Chapter 1 Introduction

Nuclear Energy for the New Millennium

Nuclear energy plays a major role in meeting the world's energy needs. At the end of 1998, there were 442 nuclear power plants operating in 32 countries. These plants account for 17% of the world's electricity. The industry remains dynamic, as evidenced by the fact that several new plants enter commercial operation every year and there are, typically, 30 or more in various stages of construction at any given time.

Generating electricity with nuclear energy permits economic and social development to be sustainable; that is, not limited by encroaching environmental concerns. A non-nuclear, baseload power plant generates electricity by burning fossil fuels day in and day out and releasing the byproducts to the environment. A nuclear plant, on the other hand, generates large amounts of electricity with virtually no impact on the environment. In quantitative terms, if the world's nuclear plants were replaced with coal-fired plants, global CO_2 emissions would increase by 8% every year. This would amount to 1600 million tons per year at a time when the world is trying to reduce emissions by 4200 million tons per year. Similarly, if the world's growing appetite for new electricity is met without nuclear energy playing a key role, CO_2 emissions would quickly rise to levels that curtail economic growth.

The Advanced Boiling Water Reactor (ABWR) advanced nuclear plant will play an important role in meeting the conflicting needs of developed and developing economies for massive amounts of new electricity and the need worldwide to limit CO_2 emissions. Two ABWRs have been constructed in Japan and are reliably generating large amounts of low cost electricity. Taiwan is constructing two more ABWRs which will enter commercial operation in 2004 and 2005. Other countries have similar strategies to deploy advanced nuclear plants, and the successful deployment of ABWRs in Japan and Taiwan, coupled with international agreements to limit CO_2 emissions, will only reinforce these plans.

The ABWR represents an entirely new approach to the way nuclear plant projects are undertaken. The ABWR was licensed and designed in detail before construction ever began. Once construction did begin, it proceeded smoothly from start to finish in just four years. Capital costs amounted to $1600/kW at which level nuclear is very competitive with other forms of power generation.

The successful design, licensing, construction and operation of the ABWR nuclear power plant ushers in a new era of safe, economic and environmentally friendly nuclear electricity. The ABWR is the first of a new generation of nuclear plants equipped with advanced technologies and features that raise plant safety to new levels that significantly improve the economic competitiveness of this form of generation.

Forty Years in the Making

The Boiling Water Reactor (BWR) nuclear plant, like the Pressurized Water Reactor (PWR), has its origins in the technology developed in the 1950's for the U.S. Navy's nuclear submarine program. The first BWR nuclear plant to be built was the 5 MWe Vallecitos plant (1957) located near San Jose, California. The Vallecitos plant confirmed the ability of the BWR concept to successfully and safely produce electricity for a grid. The first large-scale BWR, Dresden 1 (1960), then followed. The BWR design has subsequently undergone a series of evolutionary changes with one purpose in mind—simplify.

The BWR design has been simplified in two key areas—the reactor systems and the containment design. Table 1-1 chronicles the development of the BWR.

Dresden 1 was, interestingly enough, not a true BWR. The design was based upon dual steam cycle, not the direct steam cycle that characterizes BWRs. Steam was generated in the reactor but then flowed to an elevated steam drum and a secondary steam generator before making its way to the turbine. The first step down the path of simplicity that led ultimately to the ABWR was the elimination of the external steam drum

Product Line	First Commercial Operation Date	Representative Plant / Characteristics
BWR/1	1960	Dresden 1 Initial commercial-size BWR
BWR/2	1969	Oyster Creek Plants purchased solely on economics Large direct cycle
BWR/3	1971	Dresden 2 First jet pump application Improved ECCS: spray and flood capability
BWR/4	1972	Vermont Yankee Increased power density (20%)
BWR/5	1977	Tokai 2 Improved ECCS Valve flow control
BWR/6	1978	Kuo Sheng Compact control room Solid-state nuclear system protection system
ABWR	1996	Kashiwazaki-Kariwa 6 Reactor internal pumps Fine-motion control rod drives Advanced control room, digital solid-state microprocessors Fiber optic data transmission / multiplexing Increased number of fuel bundles Titanium condenser Improved ECCS: high/low pressure flooders

Table 1-1. Evolution of the GE BWR

by introducing two technical innovations—the internal steam separator and dryer (KRB, 1962). This practice of simplifying the design with technical innovations was to be repeated over and over.

The first direct cycle BWRs (Oyster Creek) appeared in the mid-1960's and were characterized by the elimination of the steam generators and the use of five external recirculation loops. Later, reactor systems were further simplified by the introduction of internal jet pumps. These pumps sufficiently boosted recirculation flow so that only two external recirculation loops were needed. This change first appeared in the Dresden-2 BWR/3 plant.

