OUTLINE OF ADVANCED BOILING WATER REACTOR

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INTRODUCTION

The ABWR design is based on construction and operational experience in Japan, USA, and Europe. It was developed jointly by the BWR suppliers, General Electric, Hitachi, and Toshiba, as the next generation BWR for Japan. The Tokyo Electric Power Co. (TEPCO) provided leadership and guidance in developing the ABWR, and in combination with five other Japanese electric power companies; Chubu, Chugoku, Hokuriku, Tohoku and the Japan Atomic Power Co. participated and provided support for testing and the development of the Joint Study Program.

The major objectives in developing the ABWR are:

(1) Enhanced plant operability, maneuverability and daily load-following capability;
(2) Increased plant safety and operating margins;
(3) Improved plant availability and capacity factor;
(4) Reduced occupational radiation exposure;
(5) Reduced rad-waste volume, and
(6) Reduced plant capital and operating costs.

These objectives were to be achieved through evolution and improvement in functional performance based on optimal selection of proven technology around the world. Extensive confirmatory tests of new features selected for the design were performed to demonstrate the plant performance and reliability.

The ABWR concept was developed as the results of a feasibility study made in 1978 - 1979 by the international design team, which we called Advanced Engineering Team (AET). The AET was made up of the following BWR suppliers: ASEA-ATOM of Sweden, Ansaldo Meccanico Nucleare (AMN) of Italy, General Electric of the USA, Hitachi, and Toshiba of Japan.

Following the conceptual design by the AET, the preliminary design and engineering were carried out to establish the ABWR concept in sufficient detail to allow a technical and economic evaluation to be made. In addition, a wide range of developmental and confirmatory tests of the new technologies and key components were done under the Joint Study Program by General Electric, Hitachi and Toshiba. Some new specific features of the ABWR, such as a Reactor Internal Pump (RIP), a Fine Motion Control Rod Drive (FMCRD), and a Reinforced Concrete Containment Vessel (RCCV), and other design features were tested by the six Japanese BWR utilities and the above three BWR suppliers under the Joint Study Program. These ABWR development program were an integral part of MITI's Third Improvement and Standardization Program and the confirmatory test of the reactor coolant recirculation system with reactor internal pumps was done by MITI.

The ABWR Phase II preliminary design was completed in 1983. Phase III, which followed and was completed in late 1985, achieved new goals by optimization of many ABWR design features, systems, and construction practices. This confirmed the technical superiority of the ABWR design and achieved significant cost reduction while retaining the overall safety and performance advantages.

PLANT DESIGN OBJECTIVES

TEPCO defined the major ABWR plant objectives very early in its development, aiming mainly at improve performance and safety and reduce costs, and these objectives remained basically unchanged throughout all development phase. These objectives guided the designers in selecting the new technologies to be applied in the ABWR design and also in developing the new features adopted. During the cost-down stages of design, these objectives were carefully reviewed and given priorities, with the cost objectives having primary importance. When cost-down items were reviewed, the design objectives were re-evaluated and the impact assessed in order to analyze the cost/benefit of each item, a process that resulted in firm recommendations for many items and the deletion of others, mainly due to some major negative impact on a particular objective.

The major plant objectives which guided the design are as described in the above "Introduction".

With these overall plant design objectives established, the designers and TEPCO developed a set of targets to help to quantify these objectives. As the design progressed and technical evaluations were completed and results compared with targets, more stringent targets were set in order to really optimize the design and make it highly competitive. This stringent goal led to much optimization of the system and equipment but also helped to achieve simplification as well. The cost reduction effort was successful and yet the resulting design also preserved the safety and performance objectives.

RESULTS OF THE PLANT DESIGN

The ABWR design represents the integration of eight years of conceptual development and design, along with the extensive confirmatory test program. The key features of the ABWR plant design include increased plant output, improved core and fuel design, reactor internal pumps for reactor coolant recirculation, fine motion control rod drives, simplified NSS systems along with an improved emergency core cooling (ECC) system, advanced controls and instrumentation utilizing microprocessor based on digital technology and multiplexed fiber optic signal transmission, a cylindrical reinforced concrete containment integrated with a compact Reactor Building and an improved turbine plant that utilizes 52-inch last-stage buckets, a two stage reheater, etc., all to improve efficiency and performance. Table 1 summarizes the major plant specifications and compares them with the present BWRs in Japan.

