DESIGN FEATURES IN KOREAN NEXT GENERATION REACTOR FOCUSED ON PERFORMANCE AND ECONOMIC VIABILITY

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Abstract

As of the end of Dec. 1999, Korea's total nuclear power capacity reached 13,716 MWe with 16 units in operation and 4 units under construction. In addition, as part of the national long-term R&D program launched in 1992, the Korean Next Generation Reactor (KNGR) is being developed to meet the electricity demands in the years to come which is expected to be safer and more economically competitive than any other conventional electric power sources in Korea. The KNGR project had successfully completed its second phase and is now on the third phase. In Phase III of the KNGR design development project, KNGR aims at reinforcing the economic competitiveness while maintaining safety goals. To achieve these objectives, the design options studied and the design requirements set up in the first phase and pursued while the second phase are being reviewed. This paper summarizes such efforts for design improvement in terms of performance and economic viability along with the status of nuclear power generation in Korea, focusing on KNGR in current.

1. STATUS OF NUCLEAR POWER GENERATION IN KOREA

The first nuclear power to Korea was introduced in early 1970s with the construction of Kori unit 1, a 600MWe Westinghouse type PWR. Two additional 600MWe plants were built, one by AECL of Canada, and the other by Westinghouse. These three units are called first generation NPPs in Korea, and were constructed through turn-key contracts. Afterward, six additional PWRs of 950MWe, Kori 3&4, Yonggwang 1&2 and Ulchin 1&2, were put on the grid during relatively short period (1978-1988), the construction of six plants in 10 years was due to the urgency of energy security caused by the unstable oil market in 1973 and 1979. These power plants was adopted non-turn key contract of which Korea Electric Power Corporation (KEPCO) took responsibility for the projects including construction management and the startup of the plants based on the experience from the construction and operation of the previous units.

To meet the electricity demand and overcome the foreign dependency of critical technology, the Yonggwang 3&4 project was started in 1987. In this project, domestic entities became the primary contractors along with foreign sub-contractors in order to absorb the technology necessary for design and construction.

In succession, Korean Standard Nuclear Power Plant (KSNP), a 1,000 MWe PWR, had been developed by improving Yonggwang # 3 and # 4. Two KSNP series, Ulchin 3&4 started the commercial operation successfully in 1998 and 1999 respectively. At this time, 4 additional units are under construction in Yonggwang and Ulchin sites and 2 KSNP+ have recently been decided to be constructed near Kori site. The plants scheduled in the Shinpo site of North Korea are also KSNP series.

As of December 1999, installed capacity consists of 6.7% hydro, 26.3% coal, 10.0% oil, 26.3% gas and 29.2% nuclear. The emergence of LNG as one of the major electric power sources in Korea implies that the portfolio of energy sources will depend not only on the cost of power generation but also on the public preference for environment protection and the manageability of power supply.

Figure 1 shows the long-term view of the electric power sources which shows the installed capacity of 68% increase in 2015 year. Based on the consideration mentioned above, it can be interpreted as follows:

1) Nuclear power plants are expected to be continuously constructed due to energy security and cost effectiveness.
2) Using coal is to be maintained at the same level in terms of composition as in the present since it has a strong merit in cost despite its impact on the environment.
3) The portion of power generation from LNG anticipated to be reduced slightly. However, LNG will remain as one of the major energy sources for power generation for the time being despite its high price in Korea.
4) The power generation from oil and hydro will vary also. However their role will be limited as in the present.

From the above prospect for the various power generation sources, it is clear that the nuclear power is anticipated to increase gradually and remain as a major power source in Korea. Its competitors are coal and LNG power generations of which merits are low cost for coal and less environmental impact and flexibility of energy management for LNG.

