# DESIGN MEASURES IN EVOLUTIONARY WATER COOLED REACTORS TO OPTIMIZE FOR ECONOMIC VIABILITY

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**Abstract**

Since the mid 1980s, there have been various efforts to develop evolutionary water cooled reactors based on the current operating plant experience. To sustain and improve the economic viability, particular attention has been paid to the following aspects in developing evolutionary water cooled reactors: design simplification and increased operating margins, standardization in design as well as construction and operation, integration of operating plant insights, and consideration of safety, operability and constructibility during the design stage. This paper reviews each item and discusses several examples from some of the evolutionary water cooled reactors being developed.

## 1. INTRODUCTION

Since the TMI-2 incident, the added regulatory burden and complexity to the plants have decreased the economic competitiveness of nuclear power. To remedy the situation, nuclear utilities worldwide have examined the requirement for the future light water reactors. In the USA, the Electric Power Research Institute developed the ALWR Utility Requirements Document [1]. European countries have developed European Utility Requirements for ALWR [2]. In Korea, KEPCO is currently developing the ALWR requirement for Korean utilities. AECL has worked closely with CANDU utilities to establish improvement requirements for the evolutionary development of the heavy water reactors [3]. All these efforts recognize the importance of economic viability and have proposed:

- Simplification and increased margins
- Standard design with repeated construction
- Integration of operating plant insights and
- the consideration of safety, operability and constructibility during the design stage.

The recent trend of deregulation of electricity market emphasizes further plant economy. In a deregulated environment, the large capital cost of nuclear compared to alternate energy sources could be a handicap if not compensated with a substantial decrease in generation costs. Shorter construction schedules, simplification of designs together with regulatory stability are thus becoming increasingly important to control costs.

Advanced water-cooled reactor designs have progressed worldwide. Examples are ABWR, AP600, CANDU9, EPR, KNGR, and System 80+ among others. ABWR (Advanced Boiling Water Reactors) is an evolutionary boiling water reactor developed by GE in cooperation with Hitachi and Toshiba. AP600 is a passive PWR developed by Westinghouse in USA. CANDU9 is a 900 MWe evolutionary HWR plant developed by AECL, Canada. EPR is an evolutionary PWR being developed by NPI. This is a joint effort between France and Germany. KNGR is an evolutionary PWR being developed by KEPCO, Korea. System 80+ is an evolutionary PWR developed by ABB-CE, USA. All of these plants were developed with the consideration of the utility requirements. Detailed descriptions of advanced light water reactor developments can be found in Ref. [4].

In this paper, we review the design improvement consideration for economic viability. More specifically, we will examine the design improvement for the four points described above with some examples.

## 2. SIMPLIFICATION AND INCREASED MARGIN

### 2.1. Simplification

We have observed the substantial increase in complexity of nuclear power plants. Stahlkopf & Chapin [5] have compared the U.S. nuclear plants built in late 60s with those built in late 70s. As a measure, concrete quantity increased from 90 cubic yd/MWe to 248 cubic yd/MWe. Cable increased from 2000 ft/MWe to 4889 Mwe. These are about 280% increase. Furthermore, the increase in craft labor was staggering: from 3500 person-hr/MWe to 21600 person-hr/MWe. One significant contributor is the substantial increase in regulatory requirements on safety systems. However, in addition to the regulatory complexity, there has been a lack of attention to adequate simplification on the part of designers over the years. The plant modification has been done too commonly by an ad-hoc process from the existing design.

The increase in complexity could result, if not adequately controlled, in the increase of the maintenance and construction cost as well as in the difficulty of operating the plants. Adding a component to the plant that is inexpensive in itself could become an expensive proposition from the life cycle point of view. As an example, Figure 1 shows the effect of removing a pump in a US environment in mid 1980s, illustrated by W. Sugnet [6].

