Development of Next-generation Boiling Water Reactor for Era of Large-scale Plant Construction

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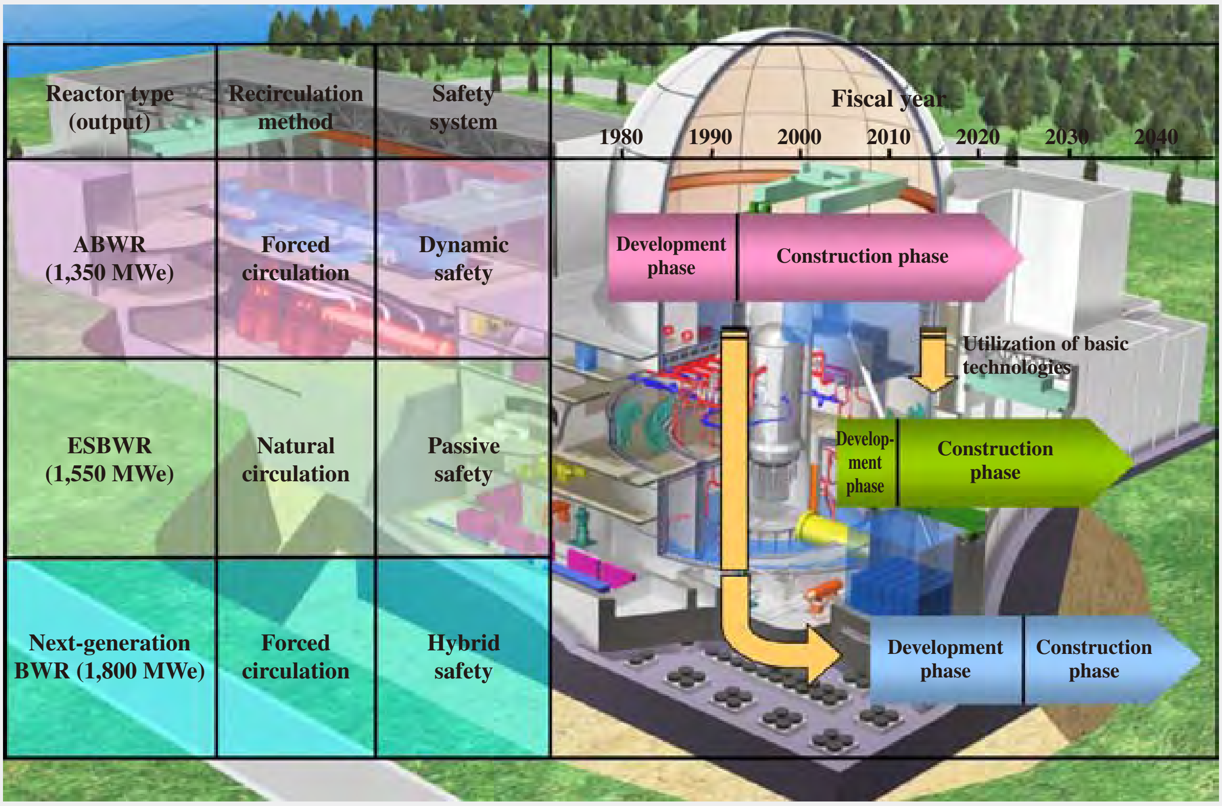
OVERVIEW: Internationally, the construction of nuclear power plants is gaining momentum as many nations re-evaluate nuclear power as an effective means of countering global warming and as an important source of electricity that can supply energy reliably. In response to the globalization of this market, Hitachi, Ltd. has merged its business with General Electric Company, a company with which it has worked as a partner since first getting involved in the nuclear power industry, to form Hitachi-GE Nuclear Energy, Ltd. in Japan and GE-Hitachi Nuclear Energy Americas LLC in the USA. Hitachi has a successful history of completing the construction of more than 20 plants. During this time, Hitachi has progressively improved safety and increased capacity, culminating in the completion of the ABWR, and subsequently is continuing to build on its unbroken record in plant construction (see Fig. 1). Based on this extensive experience, Hitachi will continue to offer solutions for expanding nuclear power globally centered around the Japanese and US companies.