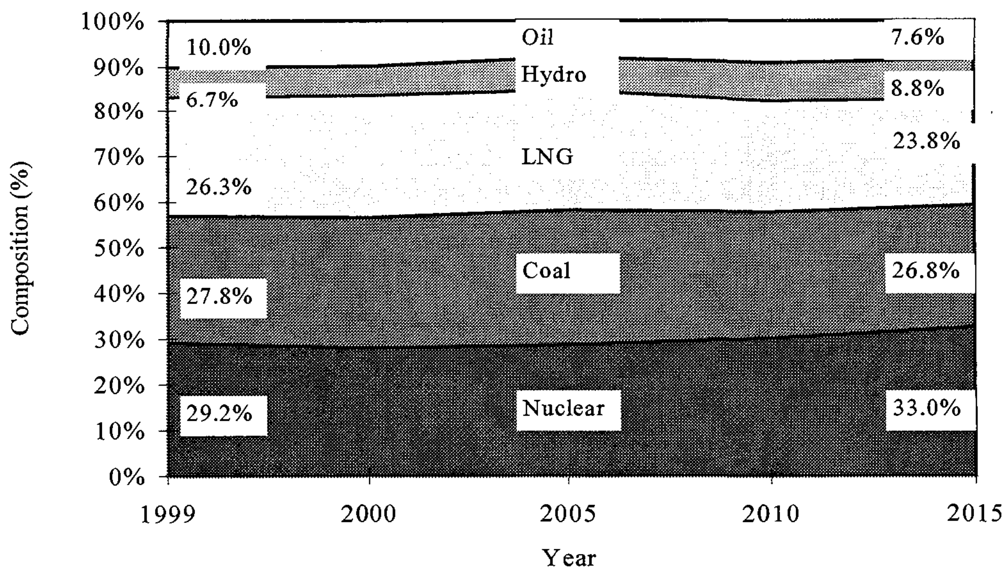

FIG.1. Future outlook for the composition of the electric power source (installed capacity).

2. KOREAN NEXT GENERATION REACTOR PROJECT STATUS AND DESIGN CHARACTERISTICS

In order to further enhance safety and economic competitiveness, a new project to develop an ALWR called KNGR, 1400 MWe PWR, was launched in 1992. Like other ALWRs being developed worldwide, KNGR reflects operating experiences as well as the technology accumulated through the KSNP design. Also, the development of KNGR is closely linked to the construction plan so that the design can be materialized in due time. This project consists of three stages in whole. The first stage, conceptual design stage, was completed on Dec. 1994, and the second stage, basic design stage, was finished also on Feb. 1999. Now the third stage is in progression to the goal of design certification of standard design by the end of 2001.

The KNGR is an evolutionary ALWR based on the current Korean Standard Nuclear Power Plant (KSNP) design with capacity increment. It also incorporates a number of design modifications and improvements to meet the utility's needs for enhanced safety and economic goals and to address the new licensing issues such as mitigation of severe accidents.

The major evolution concept of the KNGR was developed as the result of two years research of the Phase I. During this period, The design concepts had been set up to meet domestic needs and capabilities through reviewing ALWR designs being developed by leading countries in nuclear industry. To establish the safety and economic goals for the KNGR, the ALWRs were also compared quantitatively through safety and economic evaluation. The 42 top-tier design requirements had been established through this comparative study. The major requirements for KNGR are as follows;

- General Requirements
  - Type and capacity: PWR, 4000 MWth;
  - Plant lifetime: 60 years;
  - Seismic design: SSE 0.3g;
  - Safety goals: core damage frequency lower than 10^{-5}/RY and containment failure frequency lower than 10^{-6}/RY.
- Performance Requirements and Economic Goals
  - Plant availability: 90%;
  - Occupational radiation exposure: less than 1 manSv/RY;
  - Construction period: 48 months(Nth plant);
  - Economic goal: 20% cost advantages over coal power plant.

The nuclear steam supply system of the KNGR is designed to operate at rated output of 4000 MWth to produce an electric power output of around 1450 MWe. The major components of the primary circuit are the reactor vessel, two coolant loops, each containing one hot leg, two cold legs, one steam generator (SG), and two reactor coolant pumps (RCPs), and one pressurizer (PZR) connected to one of the hot legs. Two SGs and four RCPs are arranged symmetrically.

The active safety systems consist of the safety injection system (SIS), safety depressurization and vent system (SDVS), in-containment refueling water storage system (IRWST), auxiliary feedwater system (AFWS), and containment spray system (CSS).

The main design concept of the SIS is simplification and redundancy to achieve higher reliability and better performance. The safety injection lines are mechanically 4 trains and electrically 2 divisions without a tie branch between the injection lines for simplicity and independence. Each train has one safety injection pump and one safety injection tank. The common header currently installed in the SIS trains is eliminated and, finally, functions for safety injection and shutdown cooling are separated. Through the IRWST the current operation modes of high pressure, low pressure, and re-circulation can be merged into only one operation mode (i.e. safety injection). The emergency cooling water is designed to inject directly into the reactor vessel so that the possibility of spill of the injected flow through the broken cold leg is eliminated.

