Design and Licensing Experience of the Advanced Power Reactor 1400 Development


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Abstract

Advanced Power Reactor 1400 (APR1400) is a newly developed advanced reactor in Korea. It has been developed since 1992 as one of long-term national R&D projects and successfully-finished its standard design licensing review in May, 2002 and ready for the actual construction project. APR1400 is an evolutionary type nuclear power plant of a 1400 MWe class, which upgrades the safety and economic competitiveness of nuclear power incorporating up-to-date advanced technology while stands on the proven experience from Koran Standard Nuclear Power Plants (KSNP). The development project of APR1400 consisted of three phases in order to check and make any necessary adjustment at the end of each phase. In the first phase (Dec. 1992 ~ Dec. 1994), the utility requirements at the top level were established, and the reactor type and concept were determined. In the second phase (Mar. 1995 ~ Feb. 1999), the basic design was developed and the integrated plant analyses were performed in order to verify if the design goals were met. In the third phase (Mar. 1999 ~ Dec. 2001), the design optimization was carried out and the licensing review of the APR1400 standard design was performed by the regulatory body in Korea. From the beginning of the project, the importance of the licensing was recognized so that a new legislation for the standard design certification and establishment of technical regulatory requirements for new designs were pursued in parallel and in coordination with the design development. As the standard design certification was issued in May 2002, the construction project for the first APR1400 was put in the streamline and the application of the construction permit is scheduled in July 2003, aiming at the completion of construction in Sept. 2010.

KEYWORDS: APR1400, Standard design certification, KNGR, Shin-Kori 3&4

I. Introduction

Advanced Light Water Reactors (ALWR) have been developed world-wide since late 1980's, because more stringent safety standards was requested in order to take severe accidents into consideration and economic competence of nuclear power was challenged by other source of power generation such as LNG-fired power plants. Meanwhile, the nuclear industry including power utilities had accumulated a good deal of experiences in construction and operation/maintenance of light-water reactors since there were more than 400 reactors in operation. Therefore, the efforts were concentrated on developing rather practical reactors for which the accumulated experiences could be reflected. As a result, advanced light water reactors were the focus of development since light-water reactors were the majority of commercial nuclear power plants due to their outstanding experiences and proven technology.

In Korea, nuclear power greatly contributed to the electric power supply. It supplies more than 40% of electric power demand and takes near 30% of the total installed power capacity. Also, Korean nuclear industry has built and accumulated much experience in the LWR technology through the development, construction, and operation of Korean Standards Nuclear Power. In order to strengthen the competitiveness of nuclear power in the 21st century, the improvements both in safety and economics were found to be necessary in Korea as well. Therefore, a national project to develop an ALWR called the KNGR (Korean Next Generation Reactor) was launched in 1992. As the development project was finished in the end of 2001, a formal name of Advanced Power Reactor 1400 (APR1400) was designated to KNGR.

In this paper, we will introduce the overview of the development project in Chapter 2 such as the project organizations, development schedule and strategy, and we also describe the overall design features which distinguish APR1400 from the currently operating PWRs in Chapter 3. In chapter 4 and 5, we describe the regulatory frameworks developed for the APR1400 licensing and licensing review process including some examples of technical issues encountered. In the conclusion, we will briefly mention the construction plan and future prospect of APR1400.

II. Overview of the Development Project

In December 1992, the KNGR project was initiated as one of the national R&D programs so that most of the nuclear related companies and institutes in Korea joined
together and Korea Hydro & Nuclear Power Co., Ltd., led the project under the direction of the project committee and government.

The KNGR project consisted of three phases. The first phase, conceptual design stage, was completed in Dec. 1994, and the second phase, basic design stage, was finished in Feb. 1999. The third phase, design optimization stage, had been from Mar. 1999 to Dec. 2001. Now the actual construction project, Shin-Kori 3&4, has just begun.