INCREASED PLANT OUTPUT AND TURBINE DESIGN

The ABWR plant is designed for a rated thermal output of 3926 MWt which provides for an electrical output in excess of 1350 MWe. In order to improve plant efficiency, performance and economy, the turbine design incorporates a 52-inch last stage bucket design. Combined moisture separator reheaters remove moisture and reheat the steam in two stages.

IMPROVED CORE AND FUEL DESIGN

The core and fuel design were performed based upon the proven design and technology which are available today. However, the best core and fuel design that will be available at that time will be adopted for an actual ABWR project.

Table 1. ABWR Major Plant Specifications

ITEM		ABWR	BWR-5
ELECTRICAL OUTPUT		1,356MWe	1,100MWe
REACTOR THERMAL OUTPUT		3,926MWt	3,293MWt
REACTOR PRESSURE		73.1kg/cm²	71.7kg/cm²
MAIN STEAM FLOW		7,640t/h	6,410t/h
FEED WATER TEMPERATURE		215.5℃	215.5℃
RATED CORE FLOW		52.2×10^6 kg/h	48.3×10^6 kg/h
FUEL ROD ARRANGEMENT		8 × 8	8 × 8
NUMBER OF CONTROL RODS		205	185
CORE AVERAGE POWER DENSITY		50.6kW/ℓ	50.0kW/ℓ
REACTOR PRESSURE VESSEL	INTERNAL DIAMETER	7.1m	6.4m
	HEIGHT	21m	22.1m
COOLANT RECIRCULATION (NUMBER OF PUMP)		INTERNAL PUMP (10)	EXTERNAL RECIRCULATION PUMP (2) INTERNAL JET PUMP (20)
CONTROL ROD DRIVE	NORMAL	FINE MOTION ELECTRIC MOTOR (18.3mm STEP)	HYDRAULIC LOCKING PISTON DRIVE (152mm STEP)
	SCRAM	HYDRAULIC PISTON DRIVE ELECTRIC MOTOR AS BACK-UP	HYDRAULIC PISTON DRIVE
EMERGENCY CORE COOLING SYSTEM (ECCS)		DIV. I : RCIC+LPFL DIV. II : HPCS+LPFL DIV. III : HPCS+LPFL ADS	DIV. I : LPCI+LPCS DIV. II : LPCI+LPCI DIV. III : HPCS ADS
REACTOR SHUTDOWN COOLING SYSTEM		3 TRAINS	2 TRAINS
CONTAINMENT COOLING SYSTEM			
PRIMARY CONTAINMENT		REINFORCED CONCRETE CONTAINMENT WITH LINER	SELF-STANDING STEEL CONTAINMENT
TURBINE CYCLE		TC 6F-52" (2-STAGE REHEATER)	TC 6F-41" (NON-REHEAT) TC 6F-43" (·)

RCIC : REACTOR CORE ISOLATION COOLING
LPCI : LOW PRESSURE COOLANT INJECTION
LPFL : LOW PRESSURE FLOODER
HPCS : HIGH PRESSURE CORE SPRAY
LPCS . LOW PRESSURE CORE SPRAY
ADS . AUTOMATIC DEPRESSURIZATION SYSTEM

REACTOR VESSEL INCORPORATING REACTOR INTERNAL PUMPS

The most dramatic change in the ABWR from previous BWR designs is the elimination of the external recirculation loops and the incorporation of reactor internal pumps for reactor coolant recirculation.