BWR: boiling water reactor ABWR: advanced BWR ESBWR: economic and simplified BWR

Fig. 1—Development of Next-generation BWR.
Based on the successful development of the ABWR, Hitachi is undertaking design and testing work in collaboration with General Electric Company (GE) aiming practical use of the ESBWR, and is also involved in a national public-private project to develop a next-generation BWR in preparation for the period of large-scale plant construction that will occur during the 2030s and later.

INTRODUCTION

A growing "nuclear renaissance" is taking place around the world. The background to this renaissance is nuclear energy's role as an effective way of responding to global energy issues including the sudden jump in energy prices, the importance of energy security, and global environmental problems. Another factor worth noting is that, in the USA where construction of new nuclear power plants has been on hold since the 1979 accident at the Three Mile Island Nuclear Power Plant, a shift in policy toward greater use of nuclear power took place under the Bush administration against the background of the favorable operational record of nuclear power plants in recent years, and the current Obama administration has also instigated various policies to encourage new construction at the government's initiative.

Outside the USA, plans to construct new nuclear power plants are underway in many countries including in China, India, and South East Asia (see Fig. 2). Japan too is facing the prospect of an extensive period of replacement projects around 2030 when it will be necessary to replace the many nuclear power plants built during the height of construction in the 1970s and 1980s.

Against the background of this global recovery in nuclear power, an eight-year national project to develop a new light-water reactor commenced in 2008, the first such project in the 20 years since the development of the ABWR (advanced boiling water reactor). The project is being undertaken by the government, electricity companies, and plant makers working together and Hitachi is playing a major role.

This article describes the international situation for nuclear power and Hitachi's involvement in the development and global deployment of nuclear power generation equipment to facilitate the wider and smoother adoption of nuclear power as key factor for achieving environmental improvements on a global scale.

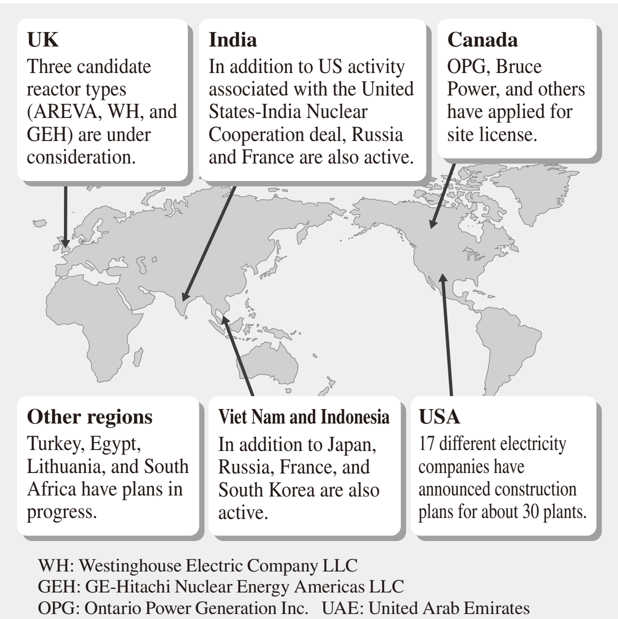


Fig. 2—Global Expansion of Nuclear Renaissance.
Nuclear power generation has a role as an effective means for solving global energy issues and plans to construct new nuclear power plants are underway in various countries.

INTERNATIONAL SITUATION FOR NUCLEAR POWER

Although the international market for nuclear power is gaining momentum, there is also an awareness of the many issues associated with the construction of nuclear power plants.

