Development of ABWR and ABWR-II

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We made good use of the experience of conventional BWR operation in the development of the Advanced-BWR (ABWR) from the late 1970s after 19 years. By following the Improvement and Standardization Program of the Japanese government, the ABWR has come to be regarded as the most successful type of Japanese-made BWR. As a result of these efforts, the first ABWRs were used for the No. 6 and No. 7 units of TEPCO’s Kashiwazaki-Kariwa NPS (Nuclear Power Station).

After introduction of the ABWR, the next-generation ABWR, the ABWR-II, has been under development for more than a decade in Japan. The new ABWR-II design will offer improved plant economy, greater safety margins, reduced maintenance and greater flexibility in terms of fuel cycle and plant operation. ABWR-IIs are expected to replace older nuclear units that are approaching the end of their lifetime. The ABWR-II has been developed to the point that it can lower power generation costs by approximately 15% compared to conventional ABWRs.

KEYWORDS: ALWR, BWR, ABWR-II

I. Introduction

53 nuclear power plants, with a combined output of 46 GWe, were in operation in Japan by 2002. The 52 Light Water Reactors (LWR) among these reactors were made up of 29 Boiling Water Reactors (BWR) and 23 Pressurized Water Reactors (PWR).

Currently more than a dozen new nuclear plants (10 ABWRs, two other types of BWR, three PWRs) are in various stages of development ranging from planning, environmental surveying, licensing or construction. Most of these will start commercial operation around 2010. Fig.1 shows their location.

![Fig. 1 New Nuclear Power Plant Project](image)

Japan's main strategy is to secure a stable energy supply through the establishment of a nuclear fuel cycle that recovers the newly produced plutonium and residual uranium present in the spent fuel. Besides the development of a Fast Breeder Reactor (FBR), it is expected that Light Water Reactors (LWR) will continue to account for the major share of nuclear power generation in Japan.

Meanwhile, the delay in FBR development that occurred because of the trouble at Prototype FBR, Monju, raised the importance of LWR much higher in the nuclear power generation scheme. Under these circumstances, in order to prepare for the replacement of operating power plants, we are implementing development of a new generation reactor that is suited to meet the highest global safety standards and improve economical competitiveness more than conventional ABWR.

In this paper, we discuss all specification of the development of the ABWR and the ABWR-II, which is a next generation design based on the ABWR. We also address the current status of development activities for ABWR-II.

II. ABWR Development History

1. Improvement and Standardization Program

In the mid 1960s, the peaceful use of nuclear energy was approved as national policy. We started construction of nuclear power plants to meet rapidly growing Japanese electricity demand, and the construction boom continued to expand in the 1970s.

To construct Japanese LWR, which is suitable to Japanese circumstances, we immediately started promoting domestic nuclear industries. Especially through operational experience including difficulty of troubleshooting, we realized the importance of establishing domestic technologies. The result of this was the start of the Ministry of International Trading and Industry's (now METI') Improvement and Standardization Program.
The program also aimed to achieve reduced radiation exposure and radioactive waste, and enhanced availability. These efforts contributed greatly to establishing nuclear power's position as a key source of electric supply, and as a means to meet continued growth in demand in Japan.

In the Japan Atomic Power Company (JAPC) Tsuruga Plant Unit No. 1(second-generation BWR-2), and in Unit No. 1 (BWR-3), Unit No. 2 (BWR-4), and Unit No. 6 (BWR-5) of TEPCO's Fukushima Daiichi Nuclear Power Station, BWR's were increased in size, and other various improvements were made, and enhancements added.

Improvements -- such as expanding reactor-containment vessel -- arising out of the first and second Improvement and Standardization Program were incorporated, particularly in plants built after Unit No. 2 (BWR-5) of the Fukushima Daini Nuclear Power Station. This resulted in significantly superior reliability and maintainability, as well as reduced radiation exposure for the workers.