The refueling water storage tank is located at the inside of the containment and the arrangement is made in such a way that the injected emergency cooling water can return to the IRWST. The susceptibility of the current refueling water storage tank to external hazard is lessened by locating it at the inside of the containment. The functions of IRWST are as follows; the storage of refueling water, a single source of water for the safety injection, shutdown cooling, and containment spray pumps, a heat sink to condensing steam discharged from the pressurizer for rapid depressurization if necessary to prevent high pressure core melt or to enable feed and bleed operation, and coolant supply to the cavity flooding system in case of severe accidents to protect core melt.

The AFWS is a 2 division and 4 train system. The AFWS is designed to supply feedwater to the SGs for RCS heat removal in case of loss of main/startup feedwater systems. The reliability of the AFWS has been increased by use of two 100% motor-driven pumps, two 100% turbine-driven pumps and two independent safety-related auxiliary feedwater storage tanks as a water source instead of condensate storage tank.

In addition to the added protection and prevention system, severe accident mitigation features and strategy are incorporated into KNGR as follows; 1) hydrogen mitigation system such as passive auto recombiner and hydrogen ignitor, 2) wide reactor cavity area and cavity flooding system, 3) POSRV(Pilot Operated Safety and Relief System) and IRWST, 4) in-vessel retention of molten core by external reactor vessel cooling.

3. KNGR DESIGN FEATURES ENHANCING PERFORMANCE AND AVAILABILITY

Since 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 future light water reactors, specially focusing on simplification and increased operational margin, standard design with repeated construction, and 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 also 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 substantial decrease in generation costs. Shorter construction schedules, simplification of designs together with regulatory stability are thus becoming increasingly important to control costs. In this section, the design improvement consideration for economic viability and performance improvement embodied in KNGR is reviewed.

3.1. Availability improvement

The sensitivity study of economics assessment indicates that the availability of the plant is the most sensitive parameter in ensuring the validity of the cost estimate of electricity. The availability improvement can be achieved by the reduction of outages: both forced outages and planned outages (normally for refueling purpose). Fault-tree model was developed to analyze each system to reduce the number of the forced outage by enhancing the system reliability. To reduce the planned outage duration, KNGR standard outage schedule was generated by reviewing the experiences from KSNP.

3.1.1. Forced outage evaluation

KNGR forced outage was preliminarily evaluated based on the operating experience study. The forced outage data of the existing plants are important to predict the forced outage characteristic for the KNGR. For this, trip records were investigated for the domestic PWRs (Kori Unit 1,2,3,4, YGN Unit 1,2,3,4, and UCN Unit 1,2). Trip causes and failure modes, time to restore, and the countermeasures against recurrence are identified for each trip case occurred during the period from 1978 to 1996 based on the annual trip report published by KEPCO. The trip cases occurred during the first one year of commercial operation were excluded in the analysis to get insights of plant lifetime considering the bathtub curve effect.

The focus is to estimate the number of the plant trip by the same root cause of the each trip case. Since the KNGR is at the basic design phase, system designers, equipment vendors, and system engineers of the plants were consulted to predict detailed design and to confirm design modifications and equipment refurbishment in each plant. Some failures were evaluated not to cause plant trip in the KNGR. For example, 5 trip cases occurred due to the failure of RTD (Resistance Temperature Detector) bypass line of the Reactor Coolant System. In the KNGR as well as some of the current plants, the thermo-well type rather than RTD is adopted for measuring temperature of the coolant, by which trip will not occur in the KNGR.

With assessment of the failure causes for the KNGR design, the trip frequency is estimated to be 0.8 per year and 2 days per year for forced outage duration which are considered achievable as a trend of today's domestic operating records.

3.1.2. Planned outage evaluation

Planned outages, during which refueling and maintenance (R/M) are performed, are the most dominant factor to the plant unavailability. The operating experiences show that the planned outage duration is characterized by normal outage and extended outage according to plant types and maintenance activity levels. Therefore, a typical 45-day normal outage schedule for a 1,000 MWe PWR was chosen as a basis to assess the planned outage of the KNGR. The RAM(Reliability, Availability, Maintainability) analysis has established the normal outage duration of the KNGR as 42 days by reducing the reactor vessel head handling work loads with little impact on the maintenance activities of the other major components like Steam Generators. Followings are some examples employed in KNGR to reduce the planned outage and operational conveniences.

