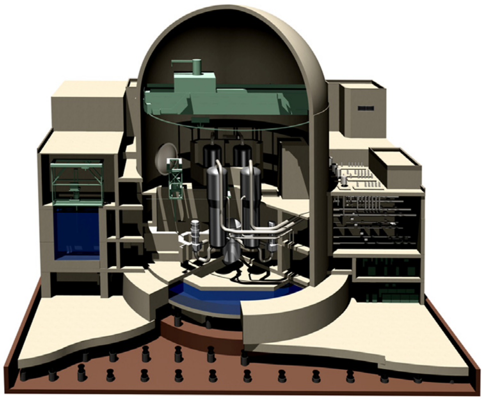
Next-generation Pressurized Water Reactor (PWR) –Development of Environmentally-friendly, Highly Effective, Economical, and 3S Achievable Autonomic Type Plant–



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MHI is developing a next-generation pressurized water reactor (PWR), featuring globally unrivalled economy and safety in the post-2030 market. MHI defines this reactor as the final PWR model that incorporates innovative advanced technologies based on the APWR design and set to become the global standard. The goal of this next-generation PWR is to achieve the three "S" elements (safety, security, and safeguard) under the basic design concepts of "environmentally-friendly", "highly effective", and "economical." This article describes the developments of those elemental technologies necessary to achieve this goal: (1) high-performance core, (2) advanced safety system, (3) seismic isolator, (4) steam generator heat transfer tube material, and (5) hull-structured containment.

1. Introduction

The development of new-generation light water reactors commenced in April 2008 as a joint program promoted by public and civil institutions: the Institute of Applied Energy (acting as host organization) and three Japanese nuclear plant manufacturers (Mitsubishi Heavy Industries, Ltd., Hitachi-GE Nuclear Energy, Ltd., and Toshiba Corporation). This article describes the design concepts and future development programs for the next-generation PWR promoted by MHI.

2. Background for Development of Next-generation PWR

Increased concerns over global warming and a steep rise in resource prices have stimulated the expanded introduction of nuclear power plants from the perspectives of energy security and CO_2 reduction. Based on such trend, the "Framework for Nuclear Energy Policy" prepared in October 2005 sets out basic government policy as follows: "Therefore, it is appropriate to aim at maintaining or increasing the current level of nuclear power generation (30 to 40% of the total electricity generation) even after 2030." In addition, the "Nuclear Energy National Plan" prepared in August 2006 states "The development of next-generation LWR should be promoted through close cooperation between the government and civil sectors and based on the outlook for domestic replacement demand and the world market." To meet domestic demand and acquire the global standard, the Ministry of Economy, Trade and Industry, Federation of Electric Power Companies, and Japan Electrical Manufacturers' Association announced the decision in September 2007 to develop a next-generation LWR, the program for which started from April 2008.

The development of the next-generation LWR will be completed within eight years from 2008 for its practical commissioning in around 2030, to cope with replacement needs arising around this period (**Figure 1**).