The first issue is the problem of nuclear non-proliferation and with the growth in the number of countries adopting nuclear power there is a movement to put in place an international framework to achieve both nuclear non-proliferation and an increase in peaceful use of nuclear power generation. In addition to the GNEP (Global Nuclear Energy Partnership) proposal from the USA and Russia's "International Nuclear Fuel Cycle Center Plan," Japan is also looking to be an active participant in the creation of such international frameworks, including support for the international expansion of the nuclear power industry as part of its "Nuclear Energy National Plan."

The second issue is the investment risk that new plants pose to electricity companies because of the very large initial investment required to construct a nuclear power plant. How to finance this investment, how to manage the investment payback period, and cost-related risk management factors including the escalating cost of materials, personnel and other inputs and the lengthening of construction schedules are also issues.

The third issue relates to the technical capabilities of suppliers. The number of new nuclear power plant construction projects fell from the mid-1970s and new construction over the past ten years has been concentrated in a small number of Asian countries, namely Japan, China, and South Korea. This has given rise to concerns that suppliers of nuclear power plant equipment and the construction industry in Europe and America lack experience. This in turn has led to raising expectations for Japanese companies because of their ongoing genuine construction experience, capabilities for producing key items of plant, and other attributes.

These factors indicate that, in addition to international cooperation at a government level, international collaborations in the supply and construction of nuclear power technology and plant will also be an important strategy for responding to the growing nuclear power market.

INVOLVEMENT WITH GLOBALIZATION

The two main reactor types competing in the international nuclear power market are the BWR (boiling water reactor) and PWR (pressurized water reactor). The BWR has a simple direct-cycle configuration in which the generated steam is supplied directly to the turbine and has primarily been developed in Japan and the USA. The BWR has many advantages for nuclear power plants and, to expand its global deployment, Hitachi and General Electric Company (GE) have concluded that it is important that they adopt a common strategy and merge their business resources and, to this end, they are proceeding with various measures including undertaking joint research, sharing design resources, and encouraging joint purchasing and shared use of manufacturing facilities. To the global presence that is underpinned by GE's track record, Hitachi can add its strength in "manufacturing capabilities," its "comprehensive engineering capabilities" based on unbroken experience in the construction of nuclear power plants, and also "research and development capabilities" that support future business development, and by doing so offer solutions for the global expansion of nuclear power.

Global Application of ABWR Construction Experience

Hitachi has built up experience from the construction of more than 20 plants in the nearly 40 years since participating in the construction of Japan's first BWR, and during this time has worked to improve their reliability, safety, and economics while building up its own store of innovations and ideas with a meticulous focus on *monozukuri* (manufacturing ethos). The ABWR was jointly developed between 1981 and 1986 with various BWR plant operators (electricity companies), GE, and Toshiba Corporation to standardize third-generation enhancements and the reactor represents the culmination of Japan's technical experience, with four of these ABWR plants currently in operation in Japan. Also, currently under construction are Unit 3 of the Shimane Nuclear Power Station of The Chugoku Electric Power Co., Inc. and the Ohma Nuclear Power Plant of Electric Power Development Co., Ltd. Hitachi is involved in the construction of all of these ABWRs. By taking advantage of this extensive experience, Hitachi has the following strengths.

(1) In addition to an extensive operating track record, certification risk can be minimized in the USA also because GE-Hitachi Nuclear Energy Americas LLC (GEH) has already acquired design certification.

(2) The risk of changes in procurement or installation costs can also be reduced because material quantities can be determined at an early stage by making effective use of the engineering data acquired through extensive construction experience.

(3) Advanced construction techniques using large cranes, large modules, and other methods solve problems such as obtaining local workers and construction project management which pose the greatest risk to the schedule.

In April, 2008 Hitachi and GEH jointly established the ABWR Project Office at San Jose, California in the USA with the objective of winning orders for the ABWR and facilitating the trouble-free construction of ABWRs in other countries. The aim is to create a standard international ABWR (unified ABWR) based on the latest ABWR design, construction experience, and other contributions from Japan that also complies with US regulatory requirements, international standards, and other rules.

