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The Evolutionary Development of Advanced Reactors

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The overwhelming trend in reactor development throughout the world is to start with the latest operating design and to build on the experiences of that design by making evolutionary improvements. This approach fosters a gradual or evolutionary advancement of a design in a step-wise manner. Incremental improvements are incorporated into the design to improve safety, enhance operability, and/or reduce power generation costs.

Since these objectives are often competing, cost benefit analyses must be performed to assure that any change incorporated into the new design has an overall positive effect. This evaluation of the tradeoffs can only be effectively accomplished through experience. History sometimes shows that what appears to be a relatively small change in the design can cause major operating problems because of its influence on the performance of the plant. Thus, caution must be exercised for each design change.

In addition, a broad range of experience is readily available from a variety of sources, including the World Association of Nuclear Operators (WANO) and the Institute of Nuclear Power Operations (INPO), as well as publications by the US Nuclear Regulatory Commission (NRC) and various technical societies. This allows reactor designers to incorporate the feedback from a large number of operating reactors into their new designs to avoid the deficiencies of the past and improve future plant performance.

An important aspect of the evolutionary approach is that it provides assurances to all the stakeholders in a nuclear project. It helps build customer confidence in a new design. Too often, dramatic changes lead to unanticipated problems that only surface during the startup and/or operating phases of a plant's life cycle, with the consequences being too large. Nuclear regulators must also bear the burden of approving the safety of a new design. Their confidence in such an approval can be strongly influenced by previous approval of a similar design by another regulatory authority. This allows them to rely, to a significant degree, on the judgment of that other agency in making their own evaluation.

Finally, one of the most important aspects of the evolutionary design development process is the self-confidence of the designer to accept project warranties with manageable financial risks. This aspect can translate directly into lower risk provisions in the contract if this confidence is due to a proven "track record" based on actual operating experience.

Key International Development Programmes

There are a number of international programmes that have followed this evolutionary approach. These include the US ALWR development programme, the European Pressurised Water Reactor (EPR) development programme, and the Korean Next Generation Reactor (KNGR) development programme.

The first of these programmes centred on the Electric Power Research Institute (EPRI) Advanced Light Water Reactor (ALWR) Utility Requirements Document, which states that its first objective was to "... provide a comprehensive set of design requirements for future LWRs which is based upon proven technology from 30 years of commercial LWR experience. At the same time, these requirements will provide improved versions of the LWR that eliminate existing design, construction and operational problems...". The US ALWR development programme is essentially complete, with the design certifications of the ABB Combustion Engineering System 80+ advanced PWR and the General Electric (GE) ABWR completed in 1997. The remaining major US design development, by Westinghouse of the AP600, is also in progress.

The EPR development programme, centred on the European Utility Requirements (EUR) Document, has followed a similar path to the US programme. The basic design of the EPR has been completed, and it is currently in the design optimisation phase. Work on the EUR Document is concentrated on adding conformance of a few selected designs to the top-tier requirements, and obtaining convergence of diverse nuclear regulatory agencies to a common set of licensing requirements.

The KNGR development programme is being conducted in three phases. The first phase, which was completed in late 1994, consisted of concept selection and planning of future work. Currently the programme is in Phase II, during which the basic design of the KNGR is being completed along with the Standard Safety Analysis Report (SSAR) for submission to the Korea Institute of Nuclear Safety (KINS), the regulatory agency. The requirements for this design are very similar to those developed under the EPRI ALWR Utility Requirements Document, but with Korea-specific requirements considered. Phase III of the KNGR programme is scheduled to start in early 1999. During this phase, all first-of-a-kind engineering will be completed.

Collaboration Between ABB-CE and Korea

The starting point, or reference design, for the collaborative programme being discussed in this paper is the ABB Combustion Engineering two steam generator NSSS design. This basic design has been used by ABB-CE since its first commercial nuclear contract in 1966. It has been implemented at power levels ranging from 500 MWe to 1300 MWe, and has a proven track record at all of these power levels. It is the foundation for the evolutionary development of plants in the Republic of Korea and the development of the System 80+ advanced standard plant that has been licensed in the United States.