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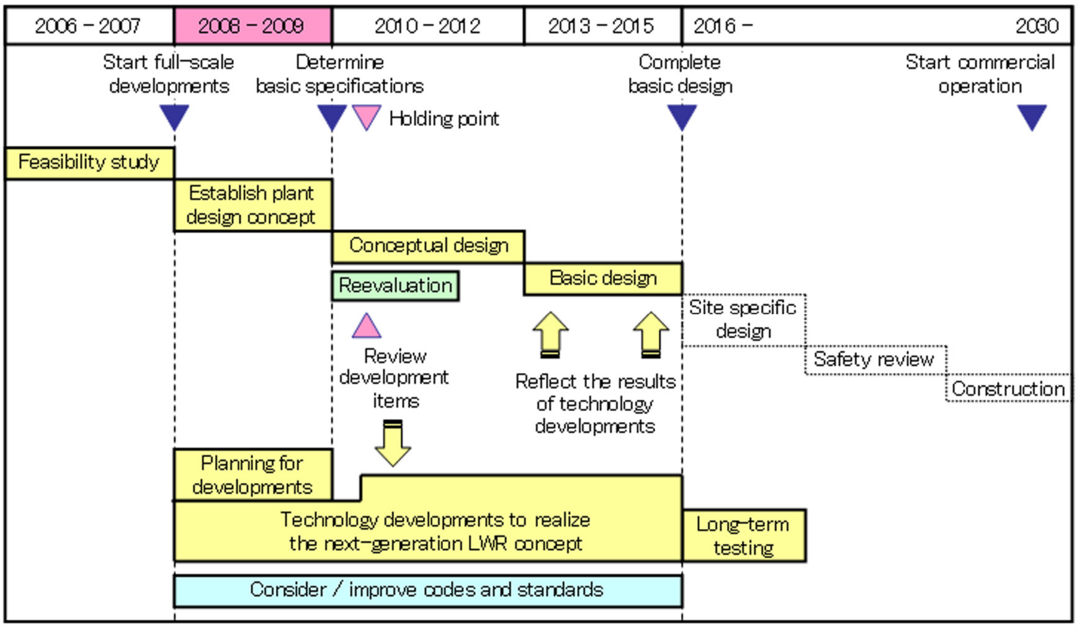

Figure 1 Next-generation LWR development roadmap

3. Concept of Next-generation PWR and Development of Elemental Technologies

3.1 Development philosophy

The next-generation LWR is a final model of a light water reactor that will meet the power demand presented by domestic power utilities and set the global standard. The next-generation PWR plant is designed based on the APWR to offer output of 1,700,000 to 1,800,000 kWe and achieve the three “S” elements (safety, security, and safeguard), striving for a basic design that is: “environmentally-friendly”, “highly effective”, and “economical.” This PWR also features an autonomous type plant. Shown below are the features to achieve such plant philosophy, which are briefly described in subsequent sections.

(1) A high-performance core that cuts the fuel cycle cost by developing ultra high burnup fuels and optimizing the fuel assembly design; drastically reducing the necessary boron concentration and boron waste generation through the positive utilization of burnable poisons and enhanced control rod performance; and an improved core safety function that can attain a subcritical state only via control rods. (See Section 3.2.)

(2) Globally unrivalled thermal efficiency (about 40 %) that offers output of 1,700,000 to 1,800,000 kWe through the introduction of an elevated coolant temperature (T_{hot}) at the core exit; steam generators featuring higher heat transfer efficiency; high-efficiency steam turbines equipped with large final-stage blades; and large primary coolant volume. (See Section 3.2.)

(3) Improved safety and security functions through the introduction of an autonomous safety system equipped with diversified final heat sinks.

(4) A standardized plant design that incorporates the seismic isolation system. (See Section 3.4.)

(5) A drastically reduced construction period through the introduction of hull-structured containment constructed with large modularized blocks. (See Section 3.5.)

(6) The development of new materials that extend the plant life to 80 years and reduce the radiation exposure. (See Section 3.6.)

3.2 High-performance core

As for the next-generation LWR, the core will be markedly improved through the development of ultra high burn-up fuels, elevation of the coolant temperature at the core exit, and optimization of the fuel assembly design, boron, control rods, and burnable poisons. The individual elemental technologies are outlined below:

(1) Ultra high burn-up fuels

New fuel cladding materials that permit ultra high burn-up will be developed to increase the average fuel assembly discharge burn-up to 90 GWd/t to attain a 24-month operation cycle and almost halve the number of replacement fuel assemblies. The ultra high burn-up will cut fuel costs by about 20 %.

(2) Elevated coolant temperature at the core exit

Along with the introduction of ultra high burn-up fuels, new materials will be developed to withstand the high-temperature environment. Consequently, the temperature of the primary coolant at the core exit is elevated to improve the thermal efficiency of the plant and thus boost electrical output by about 20 MWe.