ESBWR Performance Verification Using Large-scale Test Facilities and Advanced Simulation Techniques

Together with the ABWR, the ESBWR (economic and simplified BWR) is an important reactor for the global rush to construct nuclear power plants. The ESBWR is a simplified reactor with a large output that uses the same simple reactor system concept that is a feature of the BWR, and uses natural circulation and passive safety systems to eliminate moving parts and reduce the amount of equipment required while also reducing operation and maintenance costs (see Fig. 3).

GE is taking the lead role in working toward acquiring US design certification in early 2011 and Hitachi is providing support in areas such as equipment performance analysis and performance evaluation that are part of the approval process.

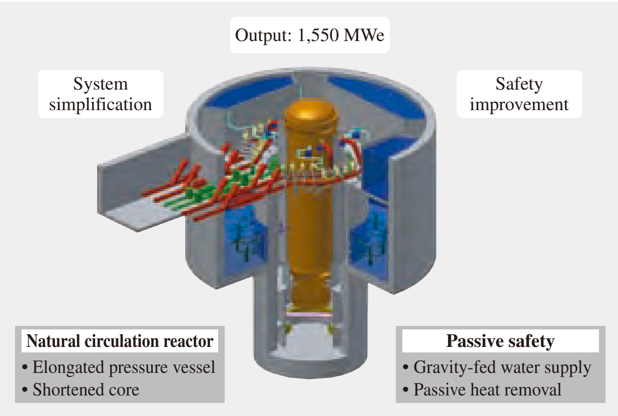


Fig. 3—ESBWR Features.
The ESBWR uses the same simple reactor system concept that is a feature of the BWR but seeks to improve economics by eliminating moving parts and lowering construction, maintenance, and other costs.

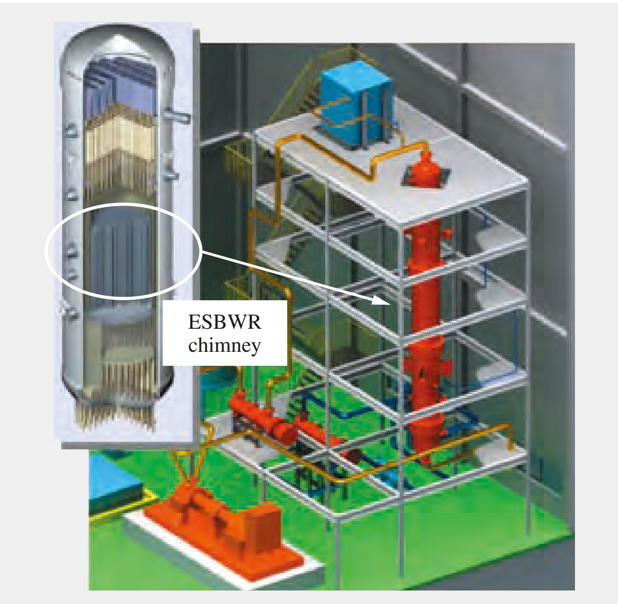


Fig. 4—HUSTLE (Hitachi Utility Steam Test Leading Facility) for Multi-purpose Steam Generation Test.
Comprehensive performance evaluation tests were conducted on the chimney which is the most important component of the ESBWR.