The effort by ALWR developers on simplification can be summarized by the ALWR simplification requirement [7]:

- Use a minimum number of systems, valves, pumps, instruments and other mechanical and electrical equipment
- Provide a man-machine interface which will simplify plant operation and reflect operator needs and capabilities [8]
- Provide system and component designs which assure that plant evolution minimizes demands on the operator
- Design equipment and arrangements which simplify and facilitate maintenance;
- Provide simplified protective logic and actuation systems, and provide automation to reduce operator testing tasks
- Use standardized components to facilitate operation and maintenance

Below, we will review several examples on simplification from the current evolutionary water cooled reactor development.

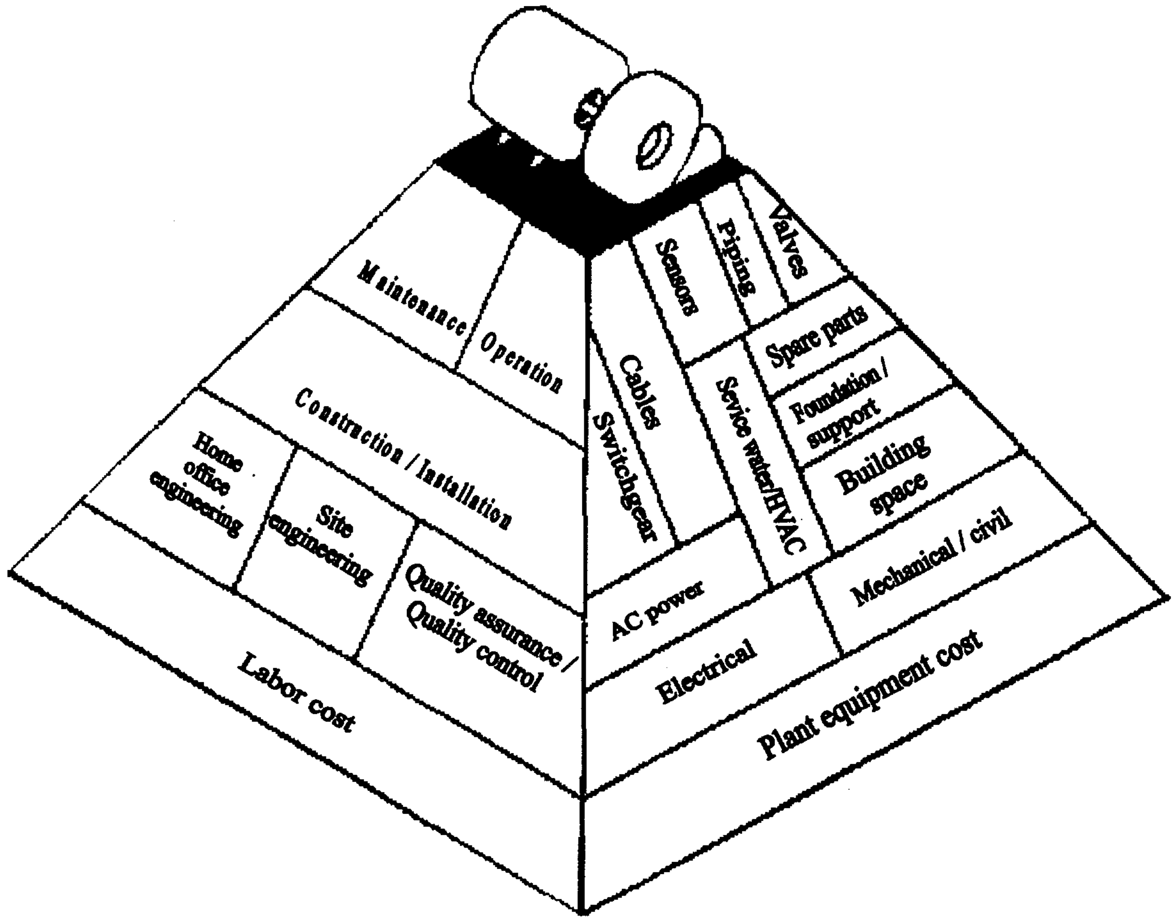

*FIG. 1 Removal of active components has great potential for simplification.*

Most of the evolutionary designs have adopted four-train configuration for important safety systems and their support systems to increase the safety of the plant. This, in itself, could increase the complexity. However, in KNGR as well as System 80+, the optimization has been achieved by removing low-pressure safety injection while increasing the capability of safety injection pump and safety injection tank. Furthermore, the injection is routed directly into the reactor vessel. Previously, the injection is through the cold leg. Direct vessel injection raises a concern on possible pressurized thermal shock of reactor vessel. Ring-forged reactor pressure vessel is used to alleviate pressurized thermal shock issue. This has an additional advantage by reducing the number of welds and corresponding inspection activities. The long-term decay removal is handled by shutdown cooling system.