(3) Optimization of the fuel assembly design

The employment of fuel for which increasing the volume ratio of moderator to fuel will improve the neutron moderation environment, and reduce the initial uranium enrichment and post-burning residual uranium enrichment, helping further conserve uranium resources, enhance security for nuclear materials, and reduce the fuel cycle cost (**Figure 2**).

(4) Optimization of boron, control rods, and burnable poisons

The positive utilization of burnable poisons and improvement of control rod performance will drastically reduce the boron concentration during the normal operation and shutdown stages and consequently cut boron waste generation to about 1/4 and tritium emissions to about 1/3. When the cold shutdown is implemented with control rods, the safety margin for the over cooling event will be enhanced (prevention of re-criticality events induced by over cooling).

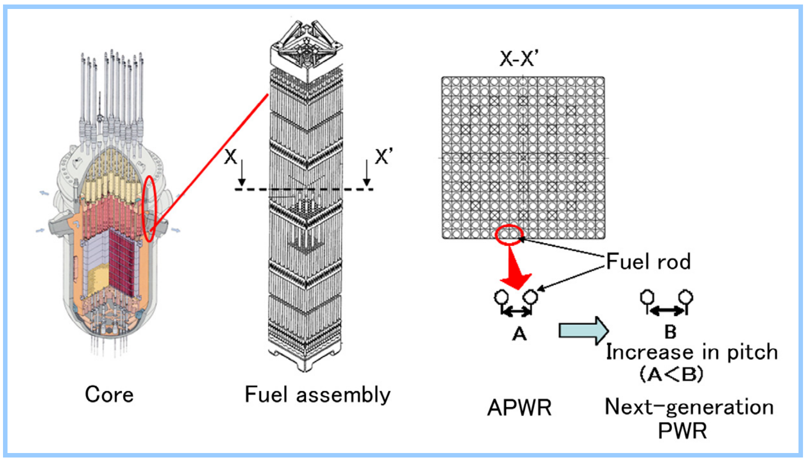

Figure 2 Optimization of the fuel assembly design - Example

3.3 Advanced safety system

The goal of the next-generation LWR is to ensure safety functions equivalent or superior to the APWR featuring globally unrivalled safety (i.e. the accident occurrence probability of the new LWR will be lower than that of the APWR) and achieve excellent economy that can be accepted in 2030. The next-generation LWR will incorporate a simple and highly reliable autonomous safety system instead of relying on CCWS (component cooling water system) and SWS (sea water system) to cool the reactor and containment if a primary coolant pipe break accident or emergency situation were to occur (**Figure 3**). The autonomous safety system employs a direct cooling cycle, where the external air is used as a final heat sink. In addition, the active network of this system consists of four trains allowing in-service maintenance.

The next-generation PWR defines CCWS and SWS as non-essential systems while they have been used to transport the heat to the final heat sinks in conventional plants during normal plant operation and accidents. This system configuration can combine the safety system using the open air as a final heat sink with a non-essential system using the sea water as a final heat sink to diversify the latter. The combination of these systems offers guaranteed cooling performance in emergencies. To make this diversified configuration economically viable, the PWR, which is equipped with steam generators, will permit the steam generators to cool and depressurize the reactor coolant system and inject the boric acid water into the core via low-pressure injection pumps if an accident were to occur. Therefore, high-pressure injection pumps are removed from the next-generation PWR. Allowing the low-pressure injection pump to serve as a containment spray pump simplifies the safety system: i.e. the number of safety-related pumps is reduced to one per train. In the next-generation LWR, these low-pressure injection pumps and air-cooled cooling equipment are installed as a bundle in the seismically-isolated reactor building to enhance resistance to earthquakes and tsunamis.

In future, MHI will implement comprehensive verification tests to examine the performance of the entire advanced safety system during accidents.

