FUTURE DIRECTIONS IN BOILING WATER REACTOR DESIGN

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ABSTRACT

The Advanced Boiling Water Reactor (ABWR) is being developed by an international team of BWR manufacturers to respond to worldwide utility needs in the 1990's. Major objectives of the ABWR program are design simplification; improved safety and reliability; reduced construction, fuel and operating costs; improved maneuverability; and reduced occupational exposure and radwaste.

The ABWR incorporates the best proven features from BWR designs in Europe, Japan and the United States and application of leading edge technology. Key features of the ABWR are internal recirculation pumps; fine-motion, electro-hydraulic control rod drives; digital control and instrumentation; multiplexed, fiber optic cabling network; pressure suppression containment with horizontal vents; cylindrical reinforced concrete containment; structural integration of the containment and reactor building; severe accident capability; state-of-the-art fuel; advanced turbine/generator with 52" last stage buckets; and advanced radwaste technology.

The ABWR is ready for lead plant application in Japan, where it is being developed as the next generation Japan standard BWR under the guidance and leadership of The Tokyo Electric Power Company, Inc. and a group of Japanese BWR utilities. In the United States it is being adapted to the needs of US utilities through the Electric Power Research Institute's Advanced LWR Requirements Program, and is being reviewed by the US Nuclear Regulatory Commission for certification as a preapproved US standard BWR under the US Department of Energy's ALWR Design Verification Program. These cooperative Japanese and US programs are expected to establish the ABWR as a world class BWR for the 1990's.

International cooperative efforts are also underway aimed at development of a simplified BWR employing natural circulation and passive safety systems. This BWR concept, while only in the conceptual design stage, shows significant technical and economic promise.

I. INTRODUCTION

The theme of this Conference is "The Outlook For Nuclear Power In The 1990's". This paper provides some perspectives on this subject as they relate to General Electric's Boiling Water Reactor.

The world nuclear industry is currently in a hiatus period between what might be termed the First and Second Nuclear Ages. The First Nuclear Age began with President Eisenhower's Atoms for Peace program in 1954, and ended with the world oil shock in 1973. It was a period of rapid expansion of nuclear power during which several light water reactor design concepts, and many variations on these concepts, were tried. Most of the world's nuclear plants have their origin in the First Nuclear Age.

The plants from the First Nuclear Age are providing a wealth of experience -- regulatory, design, construction and operating experience -- which is available to guide future designs. The challenge for future designers is to tap this experience and use it in designing the light water reactor plants which will provide the foundation of the Second Nuclear Age.

The Second Nuclear Age is likely to see a relatively small number of standard plants in contrast to the proliferation of designs in the past. This is expected to result both from the natural "sorting out" of the more successful design features, and from the high front-end costs of developing new designs. Some of these will be "international standard designs" as the worldwide industry seeks to pool its experience and share development costs.

General Electric anticipated these trends and responded in 1978 by launching its Advanced BWR program. The first step in Advanced BWR development was the formation in San Jose, California, of an "Advanced Engineering Team" (AET), consisting of representatives of worldwide BWR suppliers and leading Architect Engineer firms. The 25 member team of senior engineers was led by General Electric and included members from Hitachi and Toshiba of Japan, ASEA-Atom of Sweden and Ansaldo of Italy. The team was provided architect engineering support by NUCON of the Netherlands and Bechtel and Ebasco from the USA. The team's mission was to evaluate the worldwide BWR technology and design a world class BWR which would combine the best features and technology from around the world. The AET effort was completed in 1979 and established the basic ABWR concept.

During the period 1980-85 ABWR development was focused in Japan. Under the sponsorship of The Tokyo Electric Power Company, Inc. and a consortium of Japanese utilities, General Electric, Hitachi and Toshiba performed design development studies to confirm the ABWR's technical and economic attractiveness, and conducted a comprehensive test program encompassing the new features. This ABWR development effort was completed in late 1985. The next step in the ABWR program is expected to be realization and demonstration of the merits of the design through detailed design licensing and construction of the lead units in Japan. Section II of this paper describes the ABWR design resulting from this international development effort.