KNGR has simplified reactor vessel head area by utilizing an integrated reactor vessel head package. An Integrated Head Assembly (IHA) is designed to incorporate all of the reactor vessel head components into one module(Figure 2). 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 2 days in comparison to the typical seven-day schedule of existing plants. Prior to refueling in existing PWRs, the equipment on reactor vessel area has to be removed and temporarily stored before removing the reactor vessel head.This process has resulted in increasing the overall refueling duration as well as the personal radiation exposure. The IHA is being designed to consolidate the following into an one-package component design: the head lifting rig; lift columns; missile shield; CEDM forced air cooling system; electrical and instrumentation cabling; insulation and reactor vessel head. The IHA lifts the reactor vessel closure head and the head area equipment at one time. Therefore, the amount of critical path required to reach the reactor vessel internals can be reduced.

Furthermore, the KNGR have advanced design features such as a permanent pool seal (PPS) and a quick opening fuel transfer tube blind flange (QOBF) to reduce refueling work load. The PPS is installed between the reactor pressure vessel and the surrounding refueling canal floor to permit flooding above the vessel during refueling. Since the leak-before-break concept is applied to the reactor coolant piping, the possibility of the local pressurization in the reactor cavity is eliminated. It becomes possible to permanently install the refueling pool cavity seal (termed as pool seal). Thus the need for assembling and disassembling temporary pool seals is eliminated. The current blind flanges are installed with bolts to seals off the containment building transfer tube penetration sleeve during reactor operation. Therefore, it takes long time to lift, and to temporarily store it. The QOBF, however, can reduce workload need for lifting it during refueling.

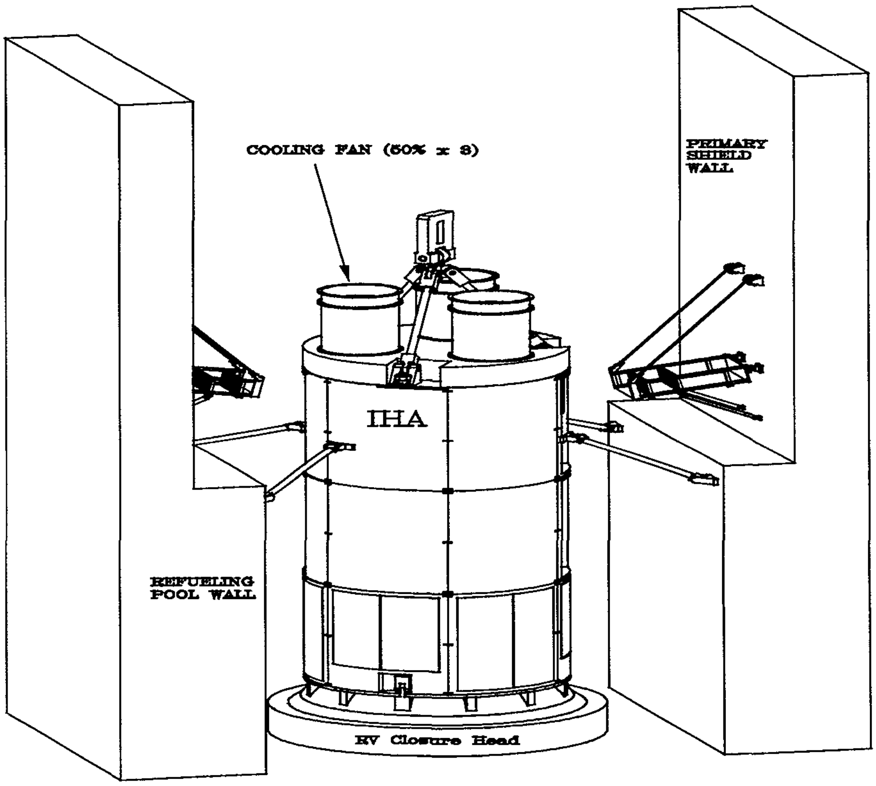

FIG. 2. Integrated head assembly (IHA) for KNGR.