For the EPR, important safety systems and their support functions are arranged in a four-train configuration. Examples are safety injection, emergency feedwater, component cooling, and emergency electric power system. The high degree of redundancy has significant advantages regarding an optimized preventive maintenance concept that makes possible maintenance and inspection during operation. Thus, plant outage time is reduced and plant availability increased.

The design of the CANDU 9 emergency core cooling (ECC) system has been simplified by reducing the number valves and using passive on-way rupture disks to separate the reactor cooling system from the emergency core cooling system. In addition, the ECC water tanks for high pressure injection were located inside containment with shorter injection lines directly into the reactor headers instead of the heat transport system piping. These simplifications will increase the reliability of this system over that of previous designs which reduce the capital cost as well as significantly reduce the operating and maintenance costs for testing, inspection, maintenance and repair over the lifetime of the plant.

KNGR has simplified reactor vessel head area by utilizing an integrated reactor vessel head package. An Integrated Head Assembly (IHA) is developed to incorporate all of the reactor vessel head components into one module. The IHA casing is designed so that one can use the multiple stud tensioner during refueling outage. The multiple stud tensioner allows simultaneously detensioning and tensioning of all the reactor vessel studs. This enables the removal of the head area components and reactor vessel head at once. The use of IHA is estimated to save almost three days in comparison to typical seven-day schedule for the reactor vessel head disassembly.

Most of the evolutionary water-cooled reactor designs are equipped with an advanced digital I&C system. This enables self-testing of the system which reduces the effort required for maintenance and testing. In conjunction with the digital system, the use of multiplexing or data-highway simplifies cable routing and reduces the amount of cables and connections.

### 2.2. Increased margin

Nuclear power plants have operated as a base load generating facility in most cases. For the base load operation, the sensitivity study on the cost of electricity indicates that the plant availability is one of the most important parameters. The increase in the operating margin may increase the initial cost but it improves the plant availability greatly by reducing the chance of shutdown. The increase of the margin has been one of common requirements among EPRI URD, EUR, and K-URD.

To improve the operating margins, evolutionary PWR and PHWR designs incorporate larger pressurizer volume and steam generator inventory. For example, System 80+ designed by ABB/CE has 33% larger pressurizer volume and 25% larger steam generator secondary inventory compared to System 80 design [4]. The increase of the steam generator secondary inventory relaxes the operator action time in the event of loss of feedwater transient. In CANDU 9, the larger pressurizer volume is capable of accomodating changes in reactor coolant volume from 100 °C to full power, which enhances the natural circulation capability during system cooldown after a loss of flow. Most of the evolutionary plants are designed with the goal of minimum operator action time of 30 minutes. As an example of design change, an orifice has been integrated to the letdown line in KNGR so that operator has more than 30 minutes to close the isolation valve.

These simplifications and improved operating margins yield economic benefits such as high availability, outage reduction, reduced staffing level, and spare parts reduction.

## 3. STANDARD DESIGN WITH REPEATED CONSTRUCTION

The use of the standard design yields the benefit of scale, learning effect, and licensing stability. The use of several or more standard plants provides, by sharing of resources, the benefit in training, maintenance, spare parts, and procurement. It will reduce the cost both in construction and operation. These benefits have been experienced by Electricite de France (EdF) as well as the Westinghouse SNUPPS family and Palo Verde plants in USA. The replication of the CANDU 6 plants from Canada to Argentina and Korea and subsequent additions of 3 more CANDU 6 units at Wolsong site have yielded progressively improved construction schedule and costs. In Korea, the KSNP series of PWRs (YGN3&4, UCN3&4) shows the similar advantage. Most, if not all, of ALWR being developed pursue the standard plant concept.