A major focus of the ABWR program from the beginning has been to establish the ABWR as a world class standard plant. Toward this end, efforts have recently been initiated in the United States to obtain regulatory certification of the design as the first certified United States standard plant. This program is moving forward under the joint sponsorship of the United States Department of Energy and General Electric, and is scheduled for completion in 1991. It is closely coordinated with the Electric Power Research Institute's ALWR Requirements Program discussed elsewhere at this meeting. Section III of this paper describes the United States ABWR Certification program.

The ABWR will provide a state-of-the-art, large plant to serve the needs of world utilities in the future. Recently, however, there has been increasing utility interest in potential future nuclear units combining the characteristics of smaller size, greater simplicity and more passive safety features. This interest is driven by a worldwide slowdown in electrical growth rates which provides an incentive for smaller capacity additions, and by a recognition that smaller nuclear units offer potential simplifications with attendant economic benefits. A Small/Simplified BWR program involving General Electric, the Electric Power Research Institute, and the US Department of Energy has recently been initiated to determine the technical and economic feasibility of a BWR plant with these characteristics. Moreover, the Japan Atomic Power Company and GE have performed a joint study to evaluate the technical feasibility of this concept. Initial results of this program, described in Section IV of this paper, are very promising.

II. ADVANCED BWR

A. Objectives

From its inception, the purpose of the program was to design an advanced LWR which compared to other designs, would meet the following objectives:

- Improved Operability
- Improved Capacity Factor
- Improved Safety & Reliability
- Reduced Occupational Exposure
- Reduced Costs
  - Construction
  - Maintenance
  - Operation
  - Fuel Cycle

These objectives and the design approach adopted are discussed in more detail in References 1, 2 and 3. Reference 3 is a paper presented at this conference by Yosho Matsuo of The Tokyo Electric Power Company, Inc.

The trend of utility requirements has been toward increased system and equipment reliability, and reduced potential for operator error through improved system/operator interfaces and simplified systems and equipment. The ABWR follows this trend.

B. Description

Plant Size/Core

The reactor thermal output is 3926 MWt which provides for a turbine-generator gross output in excess of 1356 MWe. The rector core consists of 872 fuel bundles operating at a power density of 50 kW/liter. The ABWR like all BWRs is capable of using the most current advanced fuel/core design features. Examples of recent fuel improvements are fuel rods with a zirconium barrier liner, axial variation of enrichment and gadolinia, high fuel exposure, minimal control cells, no shallow control rods and no rod pattern exchanges.

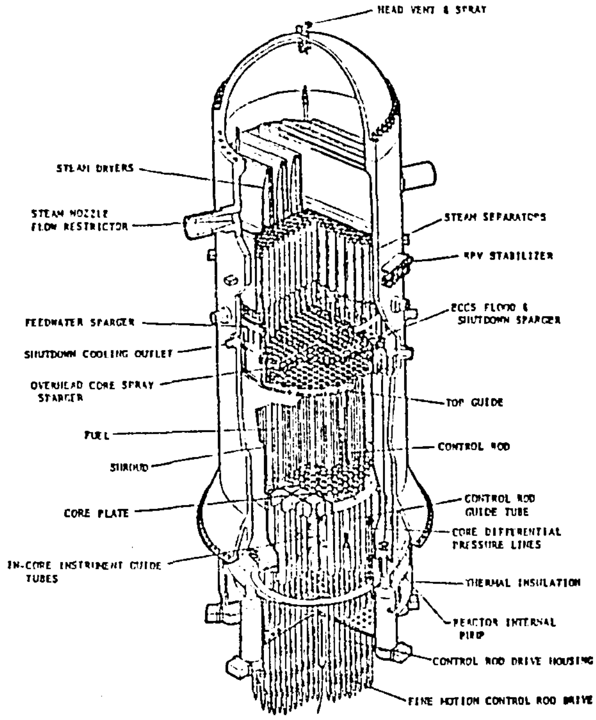

Figure 1 Advanced BWR Reactor Assembly

Reactor Assembly

The reactor assembly (Figure 1) utilizes a standard BWR reactor pressure vessel configuration equipped with 10 internal pumps for recirculation flow and with electrical-hydraulic control rod drives for fine motion rod control. The reactor pressure vessel has a single forged ring for the internal pump mounting nozzles and the conical support skirt. Forged rings are also utilized for the core region of the vessel shell sections. The elimination of the external recirculation piping and the use of the vessel forged rings has resulted in over a 50% reduction in the weld requirement for the primary system pressure boundary. This inherently increases the integrity of the system and, of course, results in a sizable capital cost and inservice inspection savings. The reactor assembly design permits the following design and operating improvements:

- Elimination of external recirc piping.
- Reduction of containment radiation level by over one-half compared to current plants.
- Over 10% excess flow capability at rated power.
- Lower recirc flow pumping power.
- Elimination of large reactor pressure. vessel nozzles below the reactor core top elevation.
- Reduced control rod drive maintenance.
- Electrically ganged control rod drives.
- Diverse control rod drive insertion capability.