While current domestic nuclear power plants are operated with 12 × 18 month refueling/maintenance(R/M) cycle, KNGR is being designed to have a capability of operating over 18 month fuel cycle, from post refueling startup to the subsequent post refueling startup as per EPRI URD. So for the KNGR, it would take 42 days for R/M cycle per 18 months (i.e. 28 days/a).

An extended outage is another type of outage. It is extended by the works such as ISI (In Service Inspection) and Turbine/Generator overhaul. Ultrasonic Test of the reactor vessel is performed according to the 10-year ISI program. Containment ILRT and turbine/generator overhaul are assumed to perform every 5 years and Steam Generators replacement is assumed once during a 60-year plant lifetime. Although the quantitative estimation of their effects are difficult, the extended outage is estimated to be 6 days per year based on the operating experience of YGN 3 and Kori Unit 1.

One of design improvements in this case is in steam generator replacement. Even if KNGR is incorporated the latest advances in materials and design to maximize the SG integrity, the overall industry experience record combined with the need to extend plant lifetime dictates that the design incorporate provisions for steam generator replacement. The containment polar crane is designed in such a way it can be utilized to remove the steam generators from their cubicles to the area of the equipment hatch. The generators can then be skidded out of containment through the equipment hatch to the auxiliary building where it will be loaded onto an awaiting transport vehicle. Containment layout provides access to piping to facilitate cutting and welding operations that will be required for this evolution

3.2. Constructibility assessment

Shortened construction period reduces the investment uncertainty and reduces the time for recovering investment. In this regard, KNGR is encouraged by the condensed construction schedule set by Tokyo electric Kashiwazaki-Kariwa-6 and 7 units. Following the practice of the Kashiwazaki-Kariwa construction as well as the AP600 construction plan, the way to adopt the advanced construction techniques is under review.

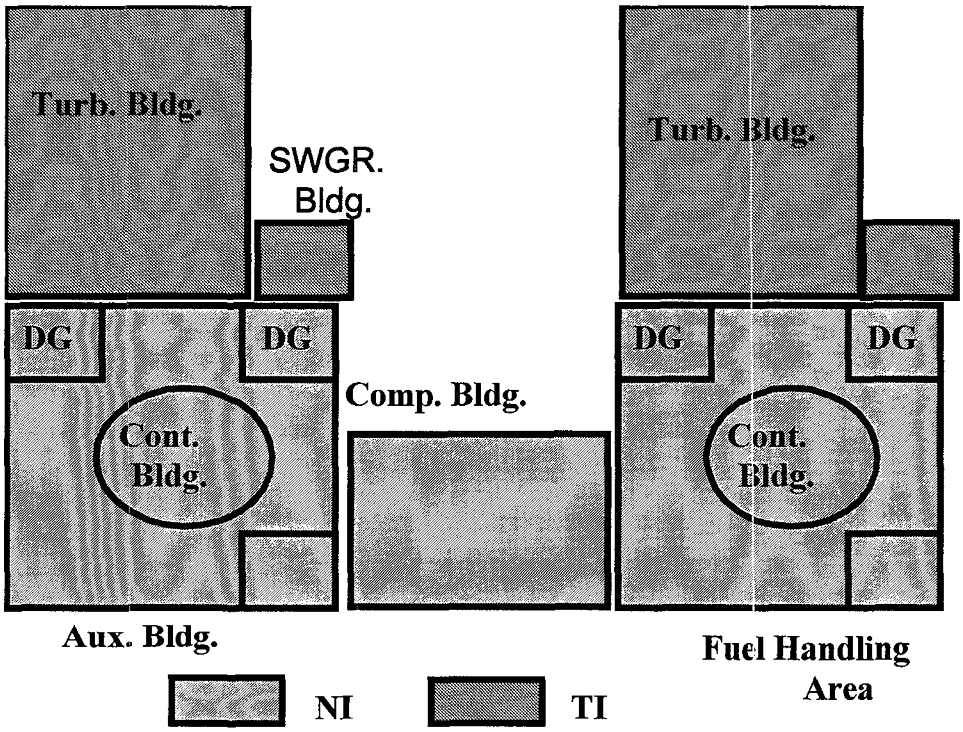

FIG. 3. The general arrangement with complex building of KNGR.

