Development Study of Nuclear Power Plants for the 21st Century

Kumiaki Moriya
Masaya Ohtsuka
Motoo Aoyama, D.Eng.
Masayoshi Matsuura

OVERVIEW: Making use of nuclear power technology accumulated since the development of a research reactor in 1955, Hitachi, Ltd. participated in the construction of Japan's first light-water reactor that began operation in 1970 as Unit 1 (357-MWe BWR) of the Tsuruga Nuclear Power Station. Following this, Hitachi continued its efforts in achieving high reliability and large-scale output, and in 1996, it completed a 1,356-MWe Advanced Boiling Water Reactor (ABWR) in cooperation with various BWR utility companies, General Electric Company, and Toshiba Corporation. Furthermore, anticipating a broad range of use for nuclear power plants in the 21st century, Hitachi is now working on developing nuclear power plants that take diversified needs and global characteristics into account. In particular, three types of reactors are being targeted: (1) ABWR-II as a large-scale centralized power supply emphasizing cost efficiency (under joint research with utility companies); (2) HABWR (medium-size ABWR) as a distributed power supply appropriate for an output scale where a large power grid does not exist; and (3) SSBWR (simplified small BWR) as an independent power supply that does not assume a power grid.

INTRODUCTION

BUILDING upon light-water-reactor and power-generating technologies first introduced from the United States, Hitachi, Ltd. has added its own novel ideas in an effort to improve reliability, safety, and cost efficiency. The Advanced Boiling Water Reactor (ABWR) was developed using the full storehouse of Japan's technical experience, and it continues to operate satisfactorily in the form of units 6 and 7 of the Kashiwazaki Kariwa Nuclear Power Station (Tokyo Electric Power Co., Inc.) achieving results commensurate with design expectations.

Now, with the experience gained from units 6 and 7, Hitachi is working to improve the ABWR and to firmly establish it as a viable reactor, and is also moving forward on the development of a 1,700-MWe ABWR-II as a large-type economical reactor in cooperation with utility companies.

At the same time, taking into account worldwide energy problems such as those related to global warming, Hitachi sees the need for nuclear power plants in many regions of the world and the importance of developing plants that can satisfy the diversified needs of those regions.

In this report, we present the direction and state of nuclear power plant development for the 21st century as seen by Hitachi, Ltd.

DIRECTION OF NUCLEAR POWER PLANT DEVELOPMENT

Ever since electricity began to be generated by nuclear power, the pursuit of cost efficiency with safety as a prime condition has been a great challenge in development work. In nuclear power plants for which plant cost is large compared to fuel cost, the scale effect has been the most effective means of improving cost efficiency, and the capacity of single reactors has been increasing using past results to build upon. At the same time, efforts have been paid to ensuring reliability with the aim of achieving high availability.

This pursuit of cost efficiency will continue into the future. In a country like Japan with an extensive power grid, it is considered basic policy to develop large-scale centralized power supplies with high levels of performance expected of the scale effect. To this end, Hitachi is now developing the ABWR-II in cooperation with utility companies.

On the other hand, if we consider that the demand for energy will be increasing all the more throughout the world, the widespread penetration of nuclear power