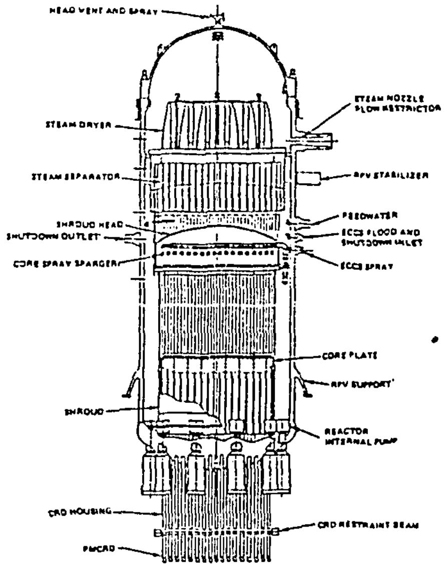


Fig. 1 RPV and Internals

The reactor pressure vessel (RPV), and core internals have been optimized for the reactor internal pump concept. As shown in Figure 1, all large pipe nozzles to the vessel below the top of the active fuel are eliminated. This alone improves safety performance during a postulated Loss of Coolant Accident (LOCA) and allows for decreased ECCS capacity, to be discussed later. The annulus formed between the vessel wall and the shroud in the core region provides the downward path for coolant flow, driven by the reactor internal pumps at the bottom of the vessel. It also allows for space requirements needed to lift the pump impellers and shafts for inspection.

The reactor pressure vessel is 7.1 m in diameter and 21 m in height. The reactor vessel height and total volume have been minimized, which have resulted in reduced volume requirements for the containment and reactor building (R/B). In-service inspection (ISI) has been reduced by incorporation of the reactor internal pumps and elimination of the recirculation pipe nozzles, and the reduced amount of welding needed during vessel fabrication. The reactor vessel has been designed to permit maximum ISI of welds, with automatic equipment. This helps to minimize manpower and reduce radiation exposure. Taking advantage of many design features and capitalizing on separator performance test data, the separator stand pipes have been shortened, the velocity limiter on the control blade was eliminated under the FMCRD design, and the new spherical RPV head all helped to reduce the RPV height by more than 1.5 meters from the present BWR design. This resulted in significant reduction cost. Other feature of the ABWR RPV design includes main steam outlet nozzles containing a reduced diameter throat and diffuser which is used to measure steam flow. This also acts to restrict flow and reduce loads on the reactor internals and reduces the containment loads during postulated LOCA. The steam driers and separators are of an improved lower pressure drop design developed for the BWR/6. This lower pressure drop contributes to increased stability margins and lower pump power costs.

The ABWR incorporates ten reactor internal pumps (see Figure 1 & 2) located inside the RPV at the bottom. This simplifies the nuclear boiler system and allows for compact space needs in the RCCV and R/B. Elimination of the external recirculation loops has yielded many advantages, the main ones being the reduction in containment radiation levels by more than 50% compared with present plants, lower pumping power requirements, and the excess flow resulting from pump design has enhanced plant operation and allows for full power operation even with one pump out of service.

The reactor internal pump is of wet motor design with no shaft seals. This provides increased reliability and has reduced the need for maintenance, resulting in reduced occupational radiation exposure. These reactor internal pumps have a lower rotating inertia, and coupled with the solid-state variable frequency power supply, can respond quickly to grid load transients and operator demands.

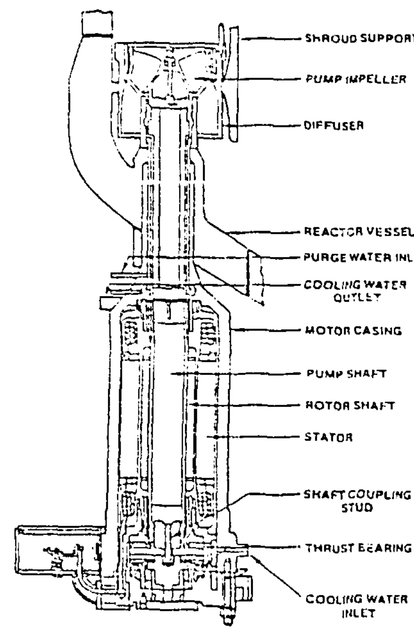


Fig. 2 Reactor Internal Pump (RIP)

FINE MOTION CONTROL ROD DRIVES (FMCRD)

The ABWR incorporates FMCRD, which provides electric fine rod motion during normal operation and hydraulic pressure for scram insertion.

