Development of Next-generation Boiling Water Reactor

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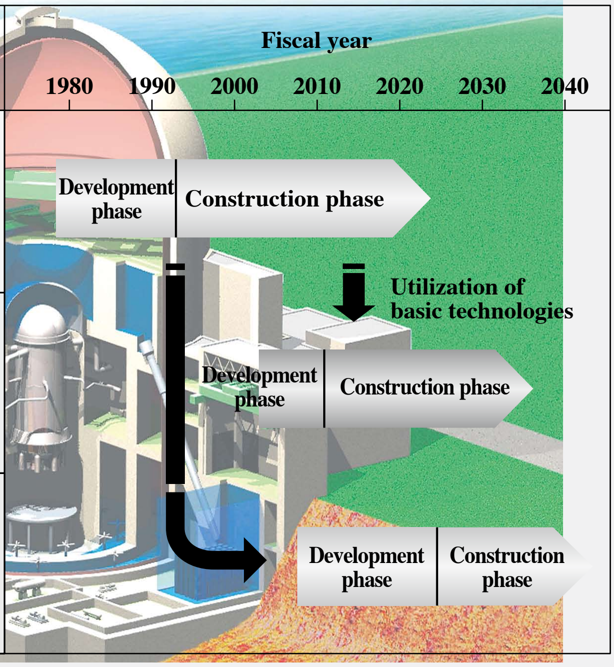
OVERVIEW: Since its participation in the construction of the BWR at the Tsuruga Power Station Unit 1 (357 MWe) for The Japan Atomic Power Company in 1970, Hitachi has successfully completed the construction of more than 20 nuclear power plants. Plant reliability and output levels have improved since that time, and during 1996 and 1997 Hitachi joined with General Electric Company of the USA and Toshiba Corporation to complete construction of the first two ABWRs at Units 6 and 7 of the Kashiwazaki-Kariwa Nuclear Power Station of The Tokyo Electric Power Company. Since then, Hitachi has undertaken a wide range of nuclear reactor development work to meet the needs of customers based on its experience handling the design and construction of all ABWRs to date, both in and outside Japan, and including plants in the planning stage. Now, for the first time in about twenty years, a national project has been initiated in Japan to develop a new light water reactor. In addition to playing a leading role in this project, Hitachi is also working with GE in the USA on design and confirmation testing as part of the ESBWR development project.

INTRODUCTION

BASED on the BWR (boiling water reactor) introduced from General Electric Company (GE) of the USA, Hitachi has worked to improve the

Reactor type (output)	Recirculation method	Safety system
ABWR (1,350 MWe)	Forced circulation	Dynamic safety
ESBWR (1,550 MWe)	Natural circulation	Passive safety
Next-generation BWR (1,800 MWe)	Forced circulation	Hybrid safety system



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

Fig. 1—Development of Next-generation BWR.
Based on its successes in the development of the ABWR, Hitachi is collaborating with General Electric Company on design and confirmation testing work to commercialize the ESBWR, and development of a next-generation BWR is underway as part of a national project run as a public-private partnership that is looking ahead to the era of large-scale construction projects in the 2030s and beyond.

reliability, safety, and economics of its products through the relentless pursuit of manufacturing excellence, and during this time has built up its own innovations and ingenuity. The development of the ABWR (advanced boiling water reactor) represented a culmination of Japan's technical experience. The reactors were developed between 1981 and 1986 as a joint effort with BWR operators, GE, and Toshiba Corporation as part of the third generation of improvement and standardization, and with four plants currently in operation in Japan and two under construction, a steady track record has been built up in ABWR construction. The reactor is also seen as a candidate for construction projects outside Japan. The ABWR is expected to remain one of the main reactor types selected for construction.

Also, against a background of concern about how to obtain reliable supplies of fossil fuels such as oil and coal, construction of nuclear power plants is gathering momentum around the world as an effective tool for preventing global warming and, in July 2007, Hitachi merged its nuclear power business with that of GE. As well as taking maximum advantage of its synergies with GE, Hitachi believes in the importance of developing nuclear power equipment that meets diverse needs from around the world.

In Japan, around the year 2030 is expected to be the start of a period in which the many nuclear power plants constructed in the 1970s and 1980s are replaced. Against the background of this resurgence in nuclear energy which has been dubbed a worldwide "nuclear renaissance," Japan launched an eight-year-long national project in 2008 that brings together the public and private sectors.