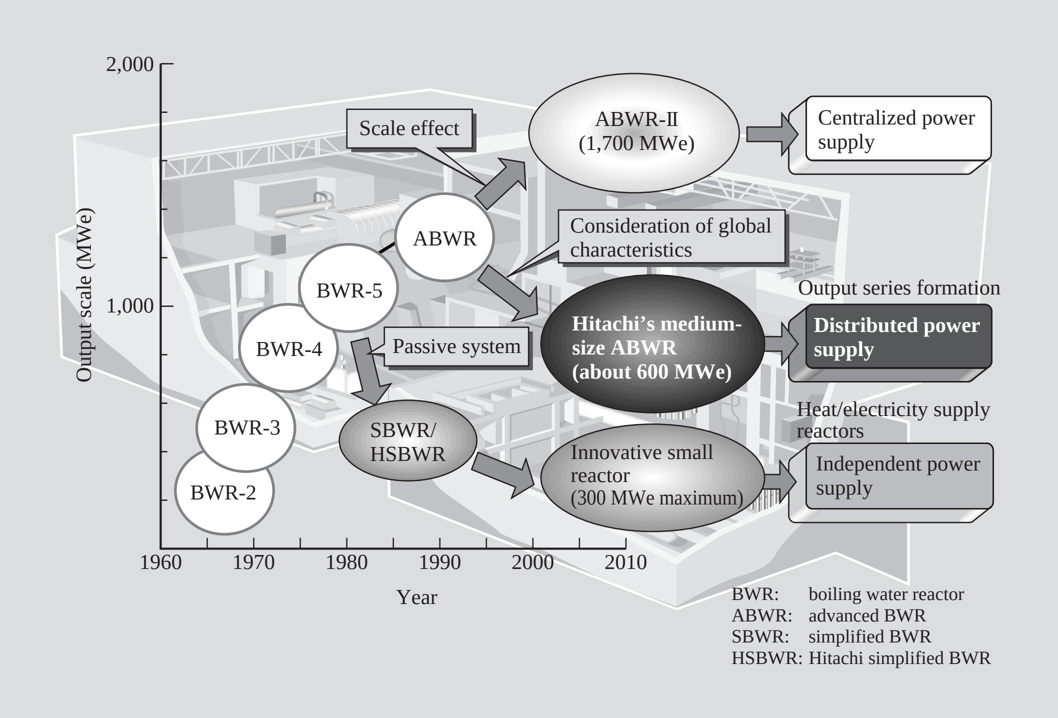

Fig. 1— Hitachi's View on the Future Direction of Nuclear Power Plants.
Hitachi, Ltd. is developing an assortment of nuclear reactors according to output scale to meet diversified needs for nuclear power plants in the 21st century.

plants will be important. In this case, if an extensive power grid cannot be expected for a region or user, the assumption that there is no power grid must be made. Anticipating such future needs, Hitachi is moving forward on the development of HABWR (medium-size ABWR) as a distributed power supply for regions having little power-transmission capacity and power demand, and SSBWR (simplified small BWR) as an independent power supply for regions having no power grid (see Fig. 1).

For the HABWR, we selected an output scale of the 600-MWe class, which is appropriate for a distributed power-supply configuration, and while keeping the special properties of the new ABWR, carried out rationalization in conjunction with output scale to recover scale-effect losses.

The SSBWR, on the other hand, is a reactor for supplying valuable energy to regions characterized by underdevelopment or life inconveniences due to difficulties in fuel transport, access, etc., and for it, we are considering an output scale of no more than 300 MWe. This small output is not an outcome of simply downsizing the ABWR. Rather, it is necessary if this reactor is to be operated safely and stably even without specialized operators.

The following describes the state of development for these three types of reactors.

CONCEPT DEVELOPMENT OF NEXT-GENERATION NUCLEAR POWER PLANTS

Development of a Large-Scale Centralized Power Plant (ABWR-II) 1)

The primary objective in developing the ABWR-II is to achieve a plant that exceeds the ABWR in cost efficiency. In this regard, the most effective way of reducing construction cost per kilowatt is to increase output. To this end, we are developing a plant concept whereby large output can be achieved without harming design margin and safety and reliability can be improved (see Fig. 2). In addition, to reduce the cost of power generation, it is important to keep fuel-cycle cost and maintenance cost down in addition to reducing construction cost. We are targeting a plant factor of at least 96% by achieving a periodic inspection period of 20 days and an operating cycle of 18 months.

Hitachi is now studying technologies with the aim of making further improvements in cost efficiency, operability, and maintainability and to contribute to an even more advanced ABWR-II. The following describes some examples of studies that are making progress in achieving such advances.

Further advances in core and fuel

The large fuel bundle core adopted for the ABWR-II features a fuel-lattice width 1.5 times that of the conventional bundle and the placement of control rods