Operation of the drive machanism allows fine motion (18 mm step) provided by a ball screw nut and shaft driven by an electric motor during normal operation. The electric motor also increases reliability through diverse rod motion to the hydraulic scram, because it acts as a backup with motor run-in following scram.

The FMCR allows for easier rod movement for small power changes and burnup reactivity compensation at rated power. It also reduces the stress on the fuel and enhances fuel rod integrity. Ganged rod motion (simultaneous driving of a group of up to 26 rods) and automated control significantly shorten startup time and improve power maneuverability for load following.

The ABWR FMCRD design was developed from the European design by reducing both length and diameter, and by adding the fast scram function. Other refinements in the FMCRD were made to reduce maintenance needs or to be able to perform easily maintenance and to reduce radiation exposure. For example, the integral shootout protection sleeve built in the FMCRD (see Figure 3) eliminates the external beam supports of present BWRs and the CRD housing is divided into two pieces (shorter CRD housing and seal housing). Figure 3 illustrates the key components of the FMCRD.

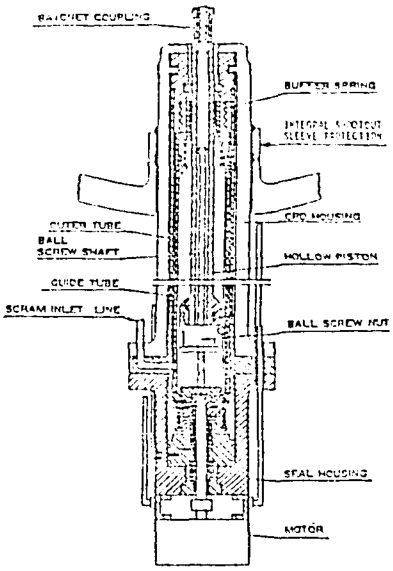


Fig. 3 Fine Motion Control Rod Drive (FMCRD)

OPTIMIZED SAFETY AND AUXILIARY SYSTEMS

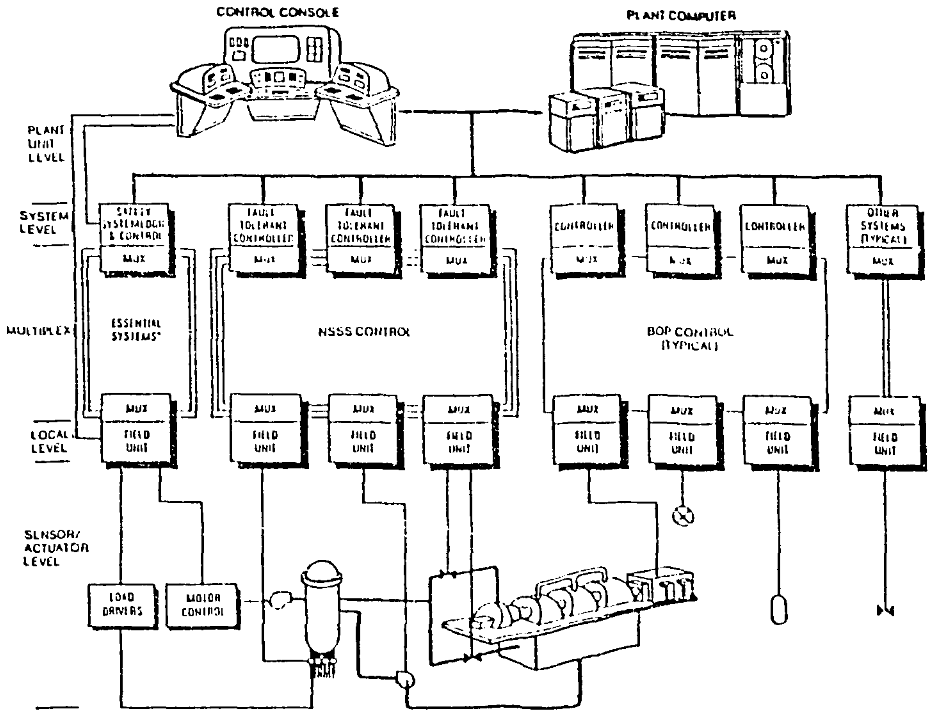
The ECCS and Residual Heat Removal (RHR) System along with the other auxiliary systems were reviewed to simplify and optimize design, which incorporates three redundant and independent divisions of ECCS and containment heat removal. The RPV, with the deletion of external loops and no large pipe nozzles in the core region, allows ECCS to reduce the capacity and yet the fuel remains covered through the full spectrum of postulated LOCAs. The ECCS network consists of three divisions each with one high pressure and one low pressure inventory makeup system. The high pressure configuration consists of two motor-dirven High Pressure Core Spray (HPCS) systems, each with its own independent overhead spray sparger and the Reactor Core Isolation Cooling System (RCIC), which has been upgraded to a safety system. The RCIC has the dual function of providing high pressure ECCS flow following a postulated LOCA, and also provides reactor cooling inventory control for reactor isolation transients. The RCIC, with its steam turbine driven power, also provides a diverse makeup source during any loss of all A-C power. The low pressure ECCS for the ABWR utilizes the three RHR pumps in the post-LOCA core cooling mode. These pumps provide Low Pressure Flooding and are labeled LPFL. The ECCS pumps provide core makeup over the full pressure range. For small LOCAs that do not depressurize the vessel and high pressure makeup is unavailable, an Automatic Depressurization System (ADS) actuates to vent steam through the safety relief valves to the suppression pool, and depressurizes the vessel to allow the LPFL pumps to provide core coolant.