This article looks at the directions being taken in the development of nuclear power equipment for the era of the "nuclear renaissance" and the current state of this development (see Fig. 1).

HITACHI'S EXPERIENCE IN BWR DEVELOPMENT

ABWR Enhancements

In addition to an uninterrupted track record in construction since completion of the first ABWR, Hitachi has made enhancements to the following key technologies and products to improve plant economics, ease-of-operation, and performance.

(1) Thick-walled nozzle for internal pump

Ability to withstand earthquakes was improved by thickening the walls of the nozzle on the internal pump located at the bottom of the reactor pressure vessel (since Unit 2 of the Shika Nuclear Power Station of the Hokuriku Electric Power Company).

(2) Adoption of magnetic coupling and induction motors in the improved control rod drive unit

A magnetic coupling is a non-contact method for transmitting the torque from an electric motor that eliminates potential leaks and improves ease-of-maintenance. The reduced equipment requirements of the power supply system for the induction motors allows the space taken up by the electrical power panel to be significantly reduced (adopted on Unit 3 of the Shimane Nuclear Power Station of The Chugoku Electric Power Co., Inc.).

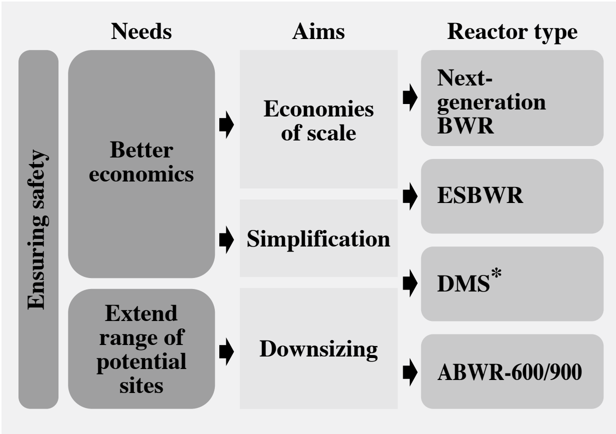
(3) Increased capacity of main steam safety relief valve

The capacity of the valve was increased (by 16%) and the number of valves reduced by enlarging the valve throat diameter (adopted since Unit No. 3 at the Shimane Nuclear Power Station).

(4) Reduced pressure loss in main steam isolation valve

The body design was changed by enlarging the valve seat inlet to approximately the same size as the connecting pipe (full bore type) to reduce pressure losses (to be adopted in next-generation reactor).

By continuing to manufacture and seek out improvements to important items of equipment in this way, Hitachi ensures that its technology is passed on, quality maintained, and improvements made.



DMS: double MS (modular simplified and medium-small reactor)
* DMS was developed by research sponsored by The Japan Atomic Power Company.

Fig. 2—Development of Reactors to Meet Diverse Customer Needs.
With the maintenance of safety as its cornerstone, Hitachi is working on the development of different types of reactor to suit diverse requirements including better plant economics and extending the range of places able to adopt nuclear power.

Range of Reactor Developments to Meet Customer Needs

Pursuit of better economics with safety as the key prerequisite has been the proposition behind Hitachi's development of nuclear reactor equipment. Because the plant cost far outweighs the fuel cost for a nuclear power plant, increasing output is the most effective way of improving plant economics (by achieving economies of scale) and Hitachi intends to continue following the development path of "better economics through greater scale" that has characterized the past development of the BWR. On the other hand, simplifications such as passive systems that eliminate active pumps or natural circulation reactors in which differences in fluid density alone drive the recirculation of the reactor coolant also provide a means for improving economics. Fig. 2 shows the range of different reactor types being developed. In addition to the "economics of scale" and "simplification" approaches to better economics, the figure also includes "downsizing" which is aimed at bringing nuclear power to developing countries.