The use of reactor internal pumps in the ABWR design has taken this process of simplification to its logical conclusion. By using pumps attached directly to the vessel itself, the jet pumps and the external recirculation systems, with all their pumps, valves, piping, and snubbers, have been eliminated altogether. This design feature is the source of many of the ABWR's safety and operational advantages. Figure 1-1 illustrates the evolution of the reactor system design.

The first BWR containments were spherical "dry" structures, similar to those still used today in PWR designs. The BWR, however, quickly moved to the "pressure suppression" containment design for its many advantages. Among these are:

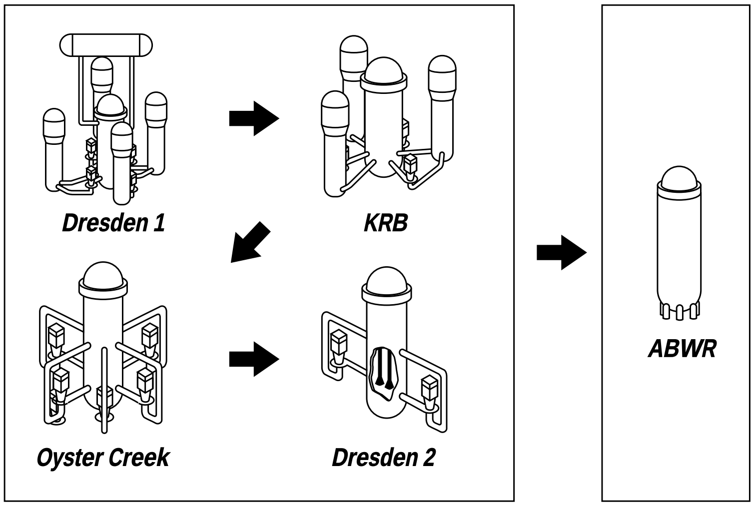

Figure 1-1. Evolution of the Reactor System Design

- High heat capacity.
- Lower design pressure.
- Superior ability to accommodate rapid depressurization.
- Unique ability to filter and retain fission products.
- Provision of a large source of readily available makeup water in the case of accidents.
- Simplified, compact design.

It is the reduction in containment design pressures, together with the elimination of the external recirculation loops, that allows the containment (and, by extension, the reactor building) to be more compact.

The Mark I containment was the first of the new containment designs. The torus used to house a large water inventory in the Mark I gives this design its characteristic light bulb configuration. The conical Mark II design has a less-complicated arrangement. A key feature is the large containment drywell that provides more room for the steam and ECCS piping. The Mark III containment design, used worldwide with BWR/6s and some BWR/5s, represented a major improvement in simplicity. Its containment structure is a right circular cylinder that is easy to construct, and provides ready access to equipment and ample space for maintenance activities. Other features of the Mark III include horizontal vents to reduce overall loss-of-coolant accident (LOCA) dynamic loads and a free-standing all-steel structure to ensure leak-tightness.

The ABWR containment is significantly smaller than the Mark III containment because the elimination of the recirculation loops translates into a significantly more compact containment and reactor building. The structure itself is made of reinforced concrete with a steel liner from which it derives its name—RCCV, or reinforced concrete containment vessel. Figure 1-2 illustrates the evolution of the BWR containment from the earliest versions to today's ABWR RCCV design.

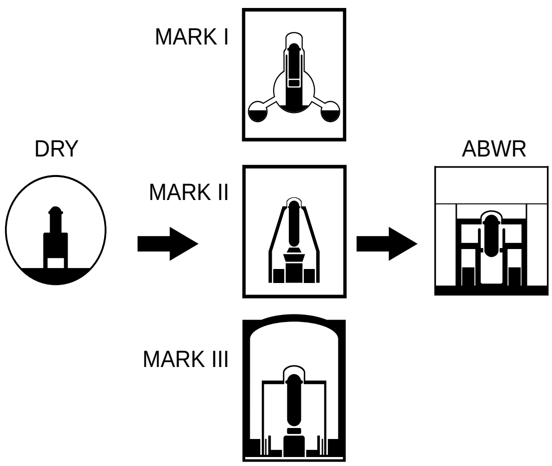

Figure 1-2. Evolution of BWR Containment

There are 92 BWRs, including two ABWRs, currently operating worldwide. Many are among the best operating plants in the world, performing in the "best of class" category. Numerous countries rely heavily upon BWR plants to meet their needs for electricity. Japan, for example, has nearly 30 BWR plants, representing nearly two-thirds of its installed nuclear capacity. The Tokyo Electric Power Company (TEPCO) owns 17 nuclear plants, all of which are BWRs. TEPCO's Kashiwazaki-Kariwa nuclear station, which consists of seven (7) large BWRs, is the largest power generation facility in the world, licensed for 8,200 MWe. Similarly, BWR plants pre-dominate in Taiwan and several European countries. In the United States, there are 37 operating BWRs.