2. ABWR Development

However, those improved and standardized designs were based on the fundamental General Electric design. Still, remarkable achievements were seen as the technological capability of domestic manufacturers rapidly improved in the course of designing and constructing BWR plants, and as the European industry made progress in the development of their own BWR technology.

Given this situation, we saw a need to combine the best BWR technologies from around the world in order to aggressively pursue the development of the most reliable, maintainable, and efficient BWR possible.

Implementing our idea, General Electric held talks on the development of an ideal BWR with Toshiba and Hitachi of Japan, Sweden's ASEA Atom, and Ansaldo Meccanica Nucleare of Italy in 1978. As a result of these discussions, the Advanced Engineering Team was organized and undertook a study of the feasibility of the project.

Upon receipt of the results of the feasibility study (Phase I, 1978-79), we decided to proceed with development of the ABWR. In cooperation with BWR utilities in Japan, we, TEPCO, brought together GE, Toshiba and Hitachi to undertake the basic design study (Phase II, 1981-83) and optimized design study (Phase III, 1984-85).

The development of the ABWR was adopted as one of the main tasks of Japan's Third Improvement and Standardization Program. The third program that was executed from 1981 to 1985 was carried out in order to establish a Japanese type of light water reactor, designed by independent technology but based on the first and the secondary revised standard plant.

After the basic ABWR design was finished, the third Improvement and Standardization Program for ABWRs was established. The target was for ABWRs to attain the status of the best and most successful type of Japanese-made BWRs. To achieve this, reliability tests of new equipment were continuously performed with the support from the Japanese Government and, through these tests, the new equipment was determined to be reliable and suitable for use in actual plants.

The verification test for the Reactor Internal Pumps (RIP) was executed in a series of the test plans. The test for the RIP was assigned by the government to the Nuclear Engineering Test Center (now the Nuclear Power Generation Organization) and was completed. Also, various research projects in connection with the ABWR were jointly undertaken by BWR utilities.

The first ABWRs developed during this process were adopted for use in the No. 6 and No.7 units of the TEPCO Kashiwazaki-Kariwa Nuclear Power Station (K-6 and K-7). K-6 construction began in 1991 and commercial operations commenced in 1996. K-7 construction began in 1992 and commercial operations commenced in 1997.

The beginning of commercial operations for the twin ABWR plants marked the end of a development period of approximately 19 years.

3. ABWR Key Design Features

The ABWR has been developed through the incorporation of advanced designs and technologies that have been proven through experience in Europe, the U.S. and Japan.

As stated in the previous section, the aims of ABWR development were

(1) Improved safety and reliability,
(2) Reduced radiation exposure (0.36 person-Sv/Year),
(3) Reduced radioactive waste,
(4) Better operability,
(5) Enhanced cost efficiency (20% reduction in Yen/kW),
(6) Higher availability (Capacity factor of 87%).

To achieve these targets the following new systems are adopted in ABWRs.

(1) Reactor Internal Pump (RIP)

In the RIP system, pumps to recirculate the reactor coolant are directly mounted to the bottom of the ABWR reactor pressure vessel. This system is
simple because no external recirculation piping or jet pump is required. The elimination of the external recirculation piping is particularly significant, as it provides a wide space inside the primary containment vessel and removes a potential radiation source. As a result, work efficiency is enhanced and radiation exposure during maintenance work is reduced. Furthermore, since there is no large-diameter nozzle below the core region of the reactor pressure vessel, there is no possibility of exposing fuel assemblies even in the case of LOCA, and thus safety is enhanced.

2. Fine Motion Control Rod Drive (FMCRD)
The FMCRDs provide improved safety protection via diverse means of control rod operation; electric motors provide the normal rod positioning function whereas rapid shutdown is achieved by hydraulic means. Furthermore, during normal operation, control rods are moved in 18-mm steps and each step only slightly raises core thermal power. The control rods can be operated even at high power levels, thus further enhancing operability. Finally, since simultaneous operation of the multiple control rods (gang mode) is possible, the plant startup time is shortened and availability increases as a result.