(1) Large-scale reactors

Because the development of large centralized power stations with high performance is the primary approach followed in developed countries such as Japan, Europe, and America with extensive distribution grids able to cope with heavy electricity demand, Hitachi started work with power companies in 1990 on the research and development of an enhanced version of the ABWR called the ABWR-II and had largely completed the plant concept by 2001. The key development objective for the ABWR-II was to enlarge the fuel bundle. The new design has control rods on two corners of the fuel bundle and the fuel lattice width is 1.5 times larger than previous design and is intended to improve core performance through enhancements such as higher output, higher burnup, and utilization of MOX (mixed oxide) fuel, while also reducing the number of fuel elements and the number of control rods and control rod drives (see Fig. 3). In terms of safety equipment, the ability to avoid severe accidents has also been strengthened by incorporating simplification technologies in many different areas of the safety systems such as introducing passive containment vessel heat removal that naturally removes the decay heat from containment vessels. Hitachi also plans to apply the results of ABWR-II development, such as the main steam isolation valve with low pressure loss, in the latest ABWRs and to use the technology as a foundation for development of the next generation of BWRs.

(2) Small and medium sized reactors

To expand the adoption of nuclear power internationally, it is essential to provide sources of power suitable for regions with limited infrastructure such as electrical transmission capacity or where growth in electricity demand is uncertain and users want to diversify their investment depending on market trends. Hitachi has developed two mid-sized ABWRs (ABWR-600 and ABWR-900) to provide nuclear power plants that can respond flexibly to these requirements and to provide a distributed power source for regions where electricity demand or the capacity of the electricity grid is small.

This downsized development of the ABWR was undertaken in stages. The first step was to develop the ABWR-600 with a power output in the 600-MWe

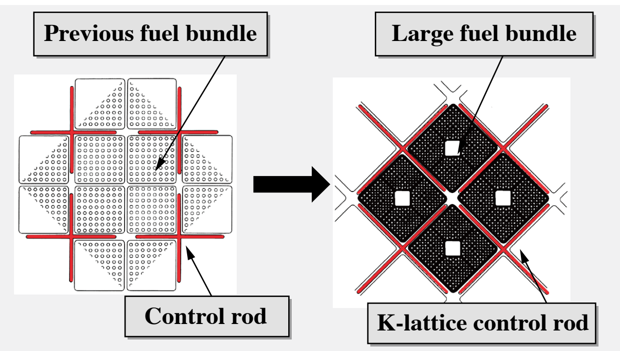


Fig. 3—Larger Fuel Bundles.
The large fuel bundle concept is shown. Large fuel bundles provide higher output, improve reactor performance, and allow the rationalization of associated equipment.

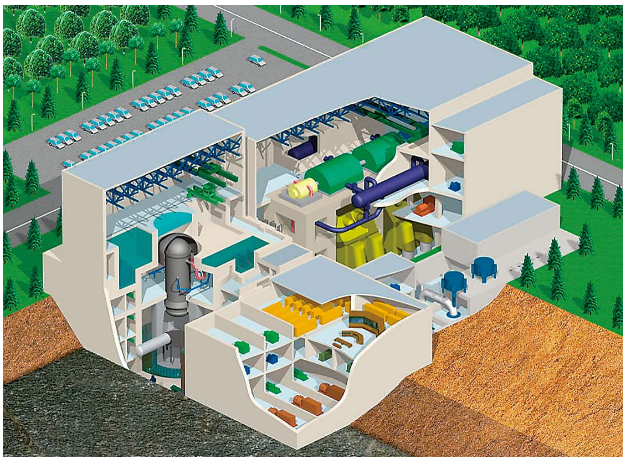


Fig. 4—Cutaway Drawing of ABWR-900 Plant.
The mid-sized ABWR was developed as a way of diversifying capital investment and coping with the limitations of the electricity grid.

class. This involved determining the plant output level that would give the best economics by finding an optimum combination of capacity and number of units for the key components in the current ABWR, including the reactor coolant recirculation pumps, turbines, and condensers. Next, techniques for uprating plant output such as increasing the power density of the fuel were used to develop the ABWR-900 in which the power output is been increased up to the 900-MWe class (see Fig. 4).

Now, Hitachi is working on the development of the DMS [double MS (modular simplified and medium-small reactor)], a 400-MWe class BWR with natural circulation to meet the need for low-output power plants. This research is sponsored by The Japan Atomic Power Company.