In KNGR design, the auxiliary building surrounds the containment (Fig. 3). Unlike arrangement of KSNP the wrap-around design of KNGR Aux. Building prevents direct access to the containment during the construction. It requires special consideration on the transport and installation of equipment in the containment. Furthermore, the reduction in the Aux. Building construction schedule becomes important since it is tied to the containment construction schedule. To alleviate the problem, the applicability of the over-the-top method is taken into account for NSSS main equipment installation using large cranes. To cut down the Auxiliary Building construction schedule, it is reviewed and decided to adopt the deck-plate method.

In conventional approach, after completion of structural construction by the high-strength shoring and placement of concrete, the installation of mechanical and electrical components commences. The deck plate construction method enables structural construction without the high-strength shoring in the slab concrete pouring. For existing plants, deck plate construction is applied partly as necessary. In KNGR, the deck-plate method will be applied to the entire auxiliary building. It is being integrated to the construction scheduling. The auxiliary building below grade is crowded with mechanical and electrical components. The construction of this area is on the critical path. To adopt the deck-plate construction method, the floor elevation of the Aux. Building has been adjusted. The recent analysis indicates that the use of the deck-plate method costs about the same as the conventional method while reduces the construction period by 15%.

To maximize the benefit of the deck-plate method, one needs to install the equipment modules by the over-the-top method at the same time. We are actively reviewing the equipment modularization. Currently, we have identified about 170 module candidates and are evaluating its effectiveness. Once chosen, the necessary design change will be made to use equipment modules.

3.3. Radiation protection

In Korea, the regulatory agency decided to apply ICRP 60, a major update of ICRP 26, for the ALWR licensing review in Occupational Radiation Exposure (ORE) and ALARA area. ICRP 60 set a lower limit for the occupational dose: an annual dose of 20mSv/a averaged over a period 5 years with an upper limit of 50 mSv in a year. ICRP 26 set the annual occupational dose limit at 50 mSV/a. Since the issuance of ICRP 60, Korean regulatory agency developed new regulatory requirement for radiation protection. The main features of this requirement are 1) for the simplicity of regulation, setting simply 20 mSv/a as annual occupational dose limit and 2) putting more emphasis on ALARA requirement than the compliance with annual dose limits.

The new regulation would increase the cost of electricity generation since it tightens the exposure limit. To minimize its impact, we paid extra attention to defining the hot zone and clean zone. The workers are not allowed to enter the clean zone from the restricted area (hot zone) except through the access building. In the process, radiation work and the worker's movement were carefully reviewed. Also, to reduce the impact of stringent requirement, we have taken the credit in the fuel failure rate based on the improved fuel performance(1% fuel failure rate to 0.25% fuel failure rate).

The reduction in the radiation exposure of workers is important not just for the ALARA but 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/a set by ICRP60 and to limit the collective exposure to less than 1 person-Sv/a 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.

3.4. Man-Machine Interfacing System(MMIS)

KNGR is equipped with digitialized Man-Machine Interface System(MMIS) which encompasses the control room systems and Instrumentation and Control(I&C) systems, reflecting the modern computer technology. The KNGR MCR design is characterized by 1) redundant compact workstations for operators, 2) seismically qualified Large Display Panel(LDP) for overall process monitoring of the plant to be shared among operating crew 3) multi-functional soft controls for discrete and modular control, 4) computerized procedure system to provide on one of the workstation CRTs with context sensitive operation guides, operational information, and navigation links to the soft controls for normal and emergency circumstances and 5) safety console for dedicated conventional miniature button type controls provided to control essential safety functions. CRTs and FPD(flat panel display) are extensively used for presentation of operational information.

The human factor engineering is an essential element of the control room facility design and Man-Machine Interface (MMI) design and its principles are systematically employed to ensure safe and convenient operation. Operating experience review analysis, function analysis, and task analysis are performed to provide systematic input to the MMI design.

One of the main features of the I&C system is the use of microprocessor-based multi-loop controllers for the safety including reactor protection and non-safety control systems. Engineering workstation computers and industrial personal computers are used for the two diverse data processing systems, respectively. To keep the plant safety against common mode failures in software due to the use of digital systems, controllers of diverse types and manufacturers will be employed in the control and protection systems. For data communication, a high speed fiber optic network is used. The remote signal multiplexer is also utilized for the safety and non-safety systems field signal transmission to save considerable amount of cables and cable trays. Since the S/W is heavily relied on in full digital MMIS, stringent S/W qualification process will be established and followed for the life cycle of KNGR. The MMIS concept to be implemented in the KNGR design is schematically depicted in Figure 4.