The reactor pressure vessel is approximately 7 meters in diameter and 21 meters in height. The vessel is of standard BWR vessel design except for two items; the annular space between the RPV shroud and the vessel wall is increased to permit the positioning of the 10 internal pumps used for recirculation flow. Also, the standard cylindrical vessel support skirt has been changed to a conical skirt -- again to permit the use of the internal pumps. The internal pumps are of the wet-motor glandless type. Significant plant operation experience with these pumps is now being accumulated in a number of European BWR plants. In addition, this type of pump has been the favored design for high pressure fossil boiler circulation pumps for many years.

Emergency Core Cooling

The emergency core cooling system (ECCS) and the residual heat removal (RHR) system have been designed on a three-division basis. Two divisions each provide high pressure core spray and low pressure coolant injection capability. A third division combines a reactor steam-driven turbine pump for high pressure coolant injection and a low pressure coolant injection system. A triple redundant water delivery/decay heat removal system provides the RHR function. The elimination of large nozzles on the reactor vessel below the core permits the design of an ECCS system with no core uncovery during the design basis Loss of Coolant Accident (LOCA), and at the same a reduction in total ECCS pump capacity to approximately one-half of that required for an equivalent-size external loop BWR plant.

Control and Instrumentation

The control and instrumentation systems feature digital/solid state equipment. This equipment permits a design which increases the system redundancy, provides fault tolerant operation and the inclusion of self-diagnostics while the system is in operation. Coupled with the digital controls is a multiplexing arrangement for C&I signal transmission. The multiplexing system complements the digital control design. It includes fiber optic isolation capability. The C&I changes defined are most dramatic and result in improved operability and availability; and save considerable construction time with a resultant decrease in capital cost.

Reactor Building/Containment

The reactor building structural design is of reinforced concrete with a seismic design basis of 300 gal. for the S1 or Operating Basis

Earthquake (OBE) and a 450 gal. for the S2 or Safe Shutdown Earthquake (SSE). The containment design is of the pressure suppression type with a covered suppression pool. From a structural design standpoint, it is a lined, reinforced concrete structure. The containment design features a unique horizontal vent system for the LOCA venting of the drywell to the suppression pool. From an arrangement standpoint (Figure 2), the elimination of the external recirc piping system permits significant improvements in drywell space utilization -- particularly in access for inspection and maintenance activity. The containment area beneath the reactor pressure vessel has also been optimized to provide operating/maintenance space for the Reactor Internal Pumps (RIP) and Fine Motion Control Rod Drives (FMCRD). The containment structure and the reactor building structure have been fully integrated from a structural design standpoint. This has permitted an improved structural capability and has also enhanced the layout of the equipment and structure. The ABWR reactor building total enclosed volume compares very favorably with past BWR plant reactor building designs.

C. Technical Evaluation

An evaluation of the ABWR design indicates that the design objectives have been achieved and the integration and optimization of the overall plant design has resulted in a superior standardized design. The ABWR Performance Characteristics are summarized below:

ABWR PERFORMANCE CHARACTERISTICS	
Electrical Output (MWe)	1350
Construction Schedule (Months)	48
Capacity Factor (%)	86
Refueling/Maintenance Outage (Days)	55
Daily Load Following Range (% of Rated Power)	<50-100
Core Damage Probability (Per Year)	$<10^{-6}$
Occupational Exposure (mrem/year)	100
Solid Radwaste (Drums/year)	100