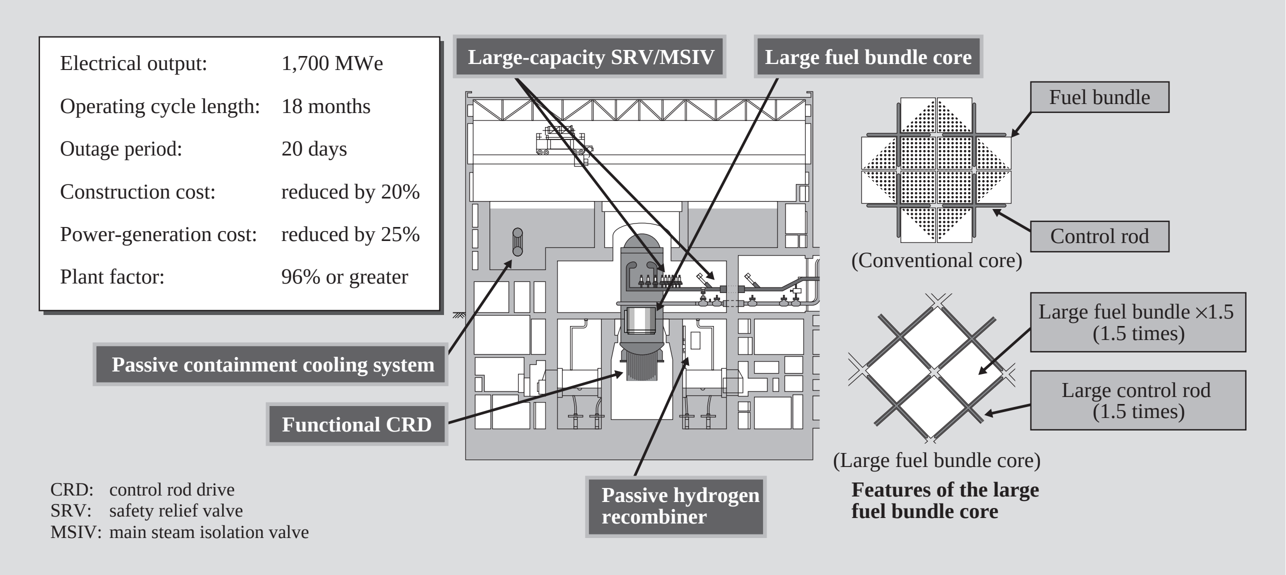

Fig. 2— ABWR-II Plant Overview and Features.
Hitachi is developing a reactor concept featuring superior cost efficiency, operability, and maintainability to be used as a next-generation large-scale centralized power plant.

at the two corners of each fuel bundle. This configuration increases the shut-down margin and enables the water-gap area between fuel bundles to be incorporated within the fuel-bundle area in which fuel rods can be loaded. These features enable the number of fuel rods to be increased, which, in addition to increasing output, achieves high burn up and more effective use of mixed oxide fuel (MOX). In short, an advanced core can be achieved and the number of fuel bundles as well as the number of control rods (CR) and control rod drives (CRD) can be reduced.

Hitachi, moreover, is planning on using the tolerance of this large fuel bundle not only to lower construction cost and improve the fuel cycle ratio, but also to lengthen the continuous-operation period and to shorten the outage period by decreasing the frequency of fuel and CR exchange.

Furthermore, the spectral shift rod (SSR) now under development by Hitachi will make it possible to increase the reactivity control effect through flow control, and in combination with the large fuel bundle core, to achieve 18 months of continuous operation though withdrawing all control rods. It will also be possible to improve operability by decreasing the frequency of control rods operation. Hitachi is also developing other technologies for enhancing core and fuel such as optimizing the core structure under the assumption of operation with all control rods withdrawn.

Advanced turbine system

To achieve greater economy, it is important that turbine thermal efficiency be improved. The present ABWR-II inherits the technology developed for the ABWR to improve thermal efficiency. In the case of a large core, however, an improvement in thermal efficiency of only 1% can mean a significant improvement in cost efficiency. Hitachi is now conducting studies on turbine systems appropriate for an increase in reactor operating pressure, and is examining, in particular, the use of an intermediate-pressure turbine that has been used in thermal-power plants.

Safety-enhancement technology

The ABWR-II installs a Passive Containment Cooling System (PCCS) (a heat exchanger using condensation by natural convection) to passively remove decay heat from the containment vessel as a countermeasure to severe accidents. In this regard, Hitachi is also studying the use of heat pipes and the like as a method to enhance heat transfer from the containment vessel without impacting cost efficiency.

Development of a Medium-Size ABWR

In Southeast Asia and other countries and regions where energy demand is predicted to increase dramatically in the years to come, we can expect the need for medium-size distributed power plants to increase due to limited investment capital and power grids. To therefore achieve early deployment in a region having no history of nuclear power plants, the nuclear reactor decided on must be supported by mature technology reflecting superior operating results in the past while being economical at the same time.