The primary goal of the Korean nuclear power industry (which includes Korea Electric Power Corp. (KEPCO), Korea Power Engineering Co. (KOPEC), Korea Nuclear Fuel Co. (KNFC), and Hanjung) was to gain self-reliance in design, manufacture and operation of nuclear power plants. Over the past twelve years, the Korean nuclear power programme has significantly matured, and the goal of self-reliance has been realised with the assistance and cooperation of ABB-CE. The

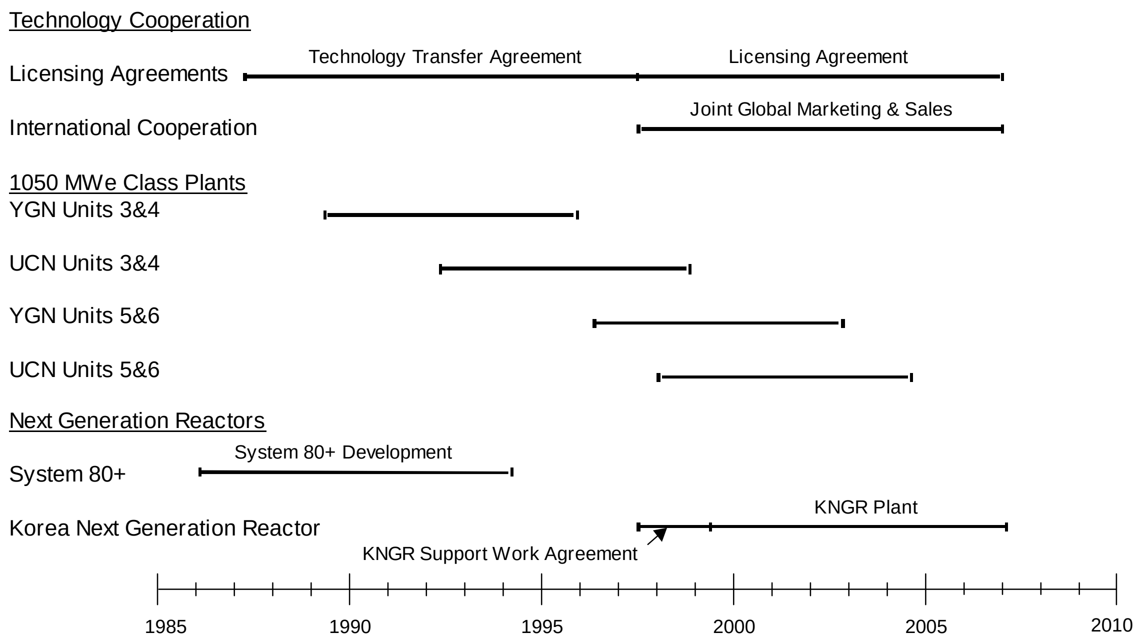

Figure 1. Overview of collaboration between ABB-CE and the Korean nuclear industry. (YGN, Yonggwang; UCN, Ulchin.)

relationship between ABB-CE and the Korean nuclear industry has included the following:

- technology transfer,
- technology support in the development of the KSNP,
- development of the System 80+ Advanced Standard Plant,
- technology support in the development of the KNGR,
- international co-operation.

An overview of the collaboration between ABB-CE and the Korean nuclear industry is summarised in Figure 1 and is discussed below.

Technology Transfer

In 1987, the Korean nuclear industry and ABB-CE entered into a ten-year comprehensive technology transfer programme, designed to meet the goals of the Korean nuclear industry. This programme not only encompassed the comprehensive range of plant design, engineering, and manufacturing methodologies, but also included a broad scope of R&D activities as well. The technology transfer programme included the following five major aspects:

- documentation transfer,
- computer code transfer,
- training for Korean engineers,
- R&D programme participation,
- consultation.

The programme provided the Korean nuclear industry with the technical knowledge and experience to help the industry reach its goal of self-reliance. A new ten-year extended and expanded licence agreement was signed in 1997, which further strengthens the relationship for future projects.

Development of the KSNP

Yonggwang units 3 and 4, rated at 1050 MWe, were the first plants in Korea to be based on ABB-CE's System 80 design. These new plants were jointly designed by ABB-CE and KOPEC. Detailed design review meetings helped KOPEC engineers acquire practical "know how" and develop a strong experience base for future design efforts. Selected design enhancements were incorporated that would not challenge the "provenness" of the design or introduce undue licensing risk.