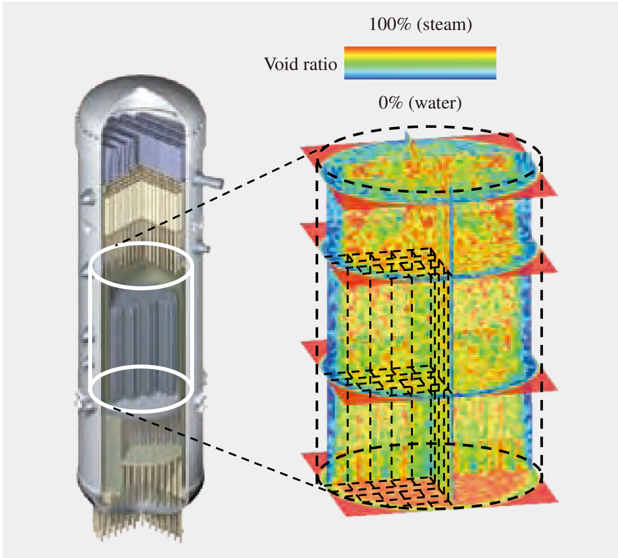


Fig. 5—Analysis of Combined Reactor and Chimney.
The experimental data was verified by 3D (three-dimensional) two-phase flow analysis to evaluate the natural circulation performance of the ESBWR.

The natural circulation performance that is the most significant feature of the ESBWR achieves the required core flow by locating a chimney on top of the reactor core so that the difference in fluid density provides the driving force. With a height of approximately 7 m and diameter of 6 m, the chimney is a large internal structure in the reactor. The chimney is the most distinctive and important component of the ESBWR and to determine the two-phase flow performance, robustness, and manufacturability, Hitachi fitted an actual-scale test chimney (height: 7 m) to its HUSTLE (Hitachi Utility Steam Test Leading Facility) test facility which is capable of reproducing the same temperatures and pressures that are used in an actual reactor and which was completed in 2008, and undertook comprehensive performance evaluation trials (see Fig. 4).

The results of a 3D (three dimensional) two-phase flow analysis were verified using experimental data and the natural circulation performance of the ESBWR evaluated through an analysis of the combined reactor and chimney (see Fig. 5).

Range of Reactor Type Developments to Meet Customer Needs

For locations such as Japan or the advanced nations of Europe and America that have extensive transmission networks able to cope with high electricity demand, the key task is to develop large centralized sources of electric power with high performance. On the other hand, there is also a need for power sources for places where electricity demand is expected to grow but the transmission capacity and other infrastructure are limited, and for users who are uncertain about the growth in electricity demand and consider it necessary to diversify their investment in accordance with market trends. It is believed that supplying nuclear power plants that can respond flexibly to these needs will contribute to the wider global adoption of nuclear power. Fig. 6 shows Hitachi's range of reactor type developments which, in addition to adopting economies of scale and

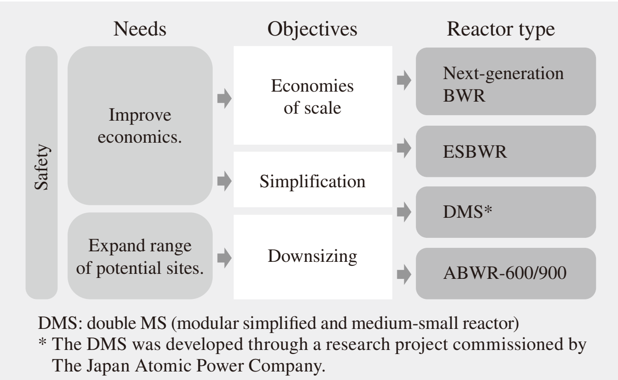


Fig. 6—Development of Reactor Types to Suit Diverse Needs.
Hitachi is working on the development of reactor types to suit a wide range of needs including improving economics and increasing the scope of potential sites while keeping safety as the key focus.

simplification in pursuit of economic benefits, also aim to achieve downsizing to expand the scope of potential sites to include emerging economies.

Hitachi is working on enhancing the ESBWR and ABWR, and is developing a large reactor as part of the national project to develop the next generation of BWRs that is described later in this article. Working on its own, Hitachi has also developed medium-sized ABWRs (the ABWR-600 and ABWR-900) for use as distributed power sources in regions where transmission capacity and electric power demand are low. In a research project commissioned by The Japan Atomic Power Company, Hitachi is also working on the development of the DMS [double MS (modular simplified and medium-small reactor)], a 400-MWe-class naturally circulated BWR designed to meet the demand for small-capacity plants.

