, if the development, construction and operation of this reactor could be performed in cooperation with other countries such as Southeast Asia, it would play a role in terms of the international contributions by Japan.

(3) AP 1000

It is expected that the plant economies can be improved by using the simplified safety systems which uses the passive equipments operated by gravity or water head instead of the conventional safety systems driven by the dynamic forces. Westinghouse developed AP 600 plant based on this concept with electrical output of 600 MWe and acquired the Design Certification by the U.S. Nuclear Regulatory Commission (NRC) in 1999. Westinghouse is also currently developing AP 1000 plant with increased electrical output of 1 000 MWe (**Fig. 19**). MHI is now co-developing the design with Westinghouse aiming at acquiring design certification for AP 1000 concept for a medium capacity plant of high safety and economic efficiency. These plants are expected to be put in the practical use in the near future.

(4) High temperature gas cooled reactor

PBMR Ltd. of South Africa has developed a small reactor (PBMR) with output of 165 MWe. It is characterized by using the direct cycle gas turbine with high thermal efficiency (higher than 40%) that uses helium gas heated to approximately 900°C and by high level of safety achieved in part by adoption of coated particle fuel (**Fig. 20**). In the context of the advanced gas turbine technology, this design is intended to achieve high efficiency and compact nuclear power plant which generates electrical power through the gas turbine generator directly driven by high temperature He gas heated in the reactor. MHI has participated in the development project of the world's first vertical helium gas driven turbine generator in response to request from PBMR Ltd. combining with both nuclear energy technology and gas turbine technology.

In addition, MHI has positively participated in the development of a high temperature gas cooled reactor known as GTHTR 300 which is promoted by the Japan Atomic Energy Research Institute and the development of the hydrogen production systems coupled with the high temperature engineering test reactor (HTTR).

(5) Fast Breeder Reactor (FBR)

The nuclear fuel cycle technology associated with the fast breeder reactor can remarkably increase the utilization factor of uranium resources as compared with that of the light water reactor. It can also reduce the level of radioactivity that remains for long period in the high level radioactive waste. Accordingly, from the viewpoint of realizing a long-term stable and safe supply of energy, it is urgently required to put those technology into practical use as soon as reasonably possible.

In "Feasibility Study on Commercialized Fast Rector Cycle System" currently undertaken by Japan Nuclear Cycle Development Institute, nine electrical utilities, Electric Power Development Co. Ltd, The Japan Atomic Power Company and the associated organizations, the concepts of the fast breeder reactor with economic efficiency comparable to the light water reactor are now under construction through introduction of the innovative technology. MHI is also

Fig. 19 AP1000 (conceptual drawing of expected completed plant)

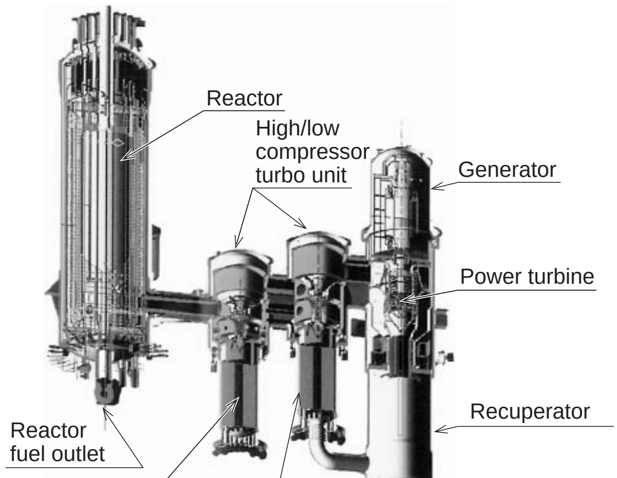

Fig. 20 Bird's eye view of PBMR

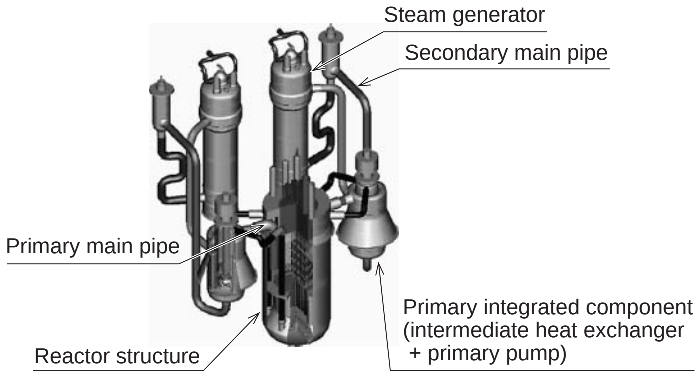

Fig. 21 Sodium-cooled, advanced loop type fast breeder reactor

actively engaged in the developments of this project. Of the technology incorporating MHI's innovative idea, the concept of the sodium cooled fast breeder reactor, as a typical example, is presented below:

For the practical use of the fast breeder reactor, it is the most important point how it can approach to the light water reactor, particularly with respect to economic efficiency. The sodium cooled advanced loop type reactor has been selected as a candidate concept for this requirement. Using the same type of sodium as in prototype "Monju" reactor for cooling system, this concept aims at significant reduction of the construction cost by introducing the novel ideas and technology such as compact reactor structures, minimized piping length by using the new materials, elimination of the numbers of loops and integrated primary system equipments (**Fig. 21**). This concept has also been nominated as a future prospective candidate model at the International Forum on Generation IV Nuclear Energy Systems. It is hoped that the "Monju" will start operation again at an early date so as to establish a base for practical use and the concept of practical fast breeder reactor will be verified at plant level.

5. Conclusion

A brief overview of the technical development activities performed by MHI, in order to assure the nuclear energy as a basic power source and realize the long-term stable energy supply in the future, has been presented above. Half a century is going to pass since Japan decided to use the nuclear power for peaceful purposes. In the mean time, Japan had experienced big changes in domestic and international economical, political and social environments. However, the starting point where Japan, as a resource-poor country, had decided to introduce the nuclear power has remained unchanged. To make this basic policy more secured, the role played by the nuclear power plant manufacturers is supposed to be important and extensive. Under the further cooperative guidance of the government, utilities and other entities concerned, MHI will continue to make every effort to assure and reinforce its technical bases for supporting the nuclear power plants, huge accumulation of various technology, and advance the new and challengeable technology toward the future.

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