NATIONAL PROJECT TO DEVELOP NEXT-GENERATION BWR

Background and Development Objectives

A national project to develop the next generation of light water reactors was launched in 2008, approximately 20 years after the development of the ABWR. The purpose of the project is to prepare for the time when a large number of Japan's reactors will need to be replaced, and for Japan to fulfill its role as a leader in the field of nuclear power in meeting international expectations for nuclear power generation. Government, power utilities, and manufacturers will collaborate together on an eight-year plan with a total development budget of 60 billion yen (however, some technical development activities such as materials testing may extend beyond the eight-year life of the project). Under the direction of the government and power utilities, Hitachi will aggressively promote the project as part of the combined nuclear power industry, working with companies such as Toshiba, Mitsubishi Heavy Industries, Ltd., Global Nuclear Fuel-Japan Co., Ltd., and general contractors in the construction sector under the coordination of The Institute of Applied Energy.

The following list specifies the basic design objectives for the next-generation BWR that is to become a standard reactor not just in Japan but internationally. The objectives were established based on the requirements for nuclear power generation equipment in the 2030s and beyond based on forecasts of future industrial growth, and on the requests of power utilities with extensive operating experience gained over many years and the requests of overseas power companies.

(1) Achieve levels of both safety and economics that are in the top class worldwide.

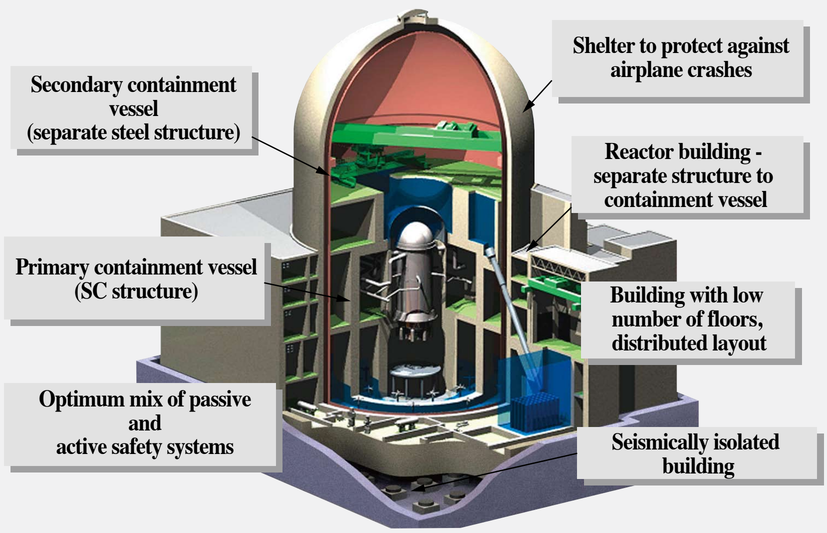
(2) Dramatically shorten time required for construction and standardize to make independent of site conditions.

(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 (life

Power output	1,700 to 1,800 MWe
Recirculation system	Forced circulation (RIP)
Safety systems	3 active safety systems Passive safety system (PCCS, IC, WW)
Containment vessel	Dual containment vessel
Construction time	30 months
Availability	97% or better



RIP: reactor internal pump PCCS: passive containment cooling system IC: isolation condenser WW: water wall SC: steel plate reinforced concrete

Fig. 5—Concept of Main Equipment Configuration for Next-generation BWR Devised by Hitachi.
Hitachi has put together a plant concept with standard specifications for basic performance and those requirements common to all countries, and optional specifications for requirements that differ depending on the circumstances specific to each country.

of approximately 80 years).

The following sections describe the configuration of the main equipment and the development of specific technologies based on these objectives.

Main Equipment Configuration

To devise a nuclear plant appropriate for the international market, it is essential that the plant concept have excellent economics while also satisfying the site requirements and the different regulatory, power generation, and other requirements of each country. The rational way to go about achieving all of these requirements is to combine the requirements common to all countries along with basic performance factors in a standard specification with optional specifications available to suit conditions in each country, and to aim for a design that allows optional specifications to be incorporated easily. Fig. 5 shows the configuration of the main plant equipment.

(1) Reactor building—separate containment vessels

The time required for construction can be significantly shortened by adopting a separate steel containment vessel because this allows construction of the reactor building and containment vessel to proceed in parallel. The standard design allows for the number of levels in the reactor building to be reduced to facilitate the use of modularization to speed up construction. Because this configuration allows for a flexible building layout design that does not need to take account of the containment vessel shape, it facilitates the incorporation of optional specifications to suit circumstances in different countries.