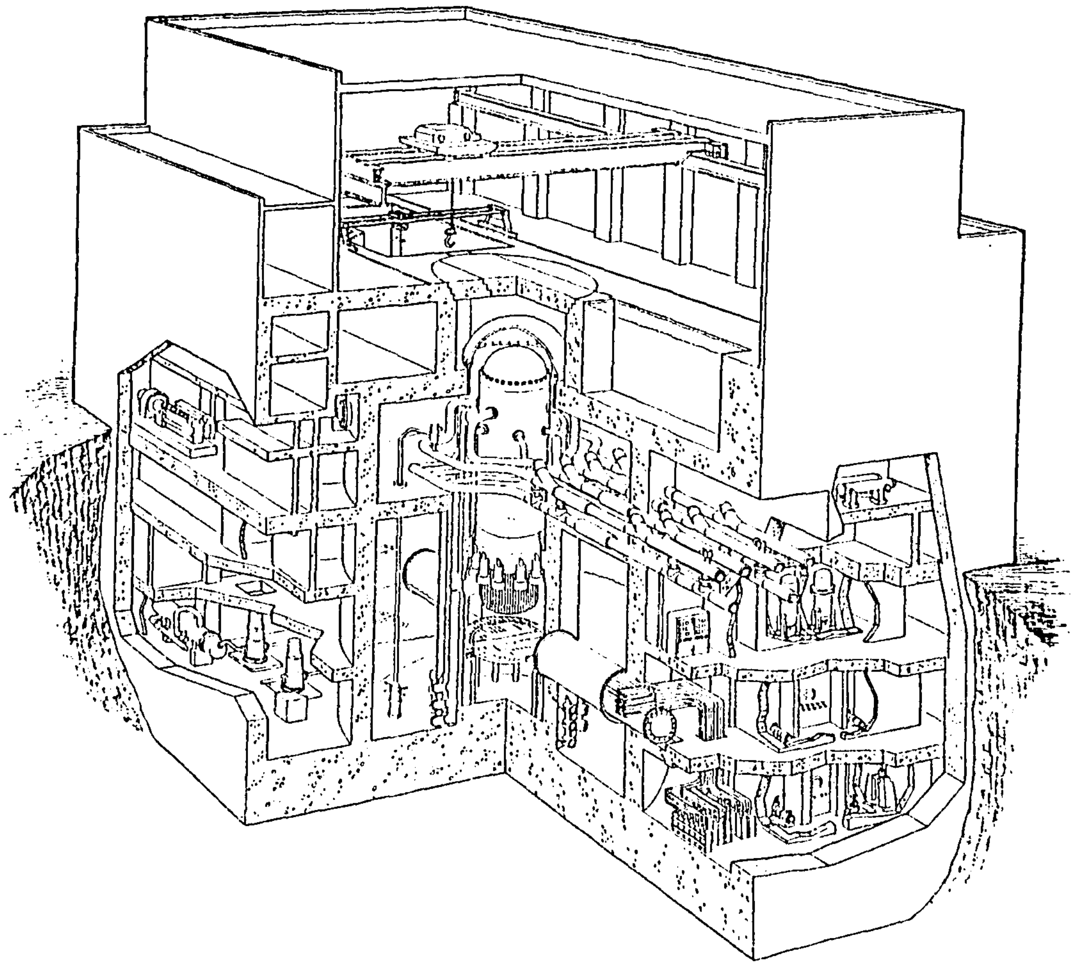

Figure 2 ABWR RCCV and Reactor Building

III. ABWR CERTIFICATION

In the fall of 1987, the USNRC will begin its technical review of the ABWR under the ABWR Certification Program. The review is expected to culminate in the first certified US Standard plant enabling it to be referenced by multiple utilities for use on multiple sites without challenge during subsequent licensing hearings. The design would be approved for a ten year period, with an option for renewal.

Certification of standardized nuclear power plant design is an important US initiative that has the potential for significantly enhancing safety, reliability, and availability, and reducing the cost of nuclear plants. The combination of certified designs and preapproved sites can significantly reduce the time and cost required for licensing and construction of nuclear power plants.

The basis for the review will be a Standard Safety Analysis Report (SSAR) that describes the ABWR plant performance characteristics, methods and results of analyses, arrangement and layout drawings all in sufficient detail to enable the NRC to complete its standard plant review. The ABWR SSAR will include information that will form the basis of construction verification and compliance reviews when the design is subsequently applied to actual projects.

The ABWR Certification Program is part of a cooperative effort of US utilities, government and industry to develop requirements and designs for future standard LWRs in the United States. This effort includes: (1) the development of utility requirements for future LWRs through the EPRI ALWR Requirements Program, (2) the development by industry of ALWR designs which address these requirements (e.g., the CE-ABWR) and (3) government sponsored certification of these designs. Figure 3 shows the relationship and schedule for those efforts.