As a result of these enhancements in the ECCS network and RHR, there is a substantial increase in the safety performance margin of the ABWR over earlier BWRs. This has been confirmed by the preliminary probabilistic risk assessment (PRA) for the ABWR, which shows that the ABWR has a factor of at least 10 higher than BWR/5 and 6 in avoiding possible core melt from degrading events.

ADVANCED CONTROL AND INSTRUMENTATION SYSTEMS

Digital technology and multiplexed fiber optic signal transmission technology have been combined in the ABWR design to integrate control and data acquisition of both the reactor and turbine plants. For the important systems, triplicated fault tolerant digital control is utilized. Multiplexing easily provides a high degree of redundancy in the control system, and also improves maintainability. Microprocessor-based digital monitoring and control (DMC) are introduced for monitoring and control functions in the ABWR plant in order to improve reliability. ABWR DMC technical advantages include self-testing, automatic calibration, user interactive front panels and full multiplex system compatibility. Plant startup and shutdown operations, TIP operation and nuclear instrumentation gain adjustments have been automated to reduce operator error and reduce plant startup time. Technological advances in the ABWR nuclear instrumentation areas include the fixed wide range in-core monitors with a period based trip design to replace the current source and intermediate range monitors and eliminate range switching during startup.

The use of multiplexed fiber optic data transmission in the ABWR is another new feature using advanced technology. The use of fiber optic multiplexing reduces the amount of cabling and cable pulling time during construction. This also reduces the overall cost of the control and instrumentation area. This multiplexing system has been applied to the plant protection and engineered safeguard system as well as nuclear steam supply and balance of plant control systems. The conceptual structure for application of this digital and optical transmission technology is shown in Figure 4.



* REPRESENTS ONE OF FOUR SAFETY DIVISIONS

Fig. 4 Multiplexing Concept

CONTAINMENT AND REACTOR BUILDING DESIGN

For the ABWR, the cylindrical RCCV with its pressure suppression concept, was selected as the reference design of the primary containment vessel. The concrete walls of the RCCV are integrated with the reactor building and form a major structural part of the building. The annular top slab of the drywell is also integrated with the upper pool girders that run across the building and have direct connection with the building's outer walls. The pressure retaining concrete wall of the RCCV is lined with leak-tight steel plate. The cylindrical design allows for easier and faster construction.

The ABWR design represents a very significant reduction in reactor building volume and cost. The reactor building volume is approximately 157,000 cubic meters including three emergency diesel generator rooms.

The reactor building is divided into three quadrants to provide separation of the three division configuration of the safety systems. Figure 5 represents the RCCV and reactor building design concept.