In USA, the standardization has become a part of the design certification rule. Operating plants in USA have been licensed on a plant-specific basis. It is a two-step process, approval of PSAR and

FSAR with the license. One-step licensing process has been legislated for ALWR through 10 CFR 52. Subpart B of 10 CFR 52 covers the standard design certification. Design once certified under 10 CFR 52 rule will be protected from new requirements or public hearings except under special circumstances. This process would eliminate the licensing instability that has been the mode of operation since TMI-2. Currently, two evolutionary LWRs, ABWR and System 80+, have been certified as a standard design in U.S. which will remain effective for 15 years. A passive PWR, AP600, is currently in the process of design certification. Similar licensing process is being pursued in Korea. KNGR design is planned to be submitted in 1999 for the review under the standard design certification rule. With the requirement that the CANDU 9 design should be licensable for both domestic and foreign potential users, the pre-project Basic Design Engineering program included a two-year formal extensive review by the Canadian regulatory Agency. The same licensing review process in the granting of the construction license for a nuclear project in Canada was used. The licensing review has been successfully completed and the final report from the AECB was issued in January 1997 [9].

The benefit of standardization can be maximized by early and broad utility involvement and a life cycle commitment by utilities. Utility participation early on the design phase was common in most of the evolutionary plant development. In USA, Utility Steering Committee was formed under EPRI ALWR program from the beginning to review and feedback the ALWR development effort. EdF and German utilities are closely working with NPI on EPR development. In Korea, KEPCO, who is the electric utility in Korea, manages the development of KNGR. Commercial standardization has been an important element of "first-of-a-kind engineering" performed by U.S. vendors on ABWR and AP-600. In this stage, equipment purchase specifications for major equipment are prepared. It is planned that these specifications will be used repeatedly. Purchase specifications of other equipment that are important to the standardization will be developed on a form-fit-function basis [10]. Commercial standardization requires broad consensus among participants for the design of the first plant and duplication of the first plant design details as well as lessons learned from construction,startup testing and operating experience. In this regard, in USA, Nuclear Power Oversight Committee (NPOC) made a policy statement.

*"Nuclear power plant standardization is a life-cycle commitment to the uniformity in the design, construction and operation of a family of nuclear power plants. Rigorous implementation of standardization is expected to achieve the efficiency and economy typically associated with increases in scale or breakthroughs in technology." [10]*

In developing EPR, the standardization concept has been applied not only between the plants but also within each plant. From the beginning of the EPR basic design phase, intensive engineering work was dedicated to compiling catalogues of equipment such as embedded parts, supports, piping, valves, and pumps, etc. Identical components, such as pumps and heat exchangers will be used as much as possible to simplify maintenance. In addition, utilities and vendors joined force to set up common codes related to the EPR design, "EPR Technical Codes". These codes will promote standardization of quality requirements and competitiveness through the use of industrial standards.

It has been shown that the repeated construction of the standard design saves the construction cost greatly. Based on the estimation made by EdF [11], the repeated construction reduces capital cost ratio per kW by 25 to 30 % by the second unit. Further repeated construction would reduce this by 40% based on the first unit cost. KEPCO has experienced similar reduction in equipment and engineering service expenses.

To benefit further from the standard design and to reduce the construction schedule, the modular construction approach has been adopted in varying degrees by all water-cooled reactor developers. Modularization has been used for some time in the area such as water treatment, demineralizer package, air compressors, and T/G subassemblies. This has been extended to structural modules as well as wider range of equipment modules. ABWR has utilized the modular construction approach. This has been shown to be essential to meet the EPRI URD required schedule of 48 month from first concrete to fuel loading. In CANDU 9, special features related to constructability are incorporated, which will result in the reduction of the construction costs and schedule. The CANDU 9 design includes a site layout and building arrangement that promotes efficient construction and incorporates the increased use of prefabrication - ranging from skid mounted packages to large structural assemblies. In Korea, KNGR design team is developing modules for the Aux. Building below grade level to improve the construction schedule. Modularization decision is made in tandem with the development of the construction schedule to maximize its benefit.