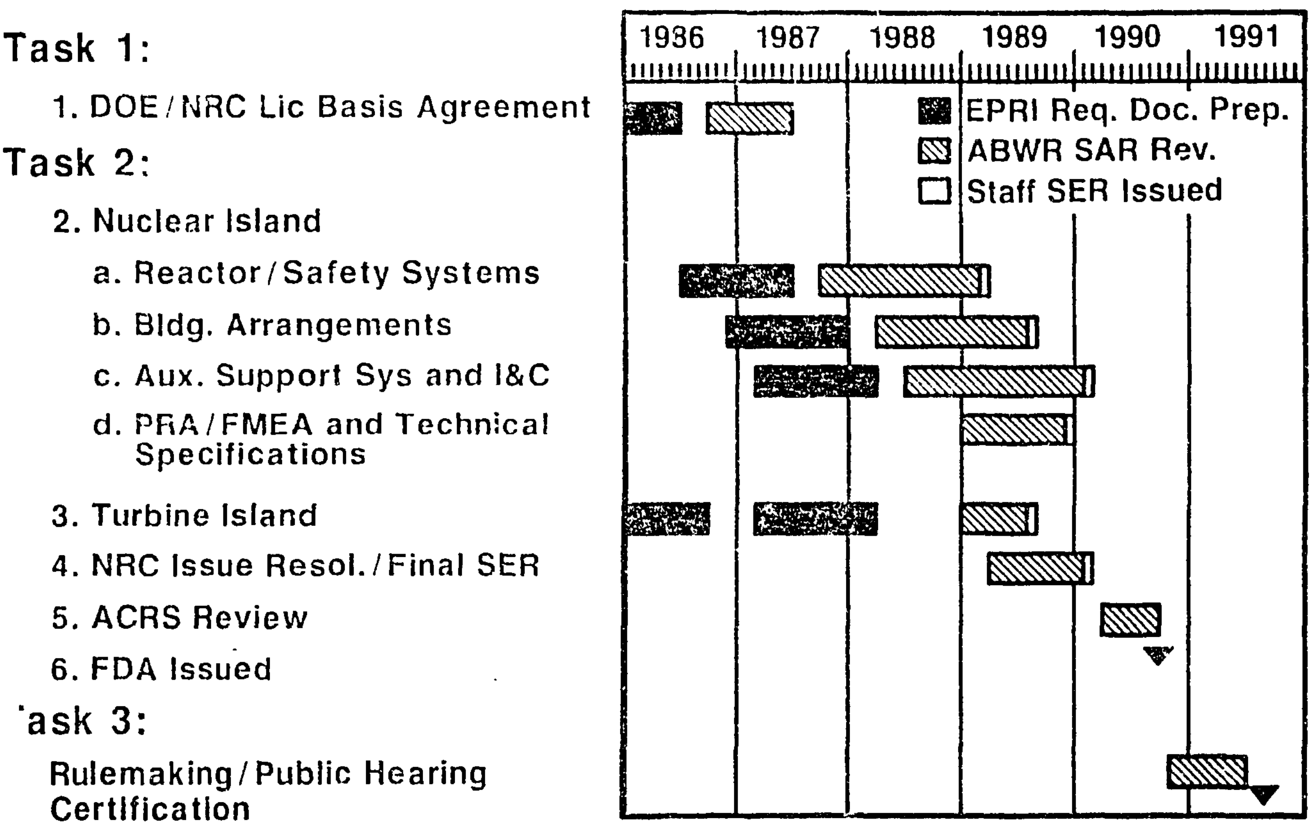

FIGURE 3 ABWR CERTIFICATION PROGRAM SCHEDULE

IV. SMALL/SIMPLIFIED BWR (SBWR)

A. Objectives

Recently there has been increasing utility interest in potential future nuclear units combining the characteristics of smaller size, greater simplicity and more passive safety features. This interest is driven by a worldwide slowdown in electrical growth rates which provides an incentive for smaller capacity additions, and by a recognition that smaller nuclear units offer potential simplifications with attendant economic benefits. In response to such interest, General Electric began development in 1982 of a 600 MWe BWR with simplified power generation, safety and heat removal systems. The following basic objectives for the new design were established:

- Power generation costs must be superior to coal.
- Plant safety systems should be simpler than those employed in current designs.
- The design should be based on existing technology.
- The design should considerably shorten construction schedules.
- Plant should have an electrical rating in the 600 MWe range.