With the experience gained from jointly designing Yonggwang-3 and -4, KOPEC assumed lead responsibility for the NSSS design of subsequent units, with ABB-CE providing consultation. The Korea Standard Nuclear Power Plant (KSNP), shown in Figure 2, emerged from the Ulchin-3 and -4 design and is the model for all subsequent 1050 MWe class plants in the Republic of Korea.[1]

In the KSNP evolutionary design process, numerous design improvements have been gradually incorporated to enhance plant safety and performance, and to meet updated licensing requirements and industry codes and standards. Once an improvement was made, it was retained in all subsequent units. A detailed listing of the design improvements made for each of these units is contained in Reference 2. Some of the key design

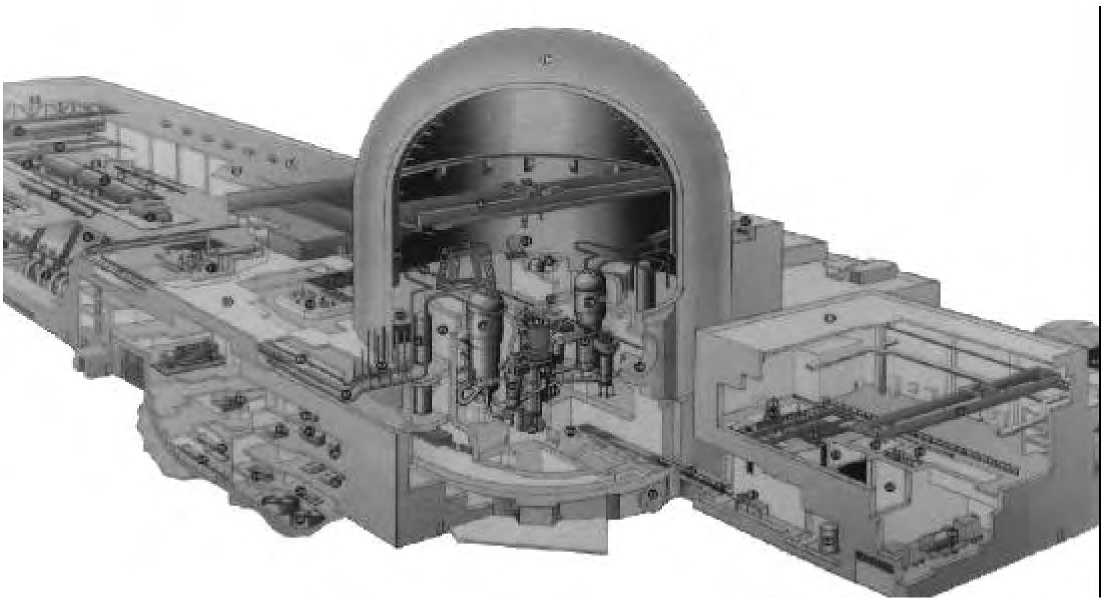

Figure 2. The Korea Standard Nuclear Power Plant (KSNP).

improvements are:

- Safety Depressurisation System added to provide an alternate means of decay heat removal and to quickly depressurise the plant in the unlikely event of a severe accident.
- Improved water level measurement instruments added to provide more accurate monitoring of reactor coolant level during reduced inventory operations.
- Improvements to the Chemical and Volume Control System (CVCS) design to minimise maintenance requirements and thus lower overall O&M costs.
- Use of Inconel-690 for longer life steam generator tubes.
- Instrumentation and control improvements by utilising state-of-the-art digital technology (additional improvements with each successive project).

While KOPEC has the lead responsibility for incorporating the design improvements, ABB-CE provides consultation for systems undergoing significant design changes. An example is the implementation of the Digital Plant Protection System (DPPS) and the Digital Engineered Safety Features Actuation System (DESFAS) for Ulchin-5 and -6. The development of the DPPS and DESFAS requires a close working relationship between ABB-CE and KOPEC engineers because of its first-of-a-kind nature.