The overall design process is schematically shown in Fig. 1. Through the comparative study among the candidate reactor types during Phase I, the evolutionary type was selected. The evolutionary type can have a higher power capacity so that the economics of power generation would be better and it is based rather on the proven technology so that the design could be more practical from the viewpoint of commercialization. Once the reactor type was selected, efforts were made to set up the top-tier utility requirements, for instance, power level, safety and economic goals, etc. Major system configurations and parameters were delineated for such items as the reactor power level, containment type, safety system features, digital I&C architectures and man-machine interface systems, etc. During the second phase, the basic design was developed following the detailed utility requirements and the integrated plant analyses such as probabilistic safety assessment, economic evaluation, and constructability study were performed. At the conclusion of the basic design phase in early 1999, the design was intensively reviewed for the feasibility of commercialization from the various point of view such as licensibility, constructability, economics, and so on. As a result of the review, the design optimization was performed to improve the economic competitiveness, operability and maintainability while maintaining the overall safety goal of the design. During the optimization process, the experiences of the utility were incorporated. Especially, the general arrangement of the APR1400 was improved for easier construction and operation.

In parallel with the APR1400 design development, the regulatory requirements and licensing process similar to the design certification in U.S. were developed and the design certification was issued as a result of licensing review. In order to support the design work especially for the advanced features, supporting R&D was carried out. For example, there were 5 major evaluation tests. They are the direct vessel injection test for the safety injection system design, full scale fluidic device test also for the safety injection system, sparger test for steam condensation in the In-containment Refueling Water Storage Tank, fatigue test of control rod element drive mechanism, and human factors evaluation for the digitalized main control room.

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Fig. 1 Major activities for the design development

III. Major Design Characteristics

3.1 General Arrangement

The general arrangement is focused on enhancing plant safety, improving economic competitiveness, and convenience of the plant operation. The APR1400 plant layout is based on the twin unit concept through which the sharing of common facilities can be maximized. The APR1400 plant consists of the nuclear island which includes the containment and auxiliary buildings, turbine island and compound building which contains common facilities. The layout scheme of the APR1400 plant is shown in Fig 2.

The containment building is made of a steel-lined, post-tensioned concrete. The containment is designed to take the load from the hydrogen burning in case of severe accidents. The auxiliary building wraps around the containment building and contains the main control room, fuel handling area, and main steam valve house. To enhance the safety against fire and flooding, the auxiliary building is divided in a quadrant scheme.

The auxiliary building is on the common base mat with the containment building so that it forms a monolithic structure, resulting in higher resistance to seismic events. The compound building is located between the auxiliary buildings of two units and consists of an access control facility, a radwaste treatment facility, a hot machine shop, and sampling facilities & laboratory which can be shared
by two units. Also, the operation-supporting center is located in the compound building.

The IRWST is one of the most significant features introduced in the PWR type ALWRs. APR1400 is also equipped with IRWST which constitutes the In-containment Water Storage System (IWSS). The IRWST is located near the bottom of the containment building and circled around the containment wall as shown in Fig. 2. The IWSS performs water collection, delivery, storage and heat sink functions inside containment during normal and accident conditions. The IWSS consists of IRWST, holdup volume tank (HVT), and the cavity flooding system (CFS).

Fig. 2 Schematics of Plant Layout and IRWST

3.2 Nuclear Steam Supply System

A schematic of the RCS with its major improvements is shown in Fig. 3. The RCS consists of two steam generators with four RCPs. It is designed to produce the rated thermal output of 4000MWt and the corresponding electrical power is around 1450 MWe. The core outlet temperature is lowered to increases a margin against steam generator’s primary side corrosion attack. The steam generator design improvements are the use of Inconel 690 material tubes, more tube-plugging margin, and adequate secondary water inventory.