Partial dynamic mockup has been constructed based on the simulator of predecessor plant(KSNP) system models. This facility is used to perform initial verification of suitability of the MMI design. In the forthcoming design stage, the mockup will be expaned for intermediate validation of the design and I&C prototyping will be undertaken for smooth development of KNGR MMIS facility

4. KNGR DESIGN OPTIMIZATION

With the completion of the basic KNGR design at the end of Phase II, we have decided to perform an integrated review on the design and to perform an optimization when necessary. The integrated review of the design was conducted from the perspective of the safety, economics, constructibility, and operation and maintainability

Various issues and questions on the design options in KNGR have arisen during the KNGR development. Some of the issues were from the plant construction and operation department. Based on the construction and operation experiences of the Korean Standard Nuclear Plant (KSNP) series, reviews on design features were requested.

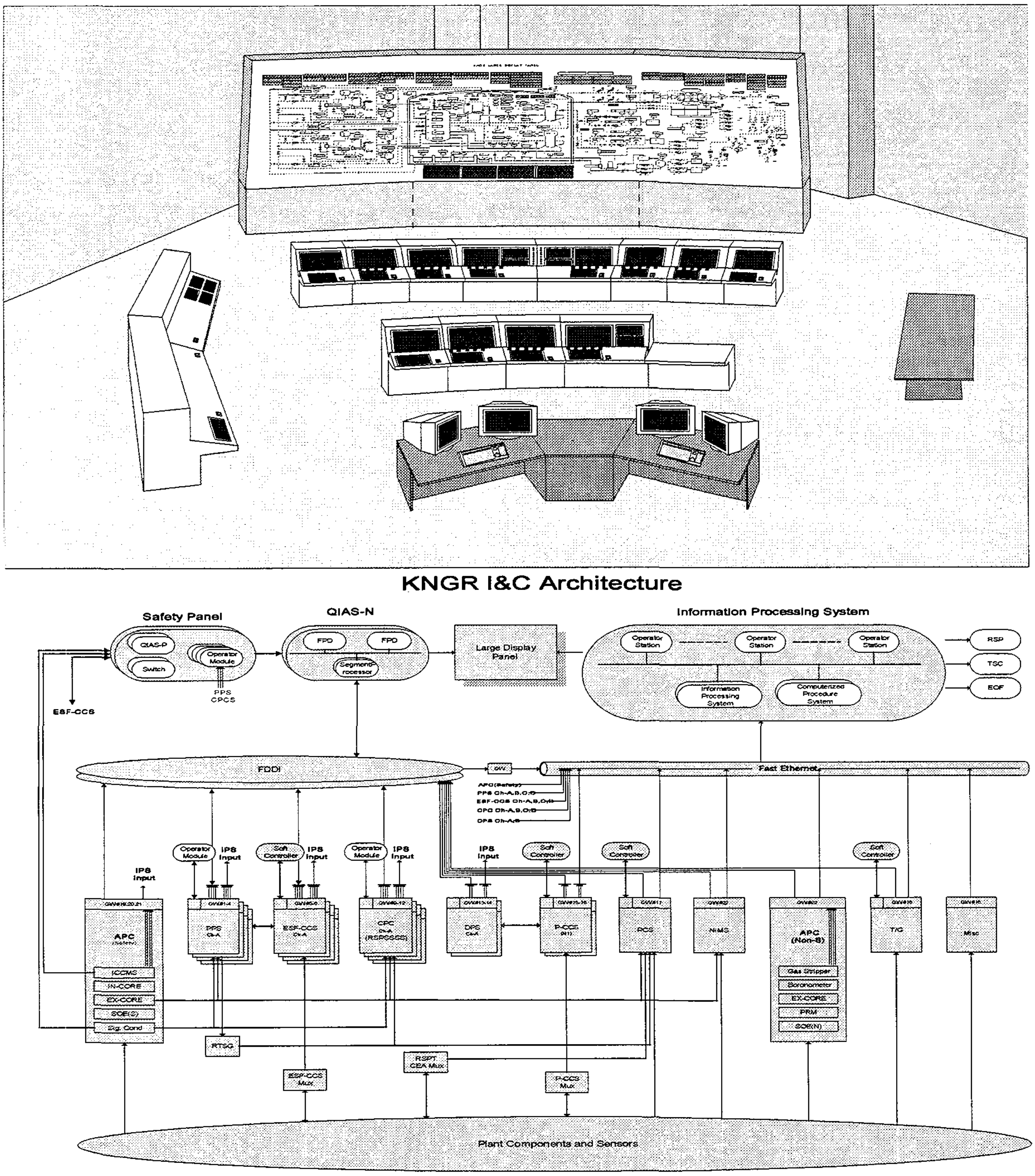

FIG. 4. KNGR man-machine interface system(MMIS).

Issues and questions were also raised regarding the cost-benefit of the safety enhancement features. During the optimization process, all these issues have been collected and grouped. More than twenty items went through the optimization study. Major items considered are 1) Electric power up-rating, 2) NSSS and BOP safety system optimization, 3) Fuel and core design optimization for thermal margin and fuel performance, 4) Containment and severe accident mitigation system optimization, 5) General arrangement (GA) and building structure optimization for convenient construction and maintenance.

Table I shows the summary of the optimization evaluation and its determining factors related to safety, operational or cost impacts. It was estimated the removal of passive secondary condensing system (PSCS) and double containment is cost-effective. The cost benefit for the removal of double containment is more than 10 millions dollars in direct cost savings without a large impact to safety. The final cost comparison after design optimization shows the cost is reduced by 60 million dollars per unit of original cost. The reduction in the construction duration is not credited at this cost assessment. The construction schedule experts estimated that the construction duration could be reduced by 1~3 months by elimination of outer containment.