Based on the above needs, basic design guidelines for a medium-size ABWR can be summarized as follows.

(1) Achieve cost efficiency equivalent to that of a large-sized reactor while maintaining safety, reliability, and operability.
(2) Design with a high degree of freedom that can respond flexibly to different regional circumstances and investment capacities and to user needs.
(3) Perform rationalized design that makes use of technologies developed for large-sized reactors.

A plant design concept corresponding to these design guidelines is shown in Fig. 3. The features of a plant based on this concept are described below.

(1) Rationalized design through tradeoff with performance

When output scale is small, the benefit of improved thermal efficiency is relatively small, and for this reason, we placed emphasis on simplifying facilities rather than improving efficiency in the development of a medium-size ABWR. From this viewpoint, turbine facilities are configured as follows. First, in contrast to a low-pressure 2-stage turbine selected for conventional BWR of equivalent power output, we opt for a 1-stage design using a 52-inch (about 132 cm) long-blade turbine already adopted and validated by ABWR. Second, the condenser is implemented as one unit and the feedwater heater as one system. This system configuration is slightly less thermally efficient than ABWR in terms of turbine efficiency and feedwater temperature, but significant facility rationalization can be expected. In addition, the amount of reserve equipment for non-safety systems like feedwater and condensate pumps is reduced to lower the cost of investment, although this becomes a factor in dropping the plant factor slightly.

(2) System simplification

We also decided to simplify the safety system while keeping the same level of safety as the actual plant. In this regard, we note that environmental testing and