The pressurizer safety valves and safety depressurization system valves replaced by four tandem POSRVs. It is to ensure more stable operation without the risk of valve chattering and leakage for any type of discharge flow condition encountered and to allow remote manual open and close operation under post-accident conditions. The most significant change made in the NSSS is the Safety Injection System (SIS) design. The safety injection lines are physically four-train and electrically two-division without tie branch between injection lines and connected directly to the reactor vessel. The direct vessel injection design provides a simpler and more reliable system performance since it avoids the need for orifice and valve adjustments in the delivery lines which are required for cold leg injection to ensure adequate injection, minimizing spillage during a cold leg break. Moreover, it eliminates the possibility of the injected water spallage through the broken cold leg. A passive flow regulating device, named Fluidic Device, is installed in each SIT discharge line providing two operation stages of safety injection into the RCS, resulting in more effective use of borated water in the SIT.

Fig. 3 Schematic of the reactor coolant system with design improvements
3.3 Main Control Room Design

The APR1400 MMI system distinguishes itself from current designs by employing all digital I&C systems and data communications, and video-based MMI which incorporate modern human factors principles. The schematic picture of APR1400 Main Control Room (MCR) is shown in Fig 4. Advanced design features being incorporated include: (1) the compact workstation-type control room layout, (2) Large Display Panel, (3) computerized operating procedures, (4) soft controls, and (5) a reduced number of fixed location displays and alarms. The key features supporting the operating crew’s ability to maintain efficient and safe plant operation include:

- Two identical full-function workstations supporting direct plant control and monitoring by a Reactor Operator and a Turbine Operator, respectively,
- A third identical workstation supporting normal monitoring and crew coordination functions by a Shift Supervisor,
- An LDP providing overall plant operational and safety information,
- A Safety Console providing controllability for all Class 1E components for the plant safe shutdown even in case of complete workstation failure.

Fig 4. Schematic Picture of Main Control Room Layout

IV. Development of Regulatory Frameworks

The regulatory frameworks including both licensing procedure and technical requirements had to be developed or revised for the APR1400 licensing, because APR1400 like the ALWWRs adopted many advanced technologies which required new licensing review guidelines.

Also, the standardization concept called for a new process of licensing focused on the design certification so that the replicating construction based on the certified design can be implemented.

4.1 Development of Safety and Regulatory Requirements & Guides

The Safety and Regulatory Requirements & Guides (SRRG) for APR1400 were developed. The basic approach to the development of the SRRG is, to reflect operating experiences obtained from the existing plants, to adopt enhanced safety concepts for strengthening the safety level, and to improve the reliability of structures, systems, and components (SSCs), which will result in upgrading of the current Korean regulatory requirements and guides. It has a hierarchy consisting of six tiers : Safety Objectives(SO), Safety Principles(SP), General Safety Criteria(GSC), Specific Safety Requirements(SSR), KINS Regulatory Guides(KRG), and Safety Review Guides(SRG).

The upper four tiers (SO, SP, GSC, and SSR) cover compulsory requirements, while the KINS Regulatory Guides(KRG) and SRG, forming the understructure of the hierarchy, are not considered as mandatory requirements but as guides.

Fig. 5 Hierarchy of Safety and Regulatory Requirements and Guides

The Safety Objectives (SO), the highest requirements in the hierarchy of the SRRG, were established to provide the directing objectives to be achieved ultimately for safety. The quantitative safety objectives and the criteria against severe accident were adopted.

The Safety Principles (SP) are the most essential elements which have to be observed for accomplishing safety objectives and General Safety Criteria (GSC) are
described general standards for measuring compliance with safety principles.

The Specific Safety Requirements (SSR) are the detailed rules which have to be applied for obeying safety principles and general safety criteria. It is composed of 5 parts (site/environment, design, operation, decommissioning, and quality assurance), 23 chapters, and 479 3-digit items were adjusted to the legislation in Notice of Minster of Science and technology.

The KINS Regulatory Guides (KRG) provide optional methodologies and features to be used in complying with mandatory regulatory requirements such as GSC and SSR. A total of 163 KRG were developed. Based on the SSR, a total of 29 drafts of the Minister's Notice were developed. The final drafts will be gradually incorporated into Notice of Minster of Science and Technology for the licensing of future NPPs. The Safety Review Guides (SRG) are internal guidance of KINS staff on safety review.