DEVELOPMENT OF NEXT-GENERATION BWR

Basic Development Plan

In preparation for the period of large-scale plant replacement that will occur from around 2030 and to meet the global expectations for nuclear power in Japan's role as the leading country in this field, Hitachi is for the first time in the 20 years since the development of the ABWR again involved in a large-scale national project to develop the next generation of light-water reactors. Taking guidance from electricity utilities and the government, the nuclear power industry including other plant manufacturers (Toshiba Corporation and Mitsubishi Heavy Industries, Ltd.), Global Nuclear Fuel-Japan Co., Ltd. (GNF-J), and general contractors are coming together to work vigorously on this project with The Institute of Applied Energy taking a central role.

The following basic design plan has been established for the next-generation BWR to produce a standard reactor not only for Japan but also for the world based on requirements that include the requests of power utilities with extensive operating experience gained over many years, the requests of overseas power companies, and the requirements for nuclear power generation equipment in the 2030s and beyond based on forecasts of future industrial growth.

(1) Achieve levels of both safety and economics that are in the top class worldwide.
(2) Dramatically shorten time required for construction and standardize to make independent of site conditions.
(3) Dramatically reduce the quantity of spent fuel produced and reduce consumption of uranium.
(4) Dramatically reduce the quantity of radioactive waste and exposure to radiation.
(5) Improve performance across total plant life (80 years).

The plant concept was formulated based on this basic plan and development is underway on specific technologies required to realize the concept.

Plant Concept and Development of Specific Technologies

Hitachi is working on the development of the key technologies that are required to implement the plant concept which is based on the basic design plan for the next-generation BWR. The main features of this development are described below (see Fig. 7).

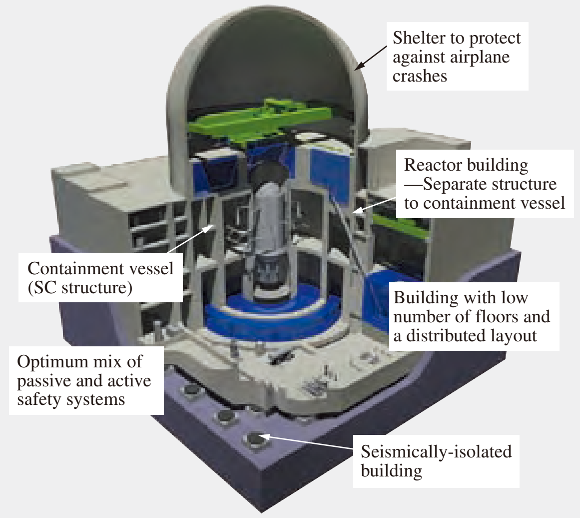
Core enhancements to reduce burden on environment

(1) Significant reduction in quantity of spent fuel

Current BWRs use fuel cladding tubes made of zirconium alloy and have an average discharge fuel burnup of approximately 45 GWd/t and fuel bundle average maximum fuel burnup of 55 GWd/t. The aim for the next-generation BWRs is to reduce the burden on the environment by lowering the amount of spent fuel to 30 to 40% of the previous amount with an average discharge fuel burnup of 70 GWd/t.