3. Reinforced Concrete Containment Vessel (RCCV)
The use of reinforced concrete provides sufficient strength to withstand the high internal pressure postulated during accident conditions, and the use of a steel liner ensures the required air seal is maintained. Because the steel containment vessel in conventional BWRs must perform both functions, the steel must be very thick. In the ABWR RCCV, however, the steel mass is reduced since only a thin steel liner is required.

4. Advanced Control and Instrumentation System
Through the adoption of expanded automation, the application of state of the art display technology, and the expansion of the scope of the digital control, advanced reliability and maintainability of the control and instrumentation systems is achieved.

5. Three Divisions of Emergency Core Cooling Systems (ECCSs)
Enhanced safety is achieved with an ECCS network that has three separate and independent Mechanical and Electrical Divisions; each Division having a high and low pressure core coolant injection system.

6. High Efficiency Turbine
A high efficiency turbine system is adopted, featuring the use of a 52-inch long blade for the last stage of the turbine, a two-stage moisture separator-reheater, and a heater drain pump-up system connected to the condensate system. Thermal efficiency is enhanced through the use of this system.

III. Development of ABWR-II
1. ABWR-II Design Requirements
The ABWR-II development project was initiated over a decade ago and has completed three phases to date. In Phase I (1991-92), basic design requirements were discussed and several plant concepts were studied. In Phase II (1993-95), key design features were selected in order to establish a reference reactor concept. In Phase III (1996-2000), based on the reference reactor concept, modifications and improvements were made to fulfill the design requirements.

In the early 1990s the project to develop a next generation reactor was initiated at a time when the first ABWR was still under construction at Kashiwazaki-Kariwa Nuclear Power Station. Initiating this project was not considered premature since replacement of operating power plants were anticipated in the next twenty years and sufficient lead-time was required to develop a new reactor.

At the initial stage of this project, developing an “Operator-friendly” plant design was the most important objective since a shortage in human resources was predicted for the 21st century. Thus, the main focus was on selecting design for easy operation and maintenance.
After the Chernobyl accident in 1986, the importance of the safety culture in the course of management of nuclear power was emphasized. Thus, we have seen some shift of the emphasis in the requirements from Operator-friendliness to Consumer-friendliness and Neighborhood-friendliness.

In the meantime, two important changes occurred in the Japanese nuclear industry. One was the delay of fast breeder reactor development due to trouble at Monju, and the other was the onset of deregulation in the electric power business. The delay of FBR development suddenly bolstered up the role of light water reactors, and the deregulation of electric power business highlighted the urgency of improving economics of nuclear power generation.

For these reasons, economical competitiveness became one of the most important objectives of developing ABWR-II. Even for Japan, escalation in fossil fuel prices or environmental restrictions on the consumption of fossil fuel will not be good enough to maintain the nuclear option. Nuclear power must exhibit clear economic advantages exclusive of price stability or energy independence in order to become a rational choice under economic globalization.

2. Improving Economical Competitiveness by Large Power Output

Judging from the past development history of nuclear reactors, we believed that increasing reactor size is a promising way to achieve better economy at nuclear power plants.

A major factor in nuclear power generation costs is capital costs. Since the rate of increase of capital costs is less than the increase of the rated power level, the so-called "merit of scale" from the power uprate can be substantial, while operation and maintenance costs are almost constant regardless of the plant's rated power level. Therefore increasing rated power level is an effective way to reduce nuclear power generation costs.

When the Phase I program started, the ABWR-II plant power output was set at 1350 MWe, the same as for ABWR. During Phase II, when the need for cost reduction increased, the reference output was increased to 1500 MWe to obtain a larger merit of scale. In Phase III, it became apparent that the target of 30 % power generation cost reduction was a tough objective. For example, engineering safety features are around 6% of the total cost and the impact on total cost reduction is rather small even if they could be eliminated completely. So, output was again increased to 1700 MWe as a reference.