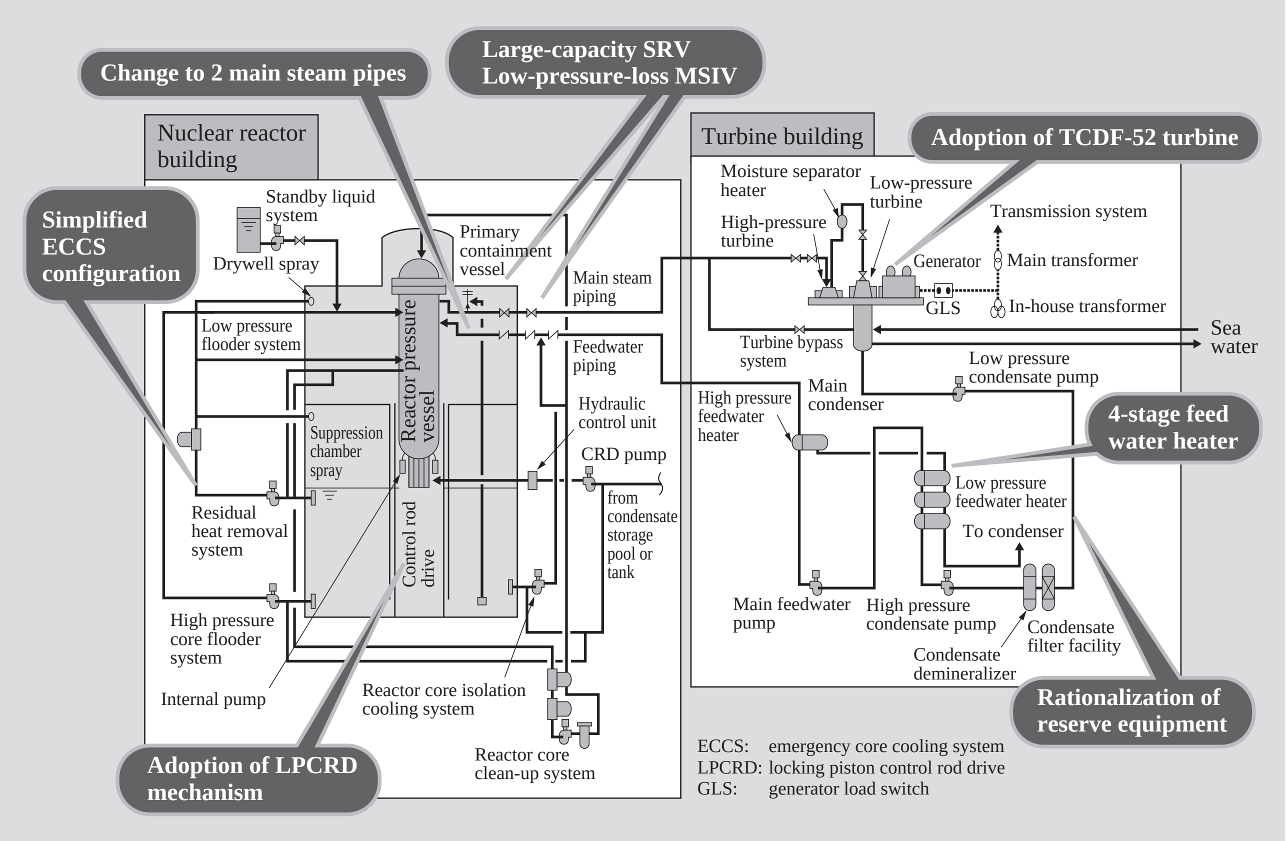

Fig. 3— HABWR Plant Concept and Features.
This type of reactor reduces the output scale of the 1,356-MWe ABWR to the 600-MWe class, and aims to rationalize the system in accordance with output scale while maintaining ABWR features.

the like must be developed for new equipment used in an emergency core cooling system (ECCS) due to the severity of usage conditions. For this reason, we took aim on achieving a "repeat effect" in equipment design by adopting the same capacity for single units of particular ECCS equipment capacity as that of ABWR (1,356-MWe class). Then, by configuring the system in accordance with such capacity, we were able to achieve significant simplification in safety facilities (a 50% reduction in the number of facility units) while maintaining the same level of safety as the actual plant.

(3) Use of technology developed for large-sized reactors

We incorporated new technology established in the development of large-sized reactors, such as the large-capacity safety relief valve (SRV) and low-pressure-loss main steam isolation valve (MSIV), with the goal of achieving efficient rationalized design and improving performance.

(4) Rationalized layout design

Significant rationalization of turbine facilities and simplification of facilities surrounding the nuclear reactor should enable a building-volume ratio of slightly more than 50% to be achieved with respect to ABWR (1,356-MWe class), as shown in Fig. 4.

(5) Flexible design to meet user needs

The plant design concept described above is treated as standard specifications, and Hitachi uses these specifications as a basis for studying optional specifications to expand the degree of freedom in actual use. Main optional specifications are (a) all control-rod withdrawn operation function (control-rod operation-free during normal plant operation) through adoption of coarse and tight hybrid lattice fuel; and (b) application of a containment vessel featuring natural heat radiation to expand the safety margin at the time of a severe accident. In the future, even greater cost efficiency can be achieved by extensive application of modularization based on thorough standardization of equipment specifications and by incorporating new technologies now under study such as seismic isolation technology and steel plate reinforced concrete (SC). In this way, it should be possible to achieve high cost efficiency equivalent to that of 1,356-MWe ABWR (equivalent construction cost), and to introduce an ABWR with output optimized according to power demand and the scale of investment.

Development of an SSBWR

To meet the demand for independent electricity supply and heat supply both inside and outside Japan, Hitachi is developing an SSBWR (simplified small BWR) that makes use of the features of BWR technology (see Fig 5).

The electrical output of an SSBWR is to be no more

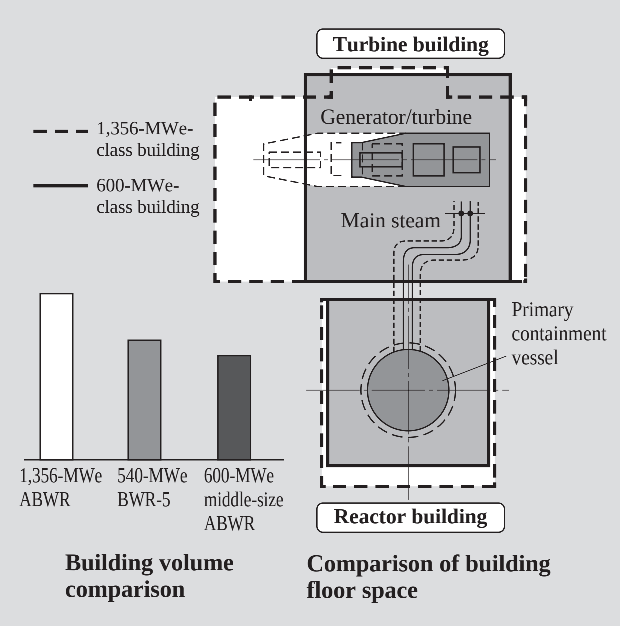

Fig. 4— Building Volume Comparison between HABWR and Current BWR.
A significant decrease in building volume is achieved over current reactors.