To date, the ABWR plant is the only advanced nuclear plant in operation or under construction.

ABWR Development and Design Objectives

Development of the ABWR took place during the 1980's under the sponsorship of the Tokyo Electric Power Company (TEPCO). The stated purpose of the development effort was to design a BWR plant that included a careful blend of (1) the best features of worldwide operating BWRs, (2) available new technologies, and (3) new modular construction techniques. Safety improvements were, as always, the top priority. Anticipating the economic challenges that lay ahead, special attention was paid to systematically reducing the capital cost and incorporating features into the plant design that would make maintenance significantly easier and more efficient.

Specific goals were set that are today referred to as "best in class" performance:

- Across-the-board safety improvements, including a reduction in core damage frequency by an order of magnitude.
- Design life of 60 years.
- Capacity factor of 87% to 90%, depending upon the length of the operating cycle.
- Less than one unplanned scram per year.
- Personnel radiation exposure of less than 100 man-rem per year.
- Radwaste volumes of less than 100 cubic meters per year.
- A 48-month construction schedule.
- Increase of power output to 1350 MWe.
- A 20% reduction in capital costs.

Development of the ABWR occurred in a series of steps. Phase 1 was a conceptual design study that determined the feasibility of the ABWR concept. Phase 2, in which most of the development work took place, included more detailed engineering and the testing of new technologies and design features. The purpose of Phase 3 was to put the finishing touches on the design and systematically reduce capital costs, which proved to be a highly successful and, in hindsight, fortuitous endeavor. The development phases came to an end in 1988 when TEPCO announced that the next Kashiwazaki-Kariwa units to be constructed would be ABWRs.

With the selection of the ABWR for the K-6&7 project, the detailed, or project, engineering began. Licensing activities with the Japanese regulatory agency, MITI (Ministry of International Trade and Industry), also started at this time and, interestingly, were conducted in parallel for some time with the review of the ABWR in the U.S. by the Nuclear Regulatory Commission (NRC). MITI and the NRC, in fact, held several meetings to discuss their respective reviews.

By 1991, the detailed design was essentially complete and MITI concluded its licensing review. An Establishment Permit, or license, was issued in May 1991. Excavation began later that year on September 17, bringing a decade of development work to a successful conclusion.

Development of an advanced nuclear plant is a major endeavor. The development of the ABWR spanned a decade and cost an estimated $500M. Such an enterprise can only be undertaken in cooperation with many other organizations. The ABWR was developed by GE in cooperation with its technical associates Hitachi Ltd. and Toshiba Corp. The sponsorship and guidance of TEPCO was instrumental. The ABWR development also received financial support from the other Japanese utilities that operate BWRs, as well as from sixteen U.S. utilities.

ABWR Projects Worldwide

Operating ABWRs in Japan

The ABWR units in Japan are now constructed and fully operational. These units are located at TEPCO's Kashiwazaki-Kariwa site 100 miles north of Tokyo on the Sea of Japan. The world's first advanced nuclear plant, Unit 6, began commercial operation on November 7, 1996. Unit 7, the second ABWR, followed shortly thereafter with commercial operation commencing on July 2, 1997. These are the sixteenth and seventeenth nuclear units operated by TEPCO and the first of many ABWRs to be built in Japan over the next 10 to 20 years.

Both ABWR units were constructed in world record times. From first concrete to fuel load, it took just 36.5 months to construct Unit 6 and 38.3 months for Unit 7, the former being 10 months less than the best time achieved for any of the previous BWRs constructed in Japan. In addition, both units were built on budget, which is an impressive record of performance, since these were first-of-a-kind units.

Both units have completed several cycles of operation. By all measures, these ABWRs have lived up to their promise. Refueling outages have been conducted in 55 days, the minimum permitted by regulation in Japan. Plant capacity factors have been correspondingly high, consistently near 90% (between outages, right at 100%). There has been only one scram since the plants started operating, the result of a lightning strike. The thermal efficiency of the plant is 35%, slightly higher than previous designs, radwaste volumes have been 100 drums per year and occupational exposure has consistently been at the level of 20 man-rems per year. In other words, all design goals have been met or exceeded in operation. See Figure 1-3 for a photo of the Kashiwazaki Units 6 & 7.