Fortunately, TEPCO has a large transmission grid that can accommodate 1700MWe; also considering the future inevitable decommissioning of those plants and the difficulties in establishing a new power site, the idea of replacing the current operating power plants with larger plants is concluded to be a practical and economical option.

3. ABWR-II Design Overview

To conform to the above design requirements, various design features were adopted as illustrated in Fig. 3.

From an economic point of view, a 1700MW electric output, large fuel bundles (1.5 times large K-lattice), low-pressure-loss MSIV, and large-capacity SRV were adopted.

The output of 1700 MWe was determined considering compatibility with Japanese grid capacity and manufacturing capacity for components such as reactor pressure vessels and generators.

The 1.5 times large K-lattice concept was selected as the reference design due to its capability for increasing fuel inventory since the bypass flow region is smaller than that in the conventional design.
For enhanced safety, the reference design implements modified ECCS – with four sub-division RHR, diversified power source incorporating gas turbine generators (GTG), and advanced RCIC (ARCIC) –, passive heat removal systems – a passive containment cooling system (PCCS) and a passive reactor cooling system (PRCS) –, and passive auto-catalytic hydrogen recombiner (PAR). A modified ECCS configuration also enables online maintenance contributing to a higher availability factor.

The larger sized MSIVs and SRVs are adopted so as not to increase their numbers relative to the increased power level.

4. Large Fuel Bundles

A large fuel assembly design increases in-core fuel inventory reducing bypass flow region between fuel assemblies and improves thermal margin. The resulting improvement in thermal margin can be used for power uprate, higher burnup, and longer cycle operation. Large fuel bundles will allow adoption of a more flexible fuel cycle.

A large assembly design minimizes the size of the reactor pressure vessel and reduces the number of control rods and their drive mechanisms. Large fuel bundles will also help shorten refueling outage duration.

On the other hand, the larger bundle concept leads to two substantial phenomena that must be dealt with. One is a smaller cold shutdown margin (CSDM) due to the decreased number of CRs. The other is a more negative void coefficient due to the harder neutron spectrum since a smaller hydrogen-to-uranium (H/U) ratio with fuel inventory increase makes the neutron spectrum harder. This harder spectrum also leads to the CSDM decrease.

The K-lattice control rod concept can be a countermeasure for CSDM decrease due to enlargement of the fuel bundle. The K-lattice concept, compared to the conventional control rod design (C-lattice), is illustrated in Fig. 4. In the K-lattice concept, the number of CRs per bundle is increased because a fuel bundle faces two control rods along all four faces. As a result, the K-lattice control concept improves CSDM and makes it possible to adopt a larger bundle size.

5. Safety Design

(1) Modified ECCS

A four sub-division RHR configuration and emergency AC power sources are adopted from both an economic and safety perspective (Fig.5).

From the safety point of view, the increased redundancy and diversity of power sources – equipped with two emergency D/Gs and two GTGs – effectively boosts reliability, especially in the case of events such as

![Fig. 3 ABWR-II Design Features Overview](image)

![Fig. 4 Lattice Configurations Comparison](image)
earthquakes occurring. The modified ECCS also includes advanced RCIC (ARCIC) – a self-standing RCIC that can continue to operate without battery depletion at SBO – enhancing the safety performance even more.

From an economical point of view, maintenance for RHR, RCW, RSW, and emergency D/G can be conducted online, enabling shorter outage duration. Online maintenance of the above mentioned systems enables them to be effective during outages, leading to reduced shutdown risk. Also, due to the fact that ABWR-II only has 2 loops of cost dominant long piping of RCW/RSW – compared with 3 loops for ABWR – construction cost related to system safety is minimized.