4.2 Establishment of New Licensing Processes

The Korean licensing process for construction of Nuclear Power Plants (NPPs) employs the two-step licensing approach, i.e. construction permit at the beginning stages and operation licensing at the final stage. However, APR1400 is based on the standard design concept, so that the NPPs referencing the standard design may be constructed successively without design changes. Therefore, it was necessary to improve the existing licensing process to avoid repetitive licensing review for the portion of the design referencing the standard design. Meanwhile, the licensing of the standard design became more important since the licensed design could be used repeatedly as a reference for a period of time and APR1400 adopted many new design features like other ALWRs that may require more prudent review.

Therefore, early interactions between designers and licensing reviewers were necessary to minimize the potential safety issues as early as possible before the design was progressed into details. As a result of these two considerations, the introduction of the following licensing systems was made as complementary measures to the current licensing system: pre-application safety review and standard design certification.

A. Pre-application Safety Review

From the developer’s point of view, it was important to secure the licensibility of the proposed design with advanced design features as early as possible, so that the development of APR1400 could be progressed under stabilized environment. From the regulator’s point of view, it was necessary to prepare for the license application which may require different standards for review. In this regard, an introduction of a Pre-application Safety Review system was introduced in Dec. 1999. It encouraged an early interaction of the applicants with regulatory body not only to identify regulatory requirements in advance, but also to carry out more timely and effective regulation. In addition, the Pre-application Safety Review system enables designers to resolve the safety concerns raised by regulatory body in an early design stage. Such an interaction in the early design stage contributed to stabilizing the licensing process and to expediting the development of the APR1400. The Pre-application Safety Review system had been applied to APR1400 by an administrative order of the Ministry of Science and Technology from Dec. 1999 to Jul. 2001.

B. Standard Design Certification

In the licensing process for nuclear facilities of Korea, the two-step licensing approach is employed based on the prescriptive regulation and practice of the U.S.A. The APR1400 was developed with a concept of a standard design so that repetitive constructions of the NPPs referencing the standard design may be possible without design changes. Under the circumstance like this, in order to avoid repetitive licensing review for the NPPs referencing the standard design, it was necessary to introduce a new licensing system. The Standard Design Certification (SDC) system was chosen as a new licensing process for standardized plants.

When the SDC is issued to the applicant who developed a standard design of a NPP, the safety evaluation for the portions of the NPP referencing the standard design will be excluded during its licensing review for construction permit and operating license. And the regulatory body cannot force changes of the standard design unless significant design defects are found in the standard design. The SDC is valid for 10 years and continuous to be effective to the date the applicant receives Operating License if the application to the Construction Permit of the NPP referencing the SDC is docketed before the expiration date. For the implementation of the SDC system, detailed licensing process requirements and guides were developed, and legislated in July, 2001 as a complementary measure to the existing licensing system.

V. Licensing of the APR1400 Standard Design

The licensing review for the design standard certification of APR1400 was performed by Korea Institute Nuclear Safety from Jan. 2000 to May. 2002 including the pre-application review. As a result of this review, Ministry of Science and Technology formally issued the standard design certification in May 7, 2002.

During the review period, there were five rounds of the request of additional information (RAI), totally 2251 RAIs.

The documents provided for review were Standard Safety Analysis Report (SSAR), Emergency Operating Guidelines (EOG), and Certification Design Material (CDM). The CDM contains the certification design description and the list of Inspection, Tests, Analyses, and Acceptance Criteria (ITAAC).

Most of the RAIs came from the advanced design features which were first applied to APR1400, for
instances, the man-machine interface design and digital I&C system, the performance of safety injection system with direct vessel injection, and design features related with accident mitigation.

5.1 MMIS and digital I&C Design

Most of the RAIs focused on the Human Factors Engineering (HFE), for instances, how it was conducted and verified. Examples of specific questions are the situation awareness and workload under the emergency conditions, effectiveness of team performance, and the impacts of the using the computerized procedure system (CPS) on the operators’ performance compared to using the paper procedures. For these RAIs, the evaluation results of HFE verification and validation were provided, which performed by the dynamic mockup of the proposed main control room design.