It is predicted that efficient designs will be achieved in KNGR by incorporation of following factors; 1) Reflecting the operation and construction experiences of Korean nuclear power plants, 2) Gaining the economic competitiveness even though the energy environment will be changed much, 3) Obtaining the consensus for the stable detailed design through mutual consent between the experts inside and outside the industries.

TABLE I. OPTIMIZATION RESULTS BY EACH DESIGN ALTERNATIVES

Group	Items	Results	Remarks
Plant Power Level	Electrical power Up-rating (3,931→4,000MWth)	- 52" Last Stage Blade (LSB) adoption - Increase in Fuel Enrichment and new Fuel in refueling	Cost saving 23M$/unit-year including 13M$ by 52" LSB
NSSS Safety System	-Safety Injection System with DVI -POSRV -Fluidic Device in Safety Injection Tank	- SIS with Direct Vessel Injection - POSRV design - Fluidic Device(FD) Adoption	- No change from basic design
Fuel and Core Design	-24M Fuel Cycle -High Burn-up Fuel -MOX Core Design	- 18 Month fuel cycle - 30% MOX design cap.	- Change to 24 Month Cycle if necessary - Long term R&D item
Containment and Severe Accident	-Double Containment -Cavity Flooding System(CFS) -Hydrogen Mitigation System	- Single Containment & In-Vessel Retention - Replacement of Fusible Plug with MOV (Motor Operated Valve) Passive Auto-catalytic Recombiner + Igniter	Accident mitigation Measure such as IVR adopted
General Arrangement	-Structural Design Optimization	- Compound building - System, Building, Structure optimization	Reduction of 5~10% of volume & bulk material
PSCS	-PSCS Removal	- - Removal of PSCS	Cost-benefit analysis
Performance Requirement	- Load Follow Capability - SG Dryout Time	- Daily load follow - Relaxation of dryout time to 20 minutes	-Excluding frequency control - Related to PSCS removal

5. CONCLUSION

Intensive efforts were made to make the KNGR economically viable and some of the examples on the design optimization, reflection of operating plant insights are presented. In general, the evolutionary ALWRs do have higher investment costs due to more stringent safety requirement. However, the extra costs is counterbalanced by performance advances in plant availability and shorter construction schedule and attention to the cost from the beginning of the design phase. The economic viability could be achieved through several design features incorporated, so it is pretty difficult to say what the final economic competitiveness of KNGR will be. It is emphasized, however, that KNGR is expected to have balanced features in terms of economics and safety.