(2) Passive Heat Removal Systems

In accordance with the safety design requirement for the combined active and passive safety systems, two passive heat removal systems – PCCS and PRCS – were introduced (Fig. 6). Besides providing a passive safety function, another virtue of PCCS and PRCS is that they are not reliant on seawater, thus providing diversity in terms of heat sinks.

PCCS is designed to passively condense steam released to the containment by heat exchangers (Hx) located in the water pool at the top of the containment vessel. Following an accident, high-pressure steam is released from the reactor pressure vessel to the drywell (D/W) and/or steam is generated in the D/W, raising the D/W pressure. The resultant pressure difference between the D/W and the suppression-chamber (S/C) drives the mixture of steam and non-condensable gas in the D/W into the PCCS-Hx through the steam line. The mixture enters the inlet header of the Hx and is distributed to the multiple heat transfer tubes in which the steam is condensed. The decay heat is transferred to the PCCS pool and subsequently diffused to the atmosphere.

PRCS is designed to passively remove heat from the primary cooling system through heat exchangers during a reactor isolation event. It is manually activated on severe accident conditions in which ARCIC and RHR becomes inoperable.

6. ABWR-II Development Plan

Development of the ABWR-II is under way, targeting its deployment in the late 2010s. Fig. 7 shows an example of schedule targeting for year 2015 deployment as the earliest scenario. Various R&D programs are planned especially to establish big components, such as the separator, lower plenum structure, SRV, MSIV, large fuel bundle, etc. Rationalization of the big component development is a key factor for ABWR-II commercialization.

In order to rationalize R & D programs, we also try to develop a design method by simulation technology, such as scaling models.

Fig. 5 Modified ECCS Configuration

Fig. 6 PCCS and PRCS Schematic.
IV. Conclusion

The next generation ABWR, the ABWR-II, has been under development for more than a decade in Japan. This new design will offer improved plant economy, greater safety margins, reduced maintenance and higher flexibility in the fuel cycle and plant operation. The ABWR-II is expected to replace older nuclear units approaching the end of their lifetime.

Table 3 presents the major design specifications of the ABWR-II along with a comparison to the ABWR.

Table 3 Major Design Specifications

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<tr>
<th>Item</th>
<th>ABWR-II</th>
<th>ABWR</th>
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<tr>
<td>Electric Power (MW)</td>
<td>1700</td>
<td>1356</td>
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<tr>
<td>Reactor thermal power (MW)</td>
<td>4960</td>
<td>3926</td>
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<tr>
<td>Maximum core flow rate (t/hr)</td>
<td>62.1x10^3</td>
<td>57.9x10^3</td>
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<td>Active core height (m)</td>
<td>3.71</td>
<td>3.71</td>
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<tr>
<td>Fuel bundle pitch (mm)</td>
<td>233.0</td>
<td>154.9</td>
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<tr>
<td>Number of CRDs</td>
<td>197</td>
<td>205</td>
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<tr>
<td>Number of fuel bundles</td>
<td>492</td>
<td>872</td>
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<tr>
<td>Volumetric power (kW/l)</td>
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<td>50.6</td>
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<tr>
<td>Power ratio (kW/kg)</td>
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<td>26.1</td>
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<tr>
<td>SRV (valves)</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>MSIV (valves)</td>
<td>8</td>
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These modifications allow the 1700MWe ABWR-II to have almost the same construction cost as the conventional 1356MWe ABWR. In addition, reducing the number of fuel bundles contributes to a shortened refueling outage period. The merits of plant initial investment and lower O&M costs are expected to provide the ABWR-II with approximately 15% lower power generation costs as compared to conventional ABWR.

Economical competitiveness is becoming a critical requirement for future energy resources due to the deregulation of electric power business.

We, TEPCO, have 17 nuclear power plants and have to prepare for their replacement in the future. ABWR-II is one of the most feasible and stable options to minimize the cost of replacing currently operating plants without incurring expensive R&D costs.

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References