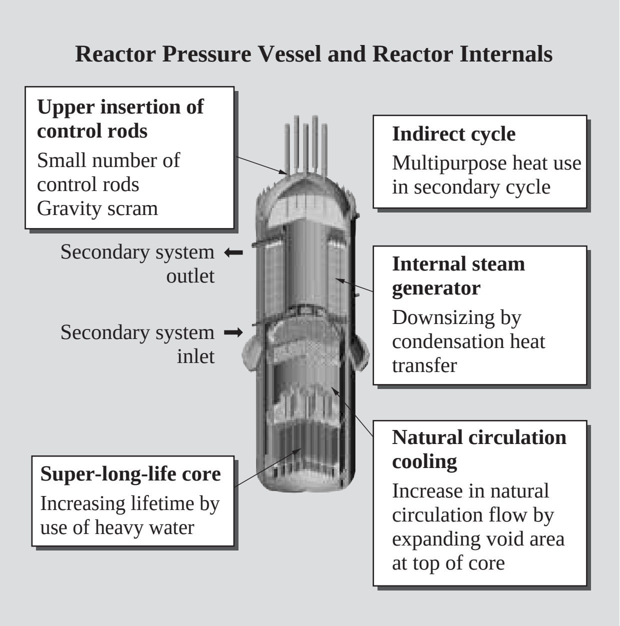

Fig. 5— Hitachi's BWR Concept Supporting Proliferation Resistance.
Development target is a small reactor excelling in safety, operability, and cost efficiency.

than 300 MWe, and main design targets are (1) ease of operation and maintenance, (2) passive safety, (3) multipurpose energy supply, and (4) cost reduction.

In the United States, an objective in developing small reactors is to meet the need for reactors that can operate for several tens of years without fuel exchange, that is, the need for proliferation-resistant reactors. To meet this demand in an SSBWR, we use heavy water in coolant and a triangle tight fuel lattice in fuel bundles to achieve a less moderated neutron spectrum and super-long-life operation. In particular, the use of heavy water decreases the large excess reactivity caused by single-batch operation, and the gradual addition of light water to heavy water compensates for increase in the void coefficient of coolant accompanying core burn up. As a result, super-long-life operation on the order of 20 years can be achieved (see Fig. 6). In addition, the decrease in excess reactivity can significantly trim the CR drive mechanism and enable reactor internals to be simplified and a cost reduction to be achieved. A steam generator (SG) using condensation heat transfer with a high heat transfer coefficient is also placed in the steam area in the upper section of the core. This makes it possible to achieve a compact reactor pressure vessel (RPV) integrated with an SG that is part of an indirect cycle for the multipurpose use of heat in a high-temperature secondary system. Finally, the use of natural circulation for core cooling that eliminates recycling pumps (active components) can improve maintainability, and the resulting elimination of feedwater and steam lines in the primary system can dramatically lower the possibly of a major loss-of-coolant accident (LOCA).

The use of a passive safety system can also improve system reliability. Specifically, placing a suppression pool in the upper section of the RPV within the primary containment vessel (PCV) and using a gravitational water injection system can remove heat from the RPV. At the time of an accident, the RPV undergoes an automatic drop in pressure and the gravitational water injection system is activated to cool the core. If a core melt down should occur, the outer section of the RPV will be filled by the gravitational injected water so that the core can be kept within the RPV. Steam evaporated within the PCV is condensed in the suppression pool and is radiated to outside air using a heat pump.

The adoption of a completely passive safety system that eliminates active components in the above way can prevent large-scale damage to the nuclear reactor at the time of a severe accident.