Figure 1-3. Kashiwazaki Units 6 & 7 (K5 to the right)

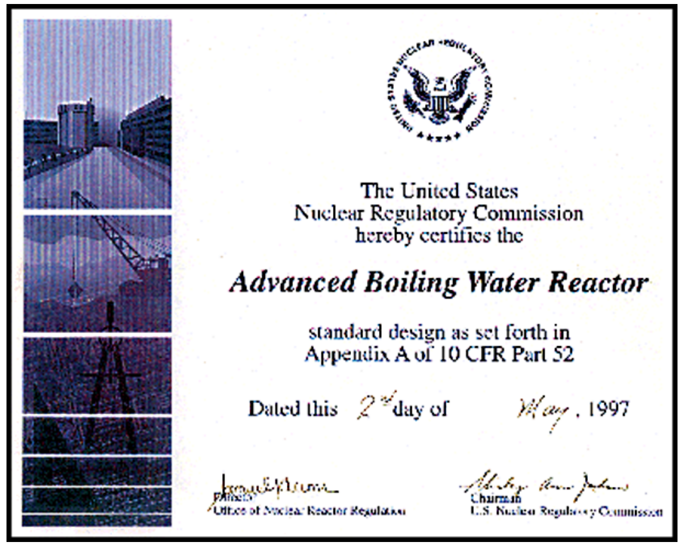

Figure 1-4. ABWR Design Certification

The ABWR in the United States

The licensing of the ABWR has been described as the most exhaustive, and perhaps exhausting, review ever undertaken by the U.S. Nuclear Regulatory Commission. The efforts of the NRC and GE came to fruition on May 2, 1997 when then Chair of the NRC, Ms. Shirley Jackson, approved and signed the ABWR Design Certification into law. This was rightly hailed by the U.S. industry as a significant accomplishment, one that has been envisioned for a long time—pre-approval of a standard design of an advanced nuclear plant. See Figure 1-4 for a reproduction of the ABWR Design Certification.

The successes continued when the ABWR First-of-a-Kind Engineering (FOAKE) program was completed in September 1996 to the praise and satisfaction of the utility sponsors. FOAKE is an equally significant accomplishment because it represents a major step toward the U.S. industry's other goal—to have a (pre-licensed) design that is 90% engineered prior to the start of construction. At the conclusion of the FOAKE program, approximately 65% of the engineering of the U.S. version of the ABWR was complete. The remaining engineering is being prepared as part of the Lungmen project, described below.

The ABWR in Taiwan

Two more ABWRs are being constructed for the Taiwan Power Company (TPC) at TPC's Lungmen site, located on the Pacific Ocean about 40 miles northeast of Taipei. The project officially started in October 1996 and the first major milestone was quickly reached in October 1997, when the Preliminary Safety Analyses Report (PSAR) was submitted to Taiwan's Atomic Energy Agency (ROCAEC). After an extensive review that involved hundreds of questions and responses, the PSAR was approved and the Construction Permit for both units was issued in March 1999. See Figure 1-5 for a description of the Lungmen Construction Permit.

The remainder of the construction schedule is given in Table 1-2. Commercial operation of Lungmen Unit 1 is expected to begin in July 2004. The schedule for Unit 2, including the start of commercial operation, is one year later.

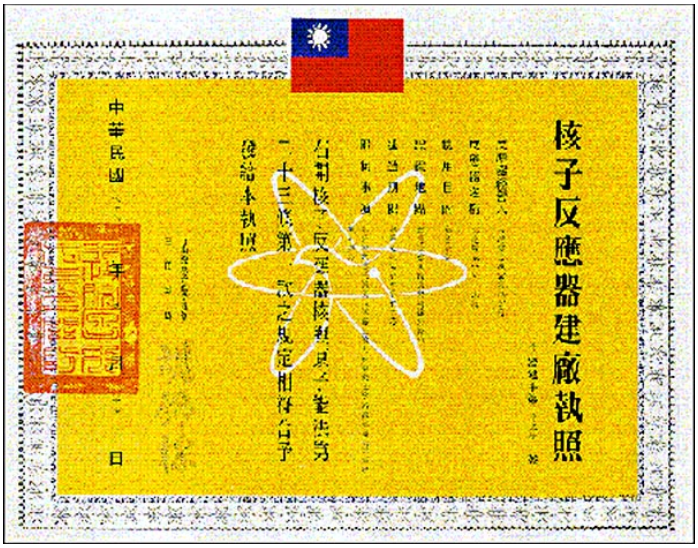

Figure 1-5. Lungmen Construction Permit

	Unit 1*
• Project start	October 1996
• PSAR submitted	October 1997
• Excavation	January 1998
• PSAR Amendment	September 1998
• Construction permit	March 1999
• RPV installation	June 2001
• FSAR to TPC	April 2002
• Fuel load	August 2003
• Comm. operation	May 2004