## 4. INTEGRATION OF OPERATING PLANT INSIGHTS

Evolutionary reactor designs are based on operating plants and improve the design based on the operating experience. For example, System 80+ is improved from System 80. Three System 80 plants have been in operation at Palo Verde site in USA. KNGR is based on operating 1000 MWe KSNP design. Three KSNP units (YGN 3&4, UCN3) are in operation. By having the operating plants as a basis, the operating plant insights have been reflected in designing the evolutionary plants. Furthermore, utility requirements developed by EPRI, by European utilities and others essentially embodies the operating experience and desired improvements. The utility requirements have been the backbone of all the evolutionary water reactor development. Attention to the operating plant experience and insights assures that the new design will be safer and economical to operate when being built.

The reduction of the radiation worker exposure is important not just for the ALARA but also for the operating cost. The KNGR design team has sought to incorporate those lessons learned by the current generation of nuclear power plant to meet the exposure limit of 20 mSv/yr set by ICRP60 and to limit the collective exposure to less than 1 person-Sv/yr which is one of the EPRI URD goals. Radiation exposure from the maintenance work of KEPCO nuclear plants has been compiled and high exposure maintenance activities have been identified. Not surprisingly, the highest exposure maintenance work is the steam generator tube inspection. The improvement in the access to steam generators and the use of Inconel 690 for SG tubing are some of the consideration given to reduce occupational radiation exposure. Other means of achieving the exposure goals are summarized as follows:

(1) The generation of crud is controlled by adopting the material with low cobalt impurities, and maintaining the pH of reactor coolant water in the range of 6.9 to 7.4.

(2) Wider use of ion exchangers instead of evaporators in radwaste system.

(3) Use of permanent and temporary shielding as an integral part of KNGR design.

## 5. CONSIDERATION OF SAFETY, OPERABILITY AND CONSTRUCTIBILITY DURING DESIGN STAGE

Unlike previous nuclear plant design, the aspect of safety, operability, constructability, and operating plant insight has been systematically considered from the beginning of the design and during the design process. For example, both ABB/CE and GE performed the PSA during the design stage and reflected in their design improvement [12]. Furthermore, ABWR has performed constructability review, construction schedule development as well as cost estimate as the part of the first-of-kind-engineering program. In the CANDU 9 design program, CANDU utilities' operating staff participated in formal design reviews and joint constructability studies were performed with construction companies to maximize the benefits of past experience, resulting in cost reduction during future plant construction and operation. It is our understanding that similar activities are being performed in AP600, as well as EPR program.

As a part of the KNGR design development, KEPCO systematically evaluates the design periodically on safety, constructability, operability, ORE, and cost impact. The result of the evaluation is being used to optimize the design further. As an example, probabilistic safety analysis result showed that the auxiliary feedwater system reliability can be improved by changing the valve arrangement and the removal of a valve. Also, automatic operation of the start-up feedwater pump was recommended based on the PSA study [13].

Cost estimate during the design stage helps to optimize the ALWR development. Latest generation cost estimate of EPR shows that it is at least 10% lower than the cost prediction for future coal plants as well as that for combined cycle gas turbines. With the current power rating, investment costs are slightly below that for N4, in terms of $/kWe. Availability improvement together with reduced construction time among others, allow further substantial decrease in terms of generation cost. Latest cost estimate of KNGR shows also that it has similar cost advantage over the coal plants.

## 6. CONCLUSION

In this paper, we reviewed the effort taken into making the evolutionary water-cooled reactors economically viable. We reviewed some of the examples in the area of simplification, standardization, and reflection of operating plant insights. In general, the evolutionary water-cooled reactors do have higher investment cost due to more stringent safety requirement. However, the extra costs are counterbalanced by performance advances in plant availability and shorter construction schedule and attention to the cost from the beginning of the design phase. For example, the recent OECD study shows the cost competitiveness of a 1300 MWe ALWR plant against other electricity generating facilities. The effort of the simplification, standardization, and the reflection of operating plant insights in developing evolutionary water-cooled reactors do pay off.

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