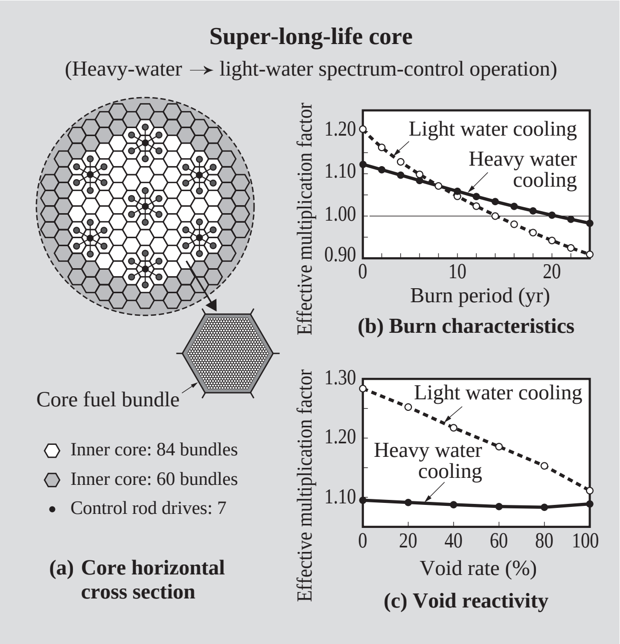

Fig. 6— BWR Core Concept Requiring No Fuel Exchange for 20 Years.
The use of heavy and light water achieves operation requiring no fuel exchange for 20 years.

In relation to small reactors, we can expect diversified needs to arise according to the format of energy usage and maintainability, safety, and cost requirements. Hitachi continues to examine innovative reactor concepts that can support various specifications such as direct/indirect cycles, heavy/light water, and active/passive safety systems.

CONCLUSIONS

In this paper, we have discussed the development of nuclear power plants for the 21st century.

Since the introduction of nuclear power technology from the United States, Japan's efforts at original development have borne fruit culminating in the completion of the ABWR through joint international development with utility companies, General Electric Company, and Toshiba Corporation.

A stable supply of energy is essential to economic expansion in the 21st century, and this together with environmental problems like global warming should serve to increase the need for nuclear electric power generation. To achieve widespread use of nuclear electric power generation, it is important that a flexible response be made to global characteristics and diversified needs. With this in mind, Hitachi intends to move forward on the development of innovative reactors of various types to satisfy a wide range of objectives.

REFERENCE

(1) S. Kosugiyama et al., "Current State of R&D in ABWR-II (Enhanced ABWR)," 7th Symposium on Power and Energy Technologies, The Japan Society of Mechanical Engineers, At the Forefront of Power and Energy Technologies 2000 (Oct. 2000) in Japanese.

ABOUT THE AUTHORS

Kumiaki Moriya

Joined Hitachi, Ltd. in 1980, and now works at the Nuclear Plant Engineering Department of Hitachi Engineering & Product Division of Nuclear Systems Division, Power & Industrial Systems. He is currently engaged in the development of nuclear power plants. Mr. Moriya is a member of the Atomic Energy Society of Japan, and can be reached by e-mail at kumiaki_moriya@pis.hitachi.co.jp.

Masaya Ohtsuka

Joined Hitachi, Ltd. in 1980, and now works at the 1st Nuclear & Industrial Systems Department of Power & Industrial Systems R&D Laboratory, Power & Industrial Systems. He is currently engaged in the development of the reactor components and system for the next nuclear power plant. Mr. Ohtsuka is a member of the Atomic Energy Society of Japan and the Japan Society of Mechanical Engineers, and can be reached by e-mail at masaya_ootsuka@pis.hitachi.co.jp.

Motoo Aoyama

Joined Hitachi, Ltd. in 1979, and now works at the 1st Nuclear & Industrial Systems Department of Power & Industrial Systems R&D Laboratory, Power & Industrial Systems. He is currently engaged in the development of the reactor core of the next nuclear power plant. Dr. Aoyama is a member of the Atomic Energy Society of Japan and the Institute of Electrical Engineers of Japan, and can be reached by e-mail at motoo_aoyama@pis.hitachi.co.jp.

Masayoshi Matsuura

Joined Hitachi, Ltd. in 1987, and now works at the Nuclear Plant Engineering Department of Hitachi Engineering & Product Division of Nuclear Systems Division, Power & Industrial Systems. He is currently engaged in designing the next nuclear power plant. Mr. Matsuura is a member of the Japan Society of Mechanical Engineers, and can be reached by e-mail at masayoshi_matsuura@pis.hitachi.co.jp.