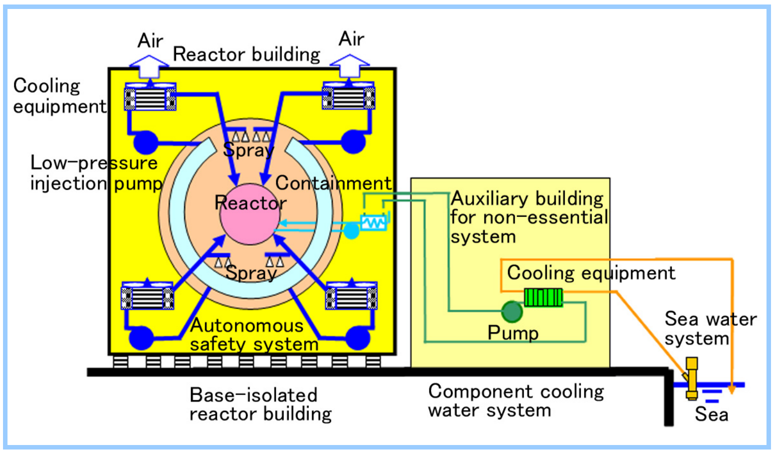

Figure 3 Advanced safety system diagram (schematic)

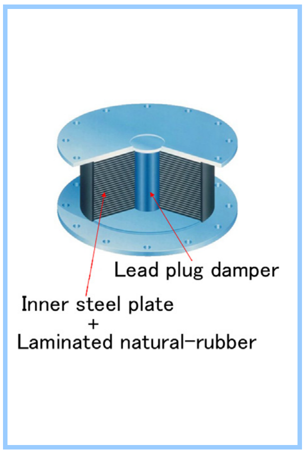

Figure 4 Seismic isolator

3.4 Seismic isolator

To achieve the objective of "establishing standardized plants that will not be influenced by site conditions through the introduction of seismic isolation technologies," MHI, in corporation with other plant makers, is developing seismic isolators fit for nuclear power plants.

Nuclear power plants already constructed in Japan have been designed based on the seismic conditions of their installation sites. Therefore, if the seismic conditions require a change in the design parameters such as the wall thickness and the floor area of the reactor building, such design change must be implemented on a plant-by-plant basis, which has prevented the standardization of plants and increased the construction costs.

The seismic isolator (**Figure 4**) that considerably reduces the seismic accelerations has recently become popular among general buildings in Japan. When this seismic isolation design is applied to buildings in nuclear power plants to eliminate site-to-site variation in seismic conditions, it is possible to construct nuclear power plants based on a standardized seismic design and eliminate site-specific seismic conditions, helping ensure complete plant standardization. In addition, not only can building structures and supports in various facilities be simplified but an increased safety margin is also expected to permit the plant to endure even major earthquakes that exceed the design basis seismic conditions.

With regard to the licensing procedures required for the introduction of a seismic isolation design, the "Seismic Design Review Guideline for Nuclear Power Reactor Facilities" was revised on September 19, 2006 and the bedrock support requirements, which were prescribed in the basic policy statement of the former version, were deleted, making it possible to use the seismic isolation design for nuclear power plants in Japan. The JEAG4614-2000 "Technical Guideline for Seismic Isolation Structure Design on Nuclear Power Stations", which is a civil standard stipulating the seismic isolation technologies, has been established. Under this civil standard, however, the behaviors of the seismic isolator observed under the simultaneous input of direct horizontal and vertical movements (which are indispensable parameters to apply the design conditions defined in the revised "Seismic Design Review Guideline for Nuclear Power Reactor Facilities" above to the next-generation reactors) have not been executed; the seismic isolator's strength at the input of seismic accelerations generated from the earthquake and exceeding the design basis has not been examined; and performance tests via full-scale seismic isolator model have not been implemented. For this reason, we must verify the behaviors and performance of the seismic isolator to establish design and evaluation methods.