Development of the System 80+

Using the successful System 80 design implemented at the Palo Verde Nuclear Generating Station in the USA as the basis, ABB-CE developed the 1400 MWe System 80+ Advanced Standard Plant (Figure 3), which incorporates many advanced design features and design improvements to meet the most recent US regulatory requirements (10CFR52), and industry needs for future plants (EPRI ALWR Utility Requirements Document).

ABB-CE received a Final Design Approval (FDA) for the System 80+ design from the US NRC in July 1994, and Design Certification in May 1997. Reference 3 discusses the System 80+ design in detail. A few of the key design features are:

- four-train safety systems,
- a dual spherical steel containment design to mitigate consequences of severe core damage accidents,

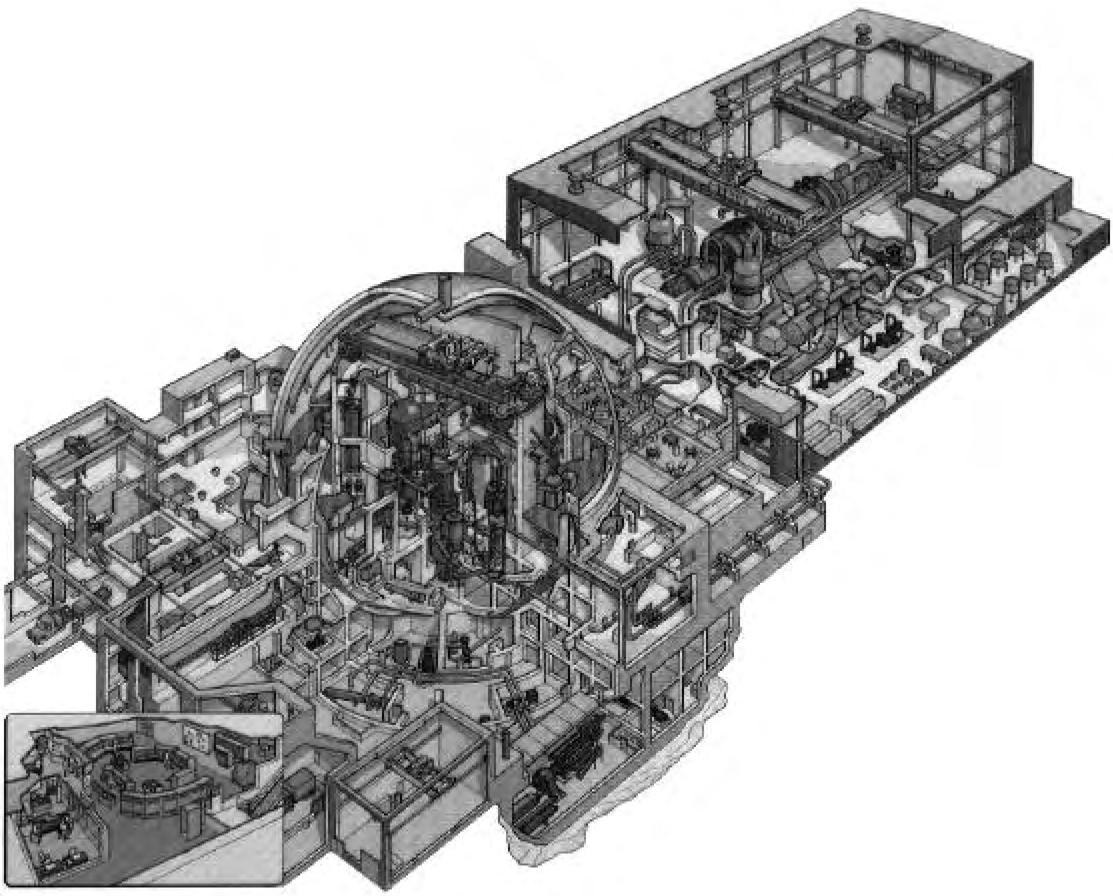

Figure 3. The System 80+ Advanced Standard Plant.

- a cavity flood system with an in-containment refuelling water storage tank,
- the Nuplex 80+ Advanced Control Complex with improved man–machine interface,
- direct vessel injection from the Safety Injection System.

These and the other design features of System 80+ have resulted in a plant design with a core damage frequency of 3.8 x 10^{-6} events / year, which is well below the international safety goal of 10^{-5} events / year.