B. Description

A brief description of the General Electric SBWR Concept (Fig.4) follows. Additional details are covered in Ref. 4.

The SBWR uses natural circulation to provide flow to the reactor core. The suppression pool is elevated to a position above the reactor. In an emergency, a gravity driven core cooling system is used. The reactor is depressurized and water from an elevated suppression pool flows by gravity to the reactor vessel to keep the reactor core covered. The concept also features a passive containment cooling system in which water flows by gravity to cool the suppression pool wall. No operator action is required for a period of at least three days. Use of these and other passive systems allows the elimination of emergency diesel generators, core cooling pumps and heat removal pumps which simplifies plant design and licensing and will reduce plant costs.

The 600 MWe SBWR Reactor Island which includes the Reactor Building and the Service Buildings mounted on a common basemat with the Turbine Island (not shown) is shown in isometric view in the figure. A summary of the major new SBWR features is provided below.

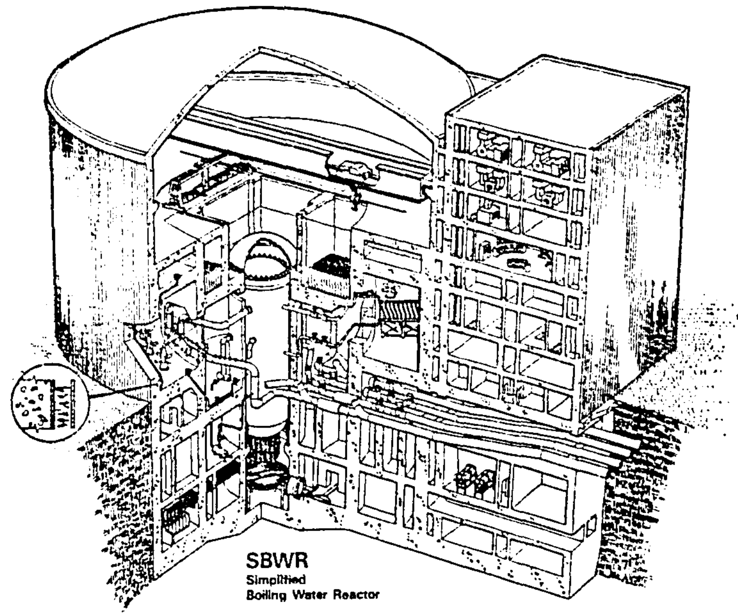

FIGURE 4 REACTOR ISLAND

Low Power Density Core and Natural Circulation

The selection of natural circulation (with power density reduced to about 36 kW/liter) as the means for providing coolant flow through the reactor provides a number of benefits to help satisfy SBWR objectives. Compared to higher power density of forced circulation designs, the natural circulation SBWR reactor offers 7-15% lower fuel cycle costs, a reduced number of operational transients and increased thermal margin for the transients which are expected to occur. In addition, elimination of the recirculation loops, pumps and controls needed for forced circulation substantially simplifies the design.

Isolation Condenser

An isolation condenser is placed in the elevated suppression pool. An isolation condenser is employed in many earlier BWR designs. When the reactor vessel is isolated from the turbine condenser, the isolation condenser controls reactor pressure automatically without the need to remove fluid from the reactor vessel. Thus, the conventional BWR safety relief valves, which open and close to discharge reactor vessel steam to the suppression pool, are not needed in the SBWR concept.

Gravity Driven Core Cooling System

The Gravity Driven Core Cooling System provides a simple approach to Emergency Core Cooling, eliminating the need for pumps or diesels.

It requires more water in the reactor vessel above the core and additional depressurization capacity so the reactor can be depressurized to very low pressures and gravity flow from the elevated suppression pool can keep the core covered. However, because there are no large pipes attached to the vessel near or below the core elevation, the design insures full core coverage for all design basis events. The additional water provided also has other benefits such as reduced pressure rates for transients and substantially more time to core uncovering in multiple failure scenarios.