For the implementation of the digital I&C system, the use of the soft-control concept was a key issue. The soft-control concept was to use workstations as a single controller both for safety and non-safety system and originally it was intended to be non-class 1E system since the hard-wired back-up system shall be provided. During the licensing review, the upgrading of the soft-controller to the important-to-safety qualified grade was recommended and implemented in the design.

5.2 Performance of SIS

The APR1400 design adopted 4 train and direct vessel injection (DVI) system. Therefore, the validity of using the computer code for LOCA analysis in the DVI simulation was raised since the computer code used in the analysis was originally developed for the cold-leg-injection cases. In order to resolve this issue, the TRAC code analysis was performed since the TRAC code could simulate the 3-dimensional effects more sophisticatedly. Also, the experiment to verify and to validate the effects of the by-pass flow during the direct vessel injection was carried out. At the end of the licensing review, the downcomer boiling phenomena during the safety injection was requested for further investigation, so that the additional analysis focused on this was carried out as a post-licensing activity.

5.3 Severe Accident Mitigation System

Like other ALWRs, APR1400 made a good deal of advances in the severe accident mitigation. It is designed to equip with the passive autocatalytic recombiner (PAR) and external reactor vessel cooling system (ERVCS) in addition to the hydrogen ignitors and reactor cavity cooling system respectively. For the effectiveness of PARs for the hydrogen removal, 3-D hydrogen distribution analysis using the up-to-date code was recommended. For the ERVCS, the design of the reactor vessel insulation which should provide a natural circulation pathway, and the potential adverse effects were major review concerns. For insulation design, additional experiments were carried out and the technical base of the effectiveness and adverse effects of the ERVCS strategy was recommended for review as a part of the accident management program during the operation license stage.

Other examples of issues raised during the license review were related with the IRWST design, consideration of environmental effects in fatigue evaluation, use of the alternative source terms, and the steam generator tube integrity. Since the S/G tube integrity is always a key concern in the PWR design, an additional study to maintain the tube integrity was recommended and carried out. For the IRWST design, the thermal hydraulic loads and temperature during the RCS discharge to IRWST were concerned, so that more experiments were recommended. Conducting a basic research program for the evaluation of the environmental effects on the fatigue was recommended and being carried out.

VI. Conclusions

Since nuclear power encounters more and more challenges regarding safety and economic competitiveness, the development of advanced reactors is inevitable. APR1400 is a result of such efforts. APR1400 is an evolutionary type PWR in a class of 1400 MWe capacity. Considering the economics of scale, technical feasibility, and feedback of valuable experiences, the evolutionary type was chosen and it was found to provide economic advantages while maintaining sufficient safety level.

Since the development of a new reactor design requires a tremendous amount of efforts and quite a long period of time, a systematic planning from the beginning of the project is very important. In the APR1400 development, therefore, the overall project was carried out in three phases; the first phase for the prudent decision making of design concepts, second phase for developing the basic design, and the last phase for design optimization and licensing.

Also, the licensing is the essential part of the development in order to the design to be implemented in the actual construction. Since APR1400 aimed at the construction as a final goal, the project comprised the activities related with the licensing, from the beginning of the project, promoting the early interactions between the licensing reviewers and design developers.

According to the long-term power development program in Korea, two units of APR1400 are scheduled for operation in September 2010 and September 2011 respectively. KHNP, the sole nuclear power plants owner in Korea, approved the construction plan of APR1400 in February 2001, and set up the detailed construction implementation plan for the construction of two units in June 2001. The site for the first APR1400 is being prepared in Shin-Kori which is located at the southeast shore of Korea. According to the construction plan, the first concrete will be poured in June 2005, the fuel will be
loaded in Sept. 2009, and the commissioning will be made in Sept. 2010 after one year of start-up testing. When APR1400 is in commercial operation in 2010, it is expected to be the first evolutionary type advanced PWR plant generating electricity.

References