On the other hand, comprehensive design standardization of the core layout can be achieved in accordance with the basic performance by incorporating important structural components, including the operating floor, into the containment vessel. Also, using SC (steel plate reinforced concrete) in the structural frame that covers the reactor pressure vessel helps modularize large blocks.

(2) Dual containment vessel concept and safety structure

The suppression chamber containing structure of the structural frame that covers the reactor pressure vessel provides an equivalent level of pressure containment performance to the steel-reinforced concrete used in current ABWR containment vessels. The area enclosed by the suppression chamber and operating floor has a structure that is divided into rupture disks and similar where the applied pressure is the design pressure for the containment vessel. This SC structural frame acts as the primary containment vessel and provides a pressure containment boundary able to withstand the standard design level of accident. In the event of a severe accident occurring that exceeds the standard design level of accident, it is contained by the separate steel containment vessel that acts as the secondary containment vessel.

As with existing ABWRs, safety systems are designed to use active equipment such as pumps so that faults can be contained quickly. Also, a water wall can be formed by allowing water into the gap around the outside of the secondary steel containment vessel to remove the heat that accumulates inside the containment vessel when an accident occurs through the steel boundary wall. This can perform long-term heat removal even if the active heat removal systems fail to function for some reason. Together with the dual containment function, this provides a margin of safety with an excellent level of public acceptability.

(3) Withstanding an airplane crash

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 for 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 flight path.

In addition to the above concepts relating to the main equipment configuration, other ways of achieving the maximum level of safety and economics include adopting large-scale equipment, on-line maintenance systems, and high-performance equipment such as high-efficiency turbines.

Development of Specific Technologies

Hitachi is working on developing the underlying technologies required to achieve the basic design objectives of the next-generation BWR. The following lists the characteristics of the most important of these technologies.

(1) Development of ultra-high burnup fuel cladding material

Current BWRs use fuel cladding tubes made of zirconium alloy and have an average discharge fuel burnup of 45 GWd/t and fuel bundle average maximum fuel burnup of 55 GWd/t. The aim for the next-generation BWR 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 Global Nuclear Fuel-Japan, Hitachi has started work on developing a cladding material for ultra-high burnup fuel (hydride-free material) that suppresses hydrogen absorption and is resistant to corrosion.

(2) Development of SSR fuel

Reducing uranium consumption is seen as extremely important for ensuring a reliable supply of energy. In addition to the uranium saving provided by adopting ultra-high burnup operation, consumption of uranium in the next-generation BWR is to be reduced by a further 10% (approx.) using technology for taking maximum advantage of the spectrum shift effect that is one of the characteristics of BWRs. BWRs use a technique called "spectrum shift operation" that increases the energy produced by each unit weight of uranium. The technique works by reducing the core flow in relative terms as the reactor goes from the early to the middle part of the operation cycle to encourage production of 239 Pu, which is a fissionable isotope, and then increasing the core flow at the end of the operation cycle to encourage fission of the 239 Pu produced. Hitachi has started work on developing technology for commercializing improved water rods called SSRs (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 flow (see Fig. 6).

(3) Development of new construction technique (SC structural technique)

SC structures are a way of enabling the modular construction of large blocks and significantly reducing the work associated with steel bars and formwork, 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. The intention is to use the SC structure for the nuclear reactor containment vessel, which takes up more than half of the critical path for plant construction, as well as in other key components. Accordingly, there is a need to

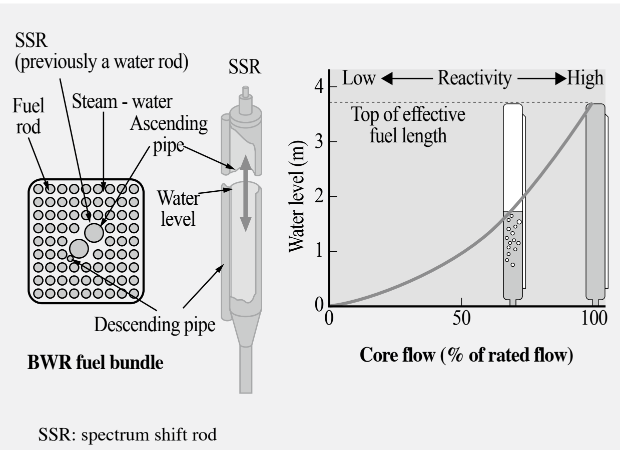


Fig. 6—Spectrum Shift Rod Fuel.
An SSR is under development that enhances the spectrum shift effect by changing the core flow to improve on the efficiency of uranium use.