** Unit 2 schedule one year later*

Table 1-2. Lungmen Project Schedule

The ABWR in Europe

Nuclear utilities in Europe are developing a comprehensive set of utility requirements for the next generation of nuclear plants to be built in Europe. These utilities, represented by the EUR (European Utility Requirements) Steering Committee, have agreed to review the ABWR design against these requirements. The ABWR review is sponsored by three major European utilities who began working with GE in 1998 to begin a preliminary review of the EURs. The development of a European ABWR (EABWR) that meets unique European requirements, but is also based upon licensed designs and worldwide project experience, is an important initiative that may, in a few years, culminate in an ABWR project in Europe.

Nuclear Plant Projects in the New Millennium

The way in which ABWR nuclear plants are designed, licensed and constructed is vastly different than was the case 10 or 20 years ago.

Design and Licensing

The ABWR nuclear plant is licensed and designed in its entirety prior to the start of construction. Today, long before first concrete is poured, all safety and engineering issues are identified and resolved. This precludes construction delays due to re-engineering, a problem which plagued so many projects in the past and contributed significantly to the high (and in some cases mind-numbing) capital costs.

The ABWR has been designed to higher levels of safety, including being designed to prevent and mitigate the consequences of a Severe Accident. Licensing documents approved by the USNRC indicate that even in the event of a severe accident, there would be no release of radioactive material to the public.

Today's nuclear plants are extensively and exhaustively reviewed by multiple regulatory bodies. In fact, the ABWR has been reviewed and approved in three countries (Japan, U.S. and Taiwan). This ensures that the licensing of the ABWR will proceed on a smooth and timely basis in other countries that choose to deploy an ABWR.

The ABWR design has been captured electronically using the latest state-of-the-art information management technology called POWRTRAK. The benefits appear not only in construction, where it has been shown over and over with fossil plants that use of this engineering tool reduces construction time and cost, but also during the operation and maintenance of the plant. POWRTRAK is both a 3D model design tool and an extensive database for plant equipment and materials.

The approach described above is being fully utilized for the Lungmen project. The design and licensing of these ABWRs are proceeding smoothly as expected.

Construction of Nuclear Plants in the 1990's

Nuclear plants today are constructed much differently than in the past. The most notable difference is the schedule. The ABWR can be built in only four years, from first concrete to the start of commercial operation. Design simplifications and the use of new construction technologies and techniques make this possible.

Today, the plant owner is spared the concern for schedule delays and cost overruns. Suppliers commit to a fixed schedule and price, largely because the design has been pre-licensed and pre-engineered.

Of course, there is no substitute for experience. The Lungmen ABWRs are being supplied by a team of U.S. and Japanese suppliers, led by GE, that were also involved in the supply of the Japanese ABWRs. This team and the supporting network of equipment sub-suppliers is accustomed to working on an international stage and can readily transplant its experience and know-how to a new host country. This is the basis for the "learning curve" effect, which reduces capital costs by about 10% with each new unit.

ABWR is Accumulating Operating Experience

The ABWRs in Japan have now accumulated several years of operating experience after having completed a highly successful construction effort. This represents a wealth of information and know-how that is of benefit to subsequent ABWR projects.

Economics of the ABWR

The design, licensing and construction of the ABWR by an experienced team have made the capital cost economically competitive with other power generation options. The Kashiwazaki ABWRs were constructed for about $1600/kW (overnight cost) and the Lungmen ABWRs will cost a comparable amount when completed. This will be described more fully in Chapter 11 (Plant Economics and Project Schedule).

The design, licensing, construction and operating performance of nuclear plants are vastly different—and better—than 10 or 20 years ago. Nuclear plants in the 1990's and in the new millennium will have a higher degree of safety, and the ABWR in particular will be licensed in multiple countries. The ABWR plant can be constructed in just four years for $1600/kW and suppliers are willing to undertake a project on a fixed price, fixed schedule basis. As a result, the ABWR nuclear plant has proven itself in Japan and Taiwan to be economically competitive with other power generation options, and estimates indicate that it can be in other countries as well.