Because hydrogen absorption in the fuel cladding tubes tends to increase in this ultra-high burnup range, there are concerns about embrittlement and corrosion. In a joint venture with fuel producer GNF-J, Hitachi-GE Nuclear Energy, Ltd. is working on developing an ultra-high burnup fuel for fuel cladding tubes (hydride-free material) that suppresses hydrogen absorption and

Electrical output	1,700 to 1,800 MWe
Recirculation system	Forced circulation (RIP)
Safety system	Three active safety systems Passive safety system (SA)
Containment vessel	SC-PCV
Construction time	30 months
Utilization	97% or better



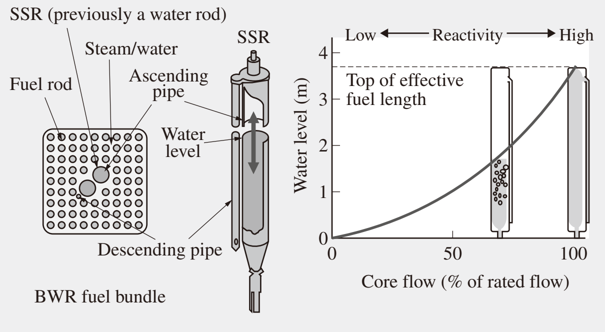
RIP: reactor internal pump SC: steel plate reinforced concrete
SA: severe accident PCV: primary containment vessel

Fig. 7—Overview of Main Equipment Used in Hitachi's Next-generation BWR.
With the aim of producing an internationally standardized reactor, Hitachi has devised a plant concept in which the main specifications and requirements common to all countries are treated as standard features and variations to suit the circumstances in specific countries as offered as options.

is resistant to corrosion.
(2) Technology for significantly reducing uranium fuel consumption

Reducing consumption of uranium resources is a particularly important part of ensuring a reliable energy supply. In addition to adopting ultra-high fuel burnup to conserve uranium, the next-generation BWR can reduce uranium consumption by 10% or more by using technology that takes maximum advantage of the spectrum shift effect that is one of the characteristics of BWRs. BWRs use spectrum shift operation whereby the core flow rate is progressively reduced from the start to the middle part of the fuel cycle to promote the formation of the fissionable isotope Pu 239, and then the core flow rate is increased again toward the end of the fuel cycle to encourage the fission of this Pu 239 which increases the energy produced from each unit weight of uranium.

Hitachi has started work on developing technology to facilitate the introduction of improved water rods called spectrum shift rods that provide even greater uranium savings by using them in place of the water rods used in previous fuel bundles to enhance the spectrum shift effect achieved by changing the reactor core flow as described below (see Fig. 8).



SSR: spectrum shift rod

Fig. 8—Spectrum Shift Rod Fuel.
Spectrum shift rod technology is under development to enhance the spectrum shift effect by changing the core flow to improve on the efficiency of uranium use.

Enhancements to construction techniques that are not dependent on construction environment

Hitachi aims to shorten significantly the construction time by making it possible for work on the cylindrical building housing the containment vessel and work on other peripheral buildings to proceed in parallel. The standard design keeps the number of floors in the building to a minimum to facilitate modularization and shorten construction time. Because this configuration allows for flexibility in the building layout design regardless of the containment vessel shape, country-specific options can also be incorporated easily.

SC (steel plate reinforced concrete) structures are a way of significantly reducing the work associated with steel bars and formwork and enabling the modular construction of large blocks, and are seen as an important technology for coping with the international rush to construct new nuclear power plants. This new construction technique will play a key role in achieving the aim of significantly shortening the construction time for the next generation of BWRs from the 50 months that is currently normal to about 30 months.

In the next-generation BWR, the intention is to use the SC structure for the nuclear reactor containment vessel, which takes up a large part of the critical path for plant construction, as well as in other key components. Accordingly, there is a need to confirm the SC structure's earthquake resistance and ability to withstand pressure under high-temperature conditions. Hitachi is undertaking basic testing to confirm the performance of the SC structure under the high-temperature conditions anticipated to apply in the actual plant, utilizing its extensive design and manufacturing technology for nuclear reactor containment vessels and the close organizational relationships it has built up with construction contractors over the past (see Fig. 9).