With this in mind, through this development program, we will determine the building seismic isolation design for the next-generation LWR, and conduct performance tests under direct horizontal and vertical movement conditions and ultimate force application tests using the full-scale seismic isolator model, vibration tests using the simulated building model mounted on the seismic isolator, and integrity verification tests for the piping arranged between buildings to demonstrate the validity of the seismic isolation design, establish the evaluation methods, and verify the safety margin of the seismic isolator.

Presently, basic tests that target the fundamental performance of the reduced-size seismic isolator have been completed and a study is now underway aiming to implement building seismic response analysis for the next-generation LWR and determining the specifications for the seismic isolator used in the buildings of the same. Subsequently, we will conduct verification tests by using the full-scale seismic isolator model discussed above.

3.5 Development of steam generator heat transfer tube material

To achieve the objective of “fusing new materials and water chemistry to achieve plant life of 80 years and drastically reduce the radiation exposure during maintenance”, MHI is developing new materials for steam generator (SG) heat transfer tubes.

In existing PWRs, SG heat transfer tubes are made of specially heat-treated GNCF690 (TT690 alloy), with outstanding resistance to primary water stress corrosion cracking (PWSCC). NCF600 (TT600 alloy), which is a former SG heat transfer tube material, is susceptible to PWSCC; hence SCC was generated on this material in actual plants. On the other hand, the SG heat transfer tubes made of TT690 alloy did not crack in the actual plants and neither was any cracking reported in a PWSCC test executed under accelerated test conditions for several tens of thousands of hours. Based on these results, we think the damage to SG heat transfer tubes by PWSCC will be completely eliminated through the introduction of the TT690 alloy.

In the secondary system, some troubles have been reported on the SG heat transfer tubes made of TT600 alloy: i.e. minor intergranular stress corrosion cracking (IGA) was generated in the minute gap between the tube and tube sheet or the tube support since impurities are easily concentrated there. The TT690 alloy has also been shown to offer higher resistance to IGA than the TT600 alloy and no cracking in the secondary system has yet been reported in actual plants. However, it has emerged in laboratory tests that the TT690 alloy has IGA susceptibility in an alkaline environment. Therefore, materials less susceptible to IGA for next-generation LWRs designed to operate over 80 years (target design life) must be used under elevated coolant temperature conditions.

The SG heat transfer tubes for the next-generation LWR must offer improved heat transfer efficiency, in addition to the increased corrosion resistance required from the perspective of the extended design life discussed above. To improve the plant thermal efficiency, the efficiency of the heat transfer to secondary systems must be enhanced, making it necessary to improve the heat transfer characteristics of the SG heat transfer tubes. Concrete measures include: the use of materials featuring higher thermal conductivity and reinforcing the strength of the tube to reduce its wall thickness.

The occupational radiation exposure in Japanese nuclear plants is higher than the international level. To reduce the former, it is important to improve the efficiency of maintenance works, use the working time efficiently, and reduce the dosage in the working environment. Therefore, we must study direct measures that can rationally reduce the radioactive corrosion product, or radiation sources.

As discussed above, MHI is developing SG heat transfer tube materials that limit the resistance to PWSCC in the primary system, ensure resistance to IGA in the secondary system, offer better heat transfer characteristics compared to the TT690 alloy tubes, and reduce radiation exposure.

MHI selected ten steel materials as candidates in the desk plan and have been presently implementing various fundamental tests to limit the candidates to two materials or so. Subsequently, MHI will conduct long-term corrosion tests with the application in actual plants in mind.