Passive Containment Cooling System

The Passive Containment Cooling System in which the suppression pool wall is cooled by natural circulation water flow provides a 3-day passive cooling capability for the containment. No active pumps or diesels are needed to provide for heat removal. Beyond 3 days, water makeup is all that is needed to continue the passive cooling functions. Containment venting is therefore not necessary to retain containment integrity. This feature, together with drywell flooding for design basis and severe accident events, offers the potential of the site radiological consequences for design basis events or severe accidents being a very small fraction of licensing limits.

Simplified Control and Electrical System

A passive natural circulation air system is used to provide habitability control for control room operators. This feature, combined with the passive gravity driven core cooling system and the passive containment cooling system allows safety grade emergency diesel generators to be eliminated from the SBWR concept. The building space needed for the control complex is less than half of that required on conventional designs because of the advanced man-machine interface incorporated into the design as well as the use of a plantwide, intelligent multiplexing system and extensive use of standard microprocessor based control and instrumentation modules.

Simplified Power Generation Systems

A tandem double flow turbine with 52-inch last stage buckets reduces building size and simplifies the condenser and piping arrangement. A single string of feedwater heaters is employed to reduce costs and simplify the feedwater and condensate system arrangement. Variable speed motor-driven feed pumps provide reduced cost and simpler controls. The pumps used to pump forward the high pressure drains have been eliminated by regulating the feed pump suction pressure to allow the drains to be pressure driven into the feedwater cycle to reduce capital and operating costs. The separate steam seal system used in earlier applications is eliminated based on evaluations which indicate that the contribution of this system to radiation exposure reduction (particularly with modern BWR fuel) is insignificant. The main condenser is located under and to the side of the turbine, allowing the turbine pedestal to be lowered, thus reducing capital costs.

Development Status

In late 1985 General Electric (teamed with Bechtel and MIT) conducted a conceptual design study for the Electric Power Research Institute (EPRI) to further develop the GE SBWR. The effort was completed in April 1986 and served as the basis for EPRI's selecting the GE team to develop the concept in more detail over the next three years.

In early 1986 the United States Department of Energy (DOE) selected GE (teamed with Bechtel and MIT) to conduct several test and design development programs in support of the GE concept. Work on this contract was initiated in August 1986 and is expected to last about three years. Tests will be performed to confirm the characteristics and operation of the Gravity Driven Core Cooling System and a Steam Injector System. A prototype Depressurization Valve will be designed and qualified by tests. Engineering work on the Advanced Containment Design and a Construction Plan which features extensive modularization will also be performed. The DOE programs are summarized below.

In 1986 Japan Atomic Power Company (JAPC) and GE completed a joint study to evaluate the preliminary technical feasibility of the SBWR concept. Those studies were performed on reactor, safety, containment and related plant arrangement/structures. Preliminary licensing evaluations have been performed. The overall plant concept appears feasible and attractive.

DOE PROGRAM		
TASK	MAJOR BENEFITS	MAJOR WORK AREA
o GRAVITY DRIVEN CORE COOLING	o PASSIVE SAFETY o EQUIPMENT ELIMINATION	o MODELS UPGRADED ECCS QUALIFICATION TESTS
o DEPRESSURIZATION VALVE	o FAIL OPEN DEPRESSURIZATION VALVE FOR GRAVITY COOLING	o VALVE DESIGN o PROTOTYPE PROCUREMENT o QUALIFICATION TEST
o PASSIVE CONTAINMENT SYSTEM	o ZERO POST ACCIDENT SEVERE RELEASE o PARTICULATES AND NOBLE GASES RETAINED IN POOL o REDUCE CAPITAL COST, CONSTRUCTION TIME	o DESIGN STUDIES o IDENTIFY BEST PASSIVE SYSTEM o DEFINE CONTAINMENT CONFIGURATION
o STEAM INJECTOR SYSTEM	o INCREASED SAFETY/ RELIABILITY (PASSIVE)	o DEFINE REQUIREMENTS o FULL SCALE QUALIFICATION TESTS
o CONSTRUCTION PLANNING	o DEMONSTRATE MINIMUM AND CREDIBLE CONSTRUCTION TIMES	o MODULARIZE STUDIES o CONSTRUCTION PLANS

SUMMARY

In summary, international cooperative programs are in place to bring it to being a new generation of BWR plants. These plants will incorporate the best features and technology from the current generation of worldwide BWRs and will represent "world class" standard plants to serve utility needs in the 1990's and beyond.

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