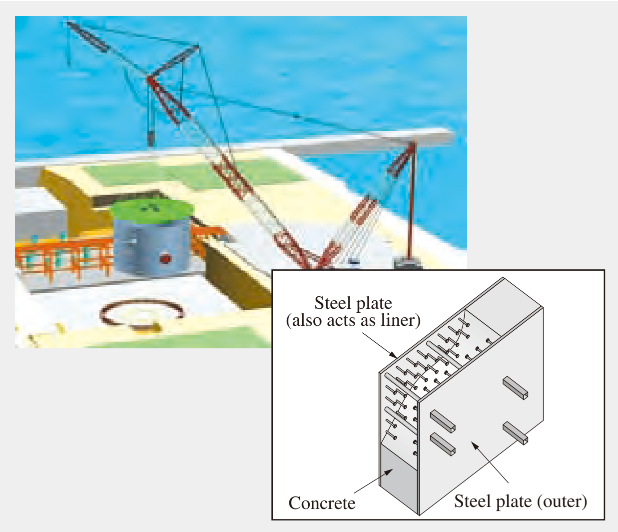


Fig. 9—SC Structural Technique.
The SC structural technique significantly reduces the work associated with steel bars and formwork, and planning of performance confirmation tests is underway to enable this technique to be used in major components as well as in the reactor containment vessel.

Technologies that provide flexibility to comply with environmental and regulatory requirements in different countries

If the nuclear power plant is to be widely adopted in the global market from 2030 and beyond, it is essential that the plant concept provides excellent economics while also being capable of modification to comply with the regulatory, electricity system, and site requirements of each country. To satisfy all of these requirements in a realistic way, Hitachi is aiming for a design that treats factors such as the basic performance and the requirements common to all countries as standard features and offers variations to suit the circumstances in specific countries as options, and that also makes it easy to incorporate new options.

In addition to estimating the probability of an airplane crash occurring at existing nuclear power facilities, a next-generation BWR that aims to become an international standard for reactors also needs to consider measures at the level of the plant equipment. In considering measures for withstanding an airplane crash, it is important to provide protection through the reactor building and frame and also protection through spatial separation. To provide protection through the reactor building and frame, the design needs to make the walls thick enough to withstand the expected impact that the flying object would impart. Protection through spatial separation requires that the location of equipment be distributed depending on the type of safety system because of the possibility of simultaneous damage to multiple systems, depending on the crash trajectory.

Other development work includes: (1) improvements in material and water chemistry that will provide the basis for the aim of extending plant life to 80 years, (2) establishing the fundamental technologies required to handle fuel with uranium enrichment levels above 5% that are a necessary prerequisite both for the adoption of ultra-high fuel burnup and the improvement of plant availability by adopting a longer operation cycle (24 months), (3) developing seismically isolated equipment that compliment the existing advanced earthquake-resistant technologies developed in earthquake-prone Japan with further risk reduction over and above the earthquake force assumed in the design and standardizing the plant design and thereby widening the range of potential sites, and (4) development of plant digital systems that will improve operational performance over the entire life of the plant (design, manufacture, construction, operation, maintenance, and decommissioning).

In this way, Hitachi is taking a leadership role in the technical side of this project by bringing together the development technologies it has accumulated over the past.

CONCLUSIONS

This article has described the international situation for nuclear power and Hitachi's involvement in the development and global deployment of nuclear power generation equipment to facilitate the wider adoption of nuclear power as a key factor for achieving environmental improvements on a global scale.

To expand steadfastly the use of nuclear power generation internationally as an effective countermeasure against global warming and to continue to enhance the BWR and bring it to the global market, it is necessary to refine the technical strengths of Japan (especially its construction technology) that are a focus of interest and expectation from the rest of the world and to prepare for the coming era of large-scale construction.

Based on its extensive and unbroken experience in construction and its success in developing the ABWR, Hitachi is working on the development of a number of different revolutionary reactor types that respond flexibly to the diverse needs of the era of the nuclear renaissance and intends to make a major contribution to a trouble-free expansion in the use of nuclear power in the era of large-scale construction.

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