3.6 Hull-structured containment

One of the development objectives of the next-generation LWR is a construction period reduced as short as 30 months from the investigation of bedrock to the start of operations. Presently, shortening the containment construction period is one of the critical factors for reducing the entire plant construction period. Constructing the containment using the large block prefabrication method is effective in shortening the construction period, making it necessary to design the containment structure accordingly. In current large PWR plants, a pre-stressed concrete containment vessel (PCCV) is used for the standard containment design and a structure has been employed whereby tendons (pre-stressed members) are mounted inside the structural body comprising reinforcing steels and concrete via liner steel plates. To build this structure, inner liners are constructed, reinforcing steels and tendons are assembled, molds are set outside the substructure, and filled with concrete. The concrete is repeatedly deposited using many lifts, thus extending the construction period. For this reason, MHI is developing containment that features a simplified structure and uses a large modular construction. After MHI studied the potential to reduce the construction period based on past construction experience, we selected a steel plate structure free of tendon sheaths. This structure is the same as that used for ships where the hull is constructed with large modular blocks. For the next-generation PWR, concrete is filled in this hull structure to construct the containment and MHI considers it the most effective approach to reduce the containment construction period.

Figure 5 shows the modularized hull-structured containment. Assuming the use of an ultra large crane, a single module weighs about 1000 tons. Consequently, the containment cylinder is divided into four modules and the dome into two. These six modules alone can form the entire containment. Although the construction of the hull-structured containment requires several prerequisites, including a large crane with hoisting capacity of 5000 tons and the working space necessary for assembling the large modules in the vicinity of the reactor, as well as considerable electric power for assembling (welding) these large modules within a reduced period of time, a relatively short construction period is expected.

Since the containment must confine radioactive materials, shield the radiation after the occurrence of an accident, and protect the reactor from ex-plant missiles, as well as reducing the construction period discussed above, MHI will study its structure and performance based on these requirements to establish the necessary specifications and standards and subsequently verify the ease of construction.

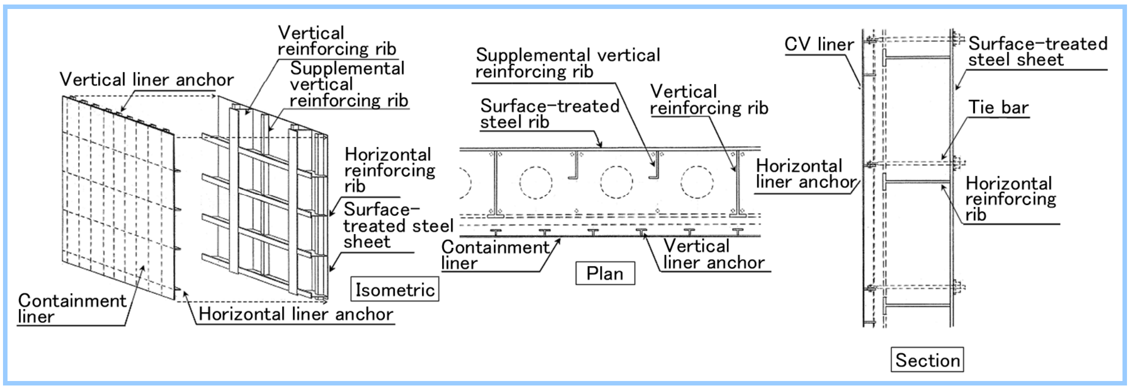

Figure 5 Hull structure (schematic)

4. Future Plan and Prospects

T As discussed above, the next-generation LWR will be developed under an eight-year program. The first two years are to be used to execute the design study in order to evaluate the plant concept. We will then implement a comprehensive evaluation at the hold point in fiscal 2010 to review the program plan for the remaining years. MHI will promote the development of next-generation PWR on our own responsibility so that the new PWR will be an attractive plant from the viewpoints of power demand in Japan and acquisition of the global standard.

5. Conclusion

MHI is now developing a conceptual design for the next-generation PWR by using the APWR, which has been created based on our accumulated experiences and technologies, as a starting point for the design with the objectives of power security in Japan and the acquisition of the global standard. MHI will promote the development toward the evaluation at the hold point under guidance from both the government and power utilities.

Acknowledgment

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Reference

1. Next Generation Light Water Reactor, distributed document at The AESJ Summer Seminar 2009, The Institute of Applied Energy