TEST AND DEVELOPMENT PROGRAM

An extensive test and development program was undertaken to support and confirm the ABWR design. These programs were initiated to confirm the feasibility and reliability of new features and advanced technologies, to continue the "test-before-use" concept. These tests also had the objective of addressing any licensing concerns.

The program was initiated by the industry and the Japanese government. The ABWR Joint Study Program was a joint effort of six Japanese utilities and the three BWR suppliers. More than twenty specific items were selected to confirm either new components or advanced technologies, and most of these programs have been completed. The Japanese government, through the Nuclear Power Engineering Test Center (NUPEC), performed a confirmatory test program, focussing on the integrated performance of the reactor system in the large scale test facility, with particular emphasis on the reactor internal pumps.

TECHNICAL EVALUATION

The technical evaluation of the ABWR design demonstrates that the integrated plant characteristics and performance are improved over existing BWRs. This resulted from the careful consideration given to new features, the application of advanced technologies, and the incorporation of proven technologies. The inte-

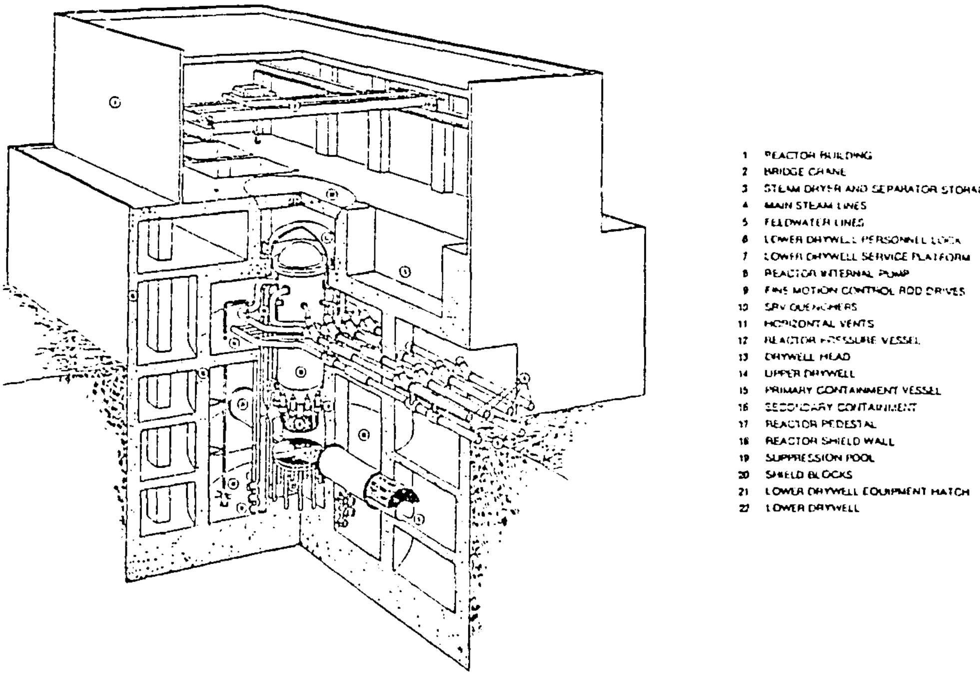


Fig. 5 RCCV and Reactor Building

gration and optimization of the overall plant design has provided a superior design, on which some of the key evaluation results are summarized below.

SAFETY

The reactor internal pump concept, which eliminated the external loops and large nozzles in the core region, along with an improved ECCS network, has improved the safety performance in relation to a postulated LOCA. For a spectrum of pipe breaks, including a Design Based Accident, the fuel remains covered and there is little core heatup. The three division redundant containment heat removal system (RHR) has also improved the long term heat sink reliability. Other features also contribute to the overall safety improvement. These safety features include: Diversified electric-hydraulic control rod insertion capability of the FMCRDs to enhance scram reliability, and the improved structural characteristics of the integrated RCCV and reactor building for increased seismic and LOCA-generated load capability.

The PRA study was performed to evaluate the relative safety of the optimized design. The ABWR PRA result was estimated to be at least a factor of 10 lower for core melt probability than present BWRs, based on Japanese initiating events and assuming a standard set of internal events.