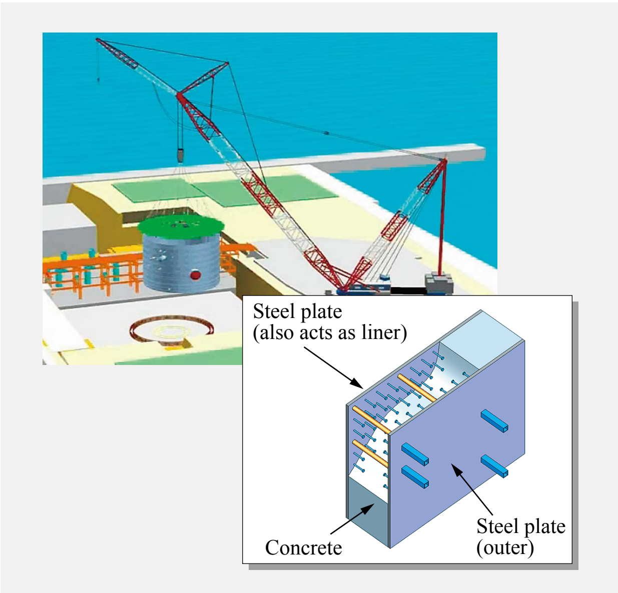


Fig. 7—SC Structural Technique.
The SC structural technique significantly reduces the work associated with steel bars and formwork. Planning of performance confirmation tests is underway to enable this technique to be used in major components as well as in the reactor containment vessel.

confirm the SC structure's earthquake resistance and ability to withstand pressure under high-temperature conditions. Hitachi has already started planning for testing to confirm the performance of the SC structure under the temperature conditions anticipated to apply in the actual plant, utilizing its extensive design and manufacturing technology for nuclear containment vessels and the close organizational relationships it has built up with general contractors over the past (see Fig. 7).

In addition, Hitachi is also working on the development of plant digital systems that will improve operational performance over the entire life of the plant (design, manufacture, construction, operation, maintenance, and decommissioning), and on establishing basic technologies for handling fuel with uranium enrichment levels above 5% that is a necessary prerequisite both for adoption of a longer operation cycle (24 months) to improve plant availability and achieve the ultra-high fuel burnup described previously, and for improvements in material and water chemistry that will provide the basis for the aim of extending plant life to 80 years.

ESBWR DEVELOPMENT

Features

The ESBWR (economic and simplified boiling water reactor) is a natural circulation reactor for high output plants (1,550 MWe) developed based on GE's experience with the ABWR and with the SBWR (simplified boiling water reactor) in which Hitachi also played a part in development. The reactor design pursues the concept of a simple nuclear reactor system, something that is a characteristic of BWRs.

This high-output simplified reactor uses a natural circulation reactor system that eliminates the need for a reactor coolant recirculation pump, and safety equipment that uses passive systems such as an emergency condenser, gravity-driven reactor cooling, and passive containment vessel cooling to reduce the amount of equipment by eliminating active components such as pumps while also reducing operating and maintenance costs (see Fig. 8).

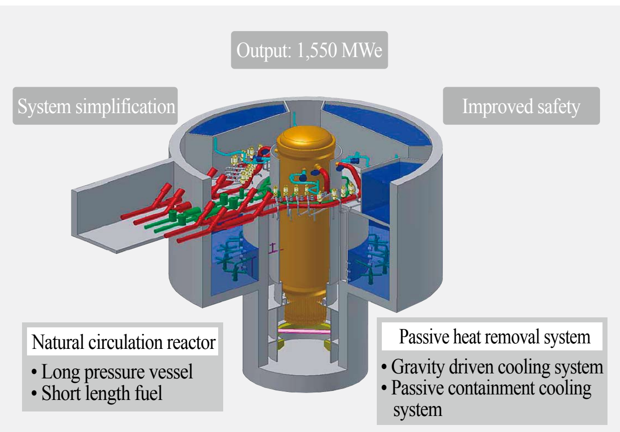


Fig. 8—ESBWR Features.
The ESBWR pursues the concept of a simple nuclear reactor system, something that is a characteristic of BWRs, and aims to provide better economics by eliminating active equipment to reduce construction and maintenance costs.