Development of the Korea Next Generation Reactor

The purpose of the KNGR programme is to develop an advanced next generation reactor for implementation in Korea in the next century. The KNGR, which is upgraded to 1400 MWe from the KSNP, incorporates many advanced features similar to those of System 80+. The various Korean companies are jointly designing the plant, with KOPEC having the lead for all plant systems and structures. Based on the experience gained with the design and licensing of the System 80+, ABB-CE is providing expert consultation to all of the companies involved in the development and licensing of the KNGR design.

The key design characteristics of the KNGR are:

- four-train safety systems,
- dual cylindrical concrete containment,
- a cavity flood system with an in-containment refuelling water storage tank,
- implementation of Pilot Operated Safety Relief Valves (POSRV) for overpressure protection,
- a control room complex which utilises a greater number of soft controllers and work stations,
- greater use of passive safety systems to complement the active systems.

It is expected that the KNGR safety analysis report will be submitted to KINS by early 1999, and it is anticipated that the first construction project will begin around the turn of the century. Reference 4 discusses the KNGR programme in more detail.

International Co-operation

ABB-CE and the Korean nuclear industry have enjoyed a successful and mutually beneficial relationship. This relationship has evolved over the past 12 years, which have included the development of evolutionary 1000 MWe-class KSNP plants and the development of 1400 MWe-class Advanced LWR designs. To date, the working relationship has resulted in eight 1000 MWe class plants in various stages of design, construction and operation in the Republic of Korea. The Korean nuclear industry and ABB-CE have long recognised the benefits of a joint relationship and are planning to work together for export to other countries.

Benefits of Evolutionary Development

Evolutionary development of the KSNP design has provided many tangible benefits to the plant owner. These benefits can be seen in assured plant performance, reduced plant construction cost, assured licensability, and the design keeping abreast of current state-of-the-art technology.

In developing each advanced feature and deciding whether to incorporate it into the design, consideration is given to its potential effect on each of these areas. Probabilistic safety assessment (PSA) modeling provides a quantitative means for assessing the relative safety importance of advanced features, while industry experience provides sound guidance for incorporating other features which do not have a significant safety importance. Tradeoff studies are performed when a specific feature could have a positive contribution in one area but might cause adverse impact in other areas. Based on these considerations, a rationale is developed for each design improvement that is incorporated into the evolutionary design. Discussed below are some of the major benefits that are realised as a result of this evolutionary process.

Assured Performance

The principle of the KSNP evolutionary design process is to maintain the major design characteristics of the plant basically unchanged from the base model, Yonggwang units 3 and 4, in order to assure the good performance of the plant. However, advanced design features are incrementally incorporated that will improve the safety and / or performance. Such incremental changes are made in each succeeding project, assuring the performance with minimal risk to the project.

Yonggwang-3, the first downsized System 80 unit in Korea, achieved commercial operation in March 1995 (the exact month scheduled at the beginning of the project). The performance of this unit has been exceptional, with one cycle (366 days) of trouble free operation (in Cycle 3). This outstanding performance confirms the belief that the series of KSNPs will meet expectations of very high performance when they have been completed.

Yonggwang-4 began commercial operation in January 1996 (three months ahead of schedule).

The performance of both units during their first three cycles has been outstanding as compared to other newly built plants. The average capacity factor (including refuelling and maintenance outage time) for the first three cycles was over 80%, while operating on annual refuelling intervals.

Assured Cost

The evolutionary design process leads to a family of plants, which can transfer experience from one project to the next. Standardisation, which is inherent in a family of nearly identical plants, plays a significant role in reducing construction and startup costs.

Substantial cost and schedule improvements are realised during construction as techniques are passed on, rework is reduced, more efficient methods are developed and familiarity with the design increases. This is evident at multi-unit sites where the subsequent units are completed in shorter times.

Cost reductions in follow-on units resulting from these series effects, which were projected by the Nuclear Energy Institute (NEI), have been realised in the series development in Korea. The NEI projected a construction cost saving of 16% for the second of a series of standardised design projects; additional savings of lesser proportions are projected for each of the following projects. The benefits of shortened construction schedules on successive units are also demonstrated on the Korean projects, with a six-month reduction in construction time from the first project to the third project. While influential in reducing construction cost, this shortened schedule also provides a quicker return on investment for the plant owner.