OPERABILITY

The ABWR has improved operability over present plants through the incorporation of reactor internal pumps and their excess core flow above the rated flow, FMCRDs, triplicated fault-tolerant digital controls, improved core design, automated reactor plant operation, and advanced control room with improved man-machine interface.

Load following with the ABWR can be done within the range of 100%-50%-100% power due to the excess core flow and automated FMCRDs. The plant has fast response to positive load demands due to ganged control rod operation of the FMCRDs, and fast response to power maneuvers due to rapid flow control with low inertia RIP and solid state variable speed power source. Increased use of automated operations throughout the plant can reduce the required crew to seven persons per two units.

ANNUAL REFUELING AND MAINTENANCE OUTAGE

For the ABWR plant, even though the number of fuel assemblies is increased, the actual duration of fuel handling is less because shuffling is reduced by core design improvements and reduction in fuel movement for CRD inspection, since there is less need for CRD removal due to adoption of FMCRD. The FMCRDs substantially reduce maintenance because complete CRD need not be removed when checking and exchanging the motor or spool piece or replacing the easy-to-repair shaft seal, due to the two piece housing design. In addition, graphite parts have been eliminated in the FMCRD, thus reducing the number of drives to be maintained. Use of automated handling and maintenance equipment for the fuel, RIP and CRD have also helped to reduce outage period. The current evaluation indicates that the annual inspection can be completed in 55 days, assuming 12 months of continuous operation.

CAPACITY FACTOR

The ABWR is projected to have a capacity factor of 86% based on past experience with the USA and Japan BWRs, with major equipment problems overcome. This is based on 12 months of continuous operation and a 55-day refueling outage. This excellent capacity factor is made possible through the application of ABWR features, such as improved barrier fuel, improved core design that eliminates rod pattern exchange during operation, automated plant startup, self-test and fault tolerant characteristics of the digital solid state controls, and others.

OCCUPATIONAL RADIATION EXPOSURE

The elimination of the large reactor coolant recirculation loops in the drywell eliminates one of the largest radiation sources in the drywell and reduced maintenance and inspection needs as well. The reduced FMCRD removal and maintenance as well as the FMCRD clean water purge reduces exposure during maintenance. Use of automated maintenance and handling equipment also reduces radiation exposure. Improved corrosion control throughout the plant and adoption of cobalt free materials all contribute to reduction of radiation levels throughout the plant.

ABWR occupational radiation exposure is estimated to be 49 man-rem/year. The above values are projections based on plant operating experience data over the past several years. The first refueling outage of K-1 (110 MW) plant for 91 days experienced extremely low occupational radiation exposure figure (i.e. 18.7 man-rem). So we expect that the occupational radiation exposure in ABWR plant will be more reduced than this estimation.

CONSTRUCTION PERIOD

The construction period from rock inspection to commercial operation is projected as 48 months. This period covers site unique conditions such as the deep base rock, the severe climate, and the interference from neighboring units during construction. Adoption of new construction practices such as modular fabrication, and the use of a large capacity crane and deck plates shortens the construction period. Reduced volume of the Reactor and Turbine Buildings are important to shorten the construction period.

ECONOMICS

As described above, the construction period of ABWR plant is shorter than current nuclear power plant, and the volume of the reactor and turbine buildings are extremely small. In these situations, the construction cost per kW for ABWR will be around 20% below the conventional BWR-5. The generating cost is expected to be more than 20% lower compared with that of BWR-5. The reason for this reduction is the construction cost reduction and higher plant efficiency, lower fuel cost and higher capacity factor, which result from the ABWR features mentioned earlier.

SUMMARY

The ABWR development objective focused on a optimized selection of advanced technologies and proven BWR technologies for an improved BWR. The description of the key ABWR features and their advantages and performance improvements demonstrate the success of the integrated plant design. The overall technical evaluation shows the superiority in terms of performance characteristics and economics which the ABWR design has achieved.

The ABWR is an optimal design for the 1990s, meeting its objectives and providing a BWR which utilizes advanced technologies, capabilities, performance improvements, and yet provides economic advantages.