Joint Undertaking Utilizing Synergies with GE

Along with the ABWR, the ESBWR is a valuable reactor type able to meet the sudden rush of nuclear power plant construction that has arisen in the USA. GE is taking a lead role in obtaining regulatory approval in the USA and applied for US DC (design certification) in August of 2005. In addition to assisting with these regulatory matters through analysis and other contributions, Hitachi is utilizing its equipment design and manufacturing capabilities to support the detailed design of equipment with new design elements such as the reactor internals, control rod drive, and containment vessel.

The ability to use natural circulation is the key feature of the ESBWR and achieves the required core flow by positioning a chimney at the top part of the core and obtaining its motive force from the difference in coolant density. The chimney is a large piece of in-reactor equipment with a height of about 7 m and diameter of about 6 m. As indicated by its name, the chimney is located at the top of the core and acts as a tunnel for the two-phase flow (mixed flow of water and steam) that is generated from inside the core. A divided chimney structure with a square lattice (forming channels with a square cross section) is used to force this two-phase flow to flow freely without becoming stationary. The chimney is the most characteristic and important component of the ESBWR and Hitachi will perform confirmation tests of its overall performance to determine its ease-of-manufacture, integrity, and the performance of the two-phase flow. The tests will be performed using the HUSTLE (Hitachi utility steam test leading facility) multi-purpose steam source test facility which was completed in 2008. In this way, Hitachi will lend its "manufacturing," "engineering capability," and "research and development capability" strengths to the ESBWR to make thorough preparations for the construction of actual plants in conjunction with GE (see Fig. 9).

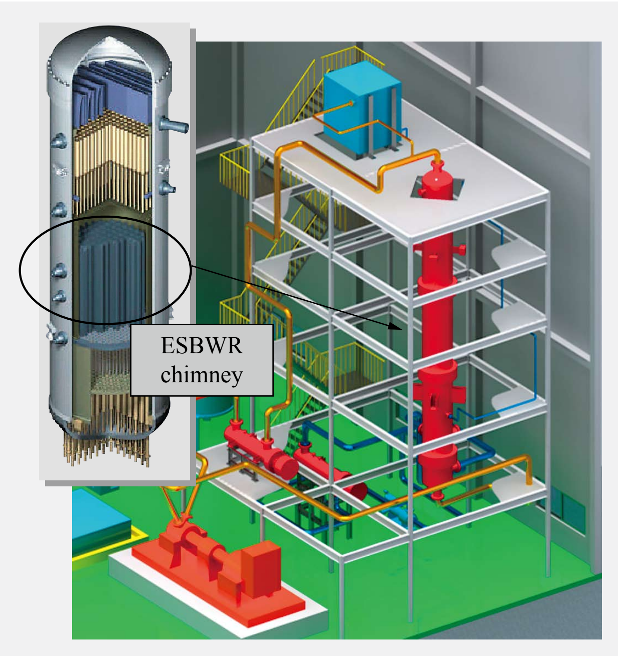


Fig. 9—HUSTLE Multi-purpose Steam Source Test Facility.
Tests will be performed to confirm the overall performance of the chimney which is the most important component in the ESBWR.

CONCLUSIONS

Against a background in which construction of nuclear power plants is gathering momentum around the world, this article has discussed the directions being taken in the development of nuclear power equipment for the era of the "nuclear renaissance" and the current state of this development. To ensure the broader adoption of nuclear power plants internationally as an effective tool for preventing global warming, and to maintain and develop the BWR and bring it to the international market, there is a need for Japan to enhance its technical skills (particularly the country's technical skills in construction) that have genuinely attracted the interest and expectations of the wider world and prepare for the coming era of extensive construction activity.

Hitachi intends to go on developing various innovative reactor designs that can respond flexibly to diverse needs in the era of the "nuclear renaissance" based on its extensive and uninterrupted track record in construction and successful experience in ABWR development.

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