Another of the more significant cost benefits of standardisation realised from series development is the savings in design and engineering. This is also demonstrated in the design and engineering efforts on the KSNP, with 20% reduction in labour hours on the NSSS system design and 33% reduction in labour hours by the architect-engineer on the second set of plants. Smaller additional savings are anticipated on subsequent units.

Assured Licensability

One of the most outstanding benefits gained from the evolutionary development is in the area of licensing. Since a basic philosophy of incorporating new evolutionary enhancements to the already proven design features is maintained, there are no fundamental barriers to the licensing of the KSNP follow-on units. The development of the evolutionary plant design for the KSNP, in parallel with the design and licensing process for the System 80+ Advanced Standard Plant in the USA, provided the means to incrementally incorporate design improvements, which had already received extensive regulatory review and approval.

Ulchin-3, which started commercial operation in 1998, received its operating licence in November 1997, after a year and a half of extensive review by the Korean regulatory authority, KINS. In addition, the safety aspects of Ulchin-3 and -4 were evaluated by an independent IAEA expert mission in May 1995. The IAEA mission concluded that these units represent significant accomplishments in the gradual improvement of safety, have added numerous design improvements, and have established the use of a reference plant concept. Subsequent units have incorporated newer advanced features, taking further steps in the evolution of the KSNP design.

Assured Innovation

Nuclear power technology is generally based on existing engineering practices, which are proven by operation and testing. However, if opportunities for advancement, improvement or innovation over existing practices are available and deemed appropriate, such changes can be applied conservatively. A balance is sought between proven technology and innovative development.

Standardisation based on proven technology guarantees plant performance that leads to a reduced financial risk for the project. However, such standardisation may not benefit from the current state-of-the-art technology, and the technology that is utilised may become outdated, resulting in low performance and not representing optimum safety. Therefore, the concept of evolving improvement from a base of proven technology is adopted to maximise confidence in safety and performance, but at the same time to reflect the current state-of-the-art as much as possible. This can be achieved by adopting systems, components, and/or design techniques which have been successfully demonstrated in other operating nuclear power plants. Alternatively, more advanced technologies can be "proven" through testing or through several years of successful operation in other applicable industries, such as thermal power plants or process industries.

The evolutionary process involved in the KSNP design incorporates feedback from operating experience, both domestic and abroad, and complies with the most up-to-date codes and standards, and regulatory requirements in order to implement the current state-of-the-art technology.

Summary of Collaboration

The objective of the initial technology transfer contracts signed in 1987 was to achieve technical self-reliance by the completion of a ten-year programme. This was achieved in the mid 1990s, with the Korean nuclear industry providing over 95% of the design, manufacturing and procurement for the third and fourth projects. As part of technical self-reliance, KOPEC developed the Korea Standard Nuclear Plant (KSNP), based on the Yonggwang-3 and -4 design. This design development, mainly accomplished by Korean engineers with support from ABB-CE, demonstrated the success of the self-reliance programme.

The successful completion of the design development and licensing of the System 80+ Advanced Standard Plant design represents another major milestone in the evolutionary design process. This programme was completed with the assistance of Korean engineers working side by side with those of ABB-CE. It allowed the Korean engineers to experience the development process on an advanced reactor design while they were formulating their own programme for the Korean Next Generation Reactor (KNGR). This successful development programme also provided the precedent for many advanced design features that will be incorporated into the KNGR.

In 1997, ABB-CE signed a co-operation agreement with the Korean nuclear industry for a ten-year extension and expansion of technology transfer. This agreement forms the foundation for co-operation in the development of the KNGR for future domestic and international deployment. Under this programme, ABB-CE is providing consultation to KOPEC and other nuclear design organisations to help evaluate and implement advanced design features.

The next chapter in the cooperation between ABB-CE and the Korean nuclear industry is the export of a design based on the KSNP. This design will add further enhancements to the KSNP to recognise market-specific trends and to capture additional enhancements from System 80+ and the KNGR. With this design, ABB-CE, together with the Korean nuclear industry, is offering a state-of-the-art design that is safe, simple and proven.

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