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Implementation of Risk Management in Korean Next Generation Reactor Design and Optimization Process

Abstract

The Korean Next Generation Reactor (KNGR), as a part of the national long-term R&D program launched in 1992, is being developed to meet the electricity demands in the coming years. The KNGR project has successfully finished its second phase and initiated the third phase in1999. At the beginning of Phase III of the KNGR design development project, the design alternatives were studied and the design requirements from the conceptual and basic design were also reviewed to reinforce the economic competitiveness while maintaining the safety goals. Implementation of comprehensive risk management is an executive management decision and performing design specific Probabilistic Safety Assessment (PSA) is an integral part of risk management program. In KNGR design and optimization process, PSA method was used extensively for this purpose. This paper exemplifies the use of PSA in the decision making process and summarizes the effort for design optimization focusing on the integration of safety, operations and cost goals for the development of KNGR.

I. Introduction

In a long-term advanced nuclear reactor development program, Korea Electric Power Corporation (KEPCO) has been developing an evolutionary PWR plant called KNGR, for the standard nuclear power plant with a 4000 MWt power output. The project has three development phases. The major goals in Phase I, finished in 1994, were to determine the type of reactor, to study feasibility on the selection of preliminary design concepts, and to develop the top-tier design requirement. Phase II was a four year program from 1995 to 1999 to develop the basic design for the licensing review, to assure safety and licensability. Basic design features include:

- Advanced Design Features (ADF)
  - Four-train safety injection system (SIS)
  - In-containment refueling water system (IRWST)
  - Pilot operated safety and relief valve (POSRV)
  - Auxiliary feedwater system (AFWS)

- Double containment with annulus ventilation system

- Passive Design Features (PDF)
  - Passive secondary condensing system (PSCS)
  - Passive auto-catalytic recombiner
  - Fusible plugs in cavity flooding system
  - Fluidic device in safety injection tank

At the completion of basic design, KNGR has been forced to design for cost optimization. All the safety systems in the basic design are believed to be superior to those of existing domestic plants and foreign ALWRs. But there was concern about the economic viability of the new design when compared to fossil plants and competing, already operating nuclear power plants.

Phase III is scheduled from 1999 to 2001 with main objective being a design optimization. Originally, the purpose was to develop the detailed design. The focus was changed to include additional consideration of the balance between safety and cost of the advanced design features in KNGR design. Therefore between Phases II and III, some technical issues were optimized through an integrated review of the adequacy and effectiveness of the basic design, taking into account safety, economy, operability and maintainability aspects.

A plant specific PSA is an integral part of risk management and could be used as an executive management decision. This paper describes the design interaction of PSA as a integral process of assuring the safety of KNGR. And the KNGR design optimization review process and some sample cases to illustrate the use of PSA are presented.

II. Insights from PSA in KNGR Design Process

PSA was used extensively in the KNGR design process. PSA was used to confirm the safety goals and to optimize the alternate design options. The insights gained from past PSAs, especially those of Ulchin 3&4 and System 80+, were used to identify vulnerabilities in previous plants. This information was then used to incorporate some design features in the KNGR design to reduce or eliminate these vulnerabilities. Examples are the adoption of PSCS to reduce the risk from loss of auxiliary feedwater. These design alternative study in view of safety was mainly done during the conceptual design stage in 1994.

During the KNGR basic design, the PSA was performed mainly to confirm the safety goal for the on-going design and also to identify any design weaknesses. For this purpose, the PSA evaluated three times during the 2^{nd} phase of the design.

The first evaluation was done at June, 1997, and the design was in the middle of the 2^{nd} phase. Thus a lot of design information for the KNGR evaluation had to be obtained from the System 80+ and Ulchin Units 3&4. Although the core damage frequency was much lower than that of the safety goals, some design improvement items were identified through intensive review of the results. And this information was informed to the design teams and was adopted for design improvement. Some major findings were as follows;

1) The common cause failure of the check valves in the auxiliary feedwater injection lines was the most dominant contributor to the AFW system unavailability. The needs of the check valves and other design alternatives were discussed with the design teams, and it was suggested that the check valves be removed.

2) The External Containment Spray Backup System(ECSBS) connection to the containment spray system was located at the IRWST return line. In order to succeed in operating the ECSBS, three normally closed MOVs must be opened which makes the availability of the system restricted. As a result of the evaluation, it was recommended that the connection of the ECSBS be moved to the utmost outside of containment to improve the ECSBS availability regardless of opening the MOVs.

The second evaluation was performed at June, 1998 when some design issues were still not resolved. The core damage frequency was 1.67 times higher than that of the 1st evaluation. Lots of sensitivity analyses were done to identify the cause of the high core damage frequency. It was found that the major cause came from the changes of the modeling, e. g, human error rates and CCF factors. Also, the major design changes were as follows;

1) The recommended design improvement items identified from the 1st PSA were adopted.

2) The refill method for the PSCS condenser was improved to manual refill from automatic method from reactor makeup water tank. This will worsen the unavailability of the PSCS, but it could reduce risk from the station blackout in which no supporting systems are available.

3) The CCW system was changed to three 50% heat exchangers per division from two 100% heat exchangers.

To identify the impact of these design changes, a sensitivity evaluation was performed using the PSA model of 1st evaluation. It showed that the CDF was decreased by 11.3%. It was concluded that the design was improved in terms of safety by excluding the influence of modeling methods.

The final evaluation in the basic design was performed at February, 2000, and the major design changes based on the 2nd evaluation were reviewed. And a sensitivity study was performed to see the effect of design improvements such as PSCS, POSRVs.

1) The PSA was used as a major tool in deciding whether the improvement was needed in the PSCS design. The sensitivity analyses showed that the unavailability of PSCS with 50% capacity per division was increased by order of magnitude from that of 100% capacity per division, but the CDF for the 50% per division was increased a little. Considering the results from the sensitivity analyses and other factors, it was decided that PSCS design was changed to 50% capacity per division from 100% capacity per division. The success criteria of PSCS was changed to the two of two divisions from one of two divisions as the design made progressed. Also, a sensitivity analysis was performed to evaluate the impact of PSCS removal on the CDF. The results showed that the present core damage frequency would be increased to 3 fold when the PSCS were removed.

2) The SDS valves were modified to POSRVs and a sensitivity analysis was performed to evaluate the impact of modification from SDS valves to POSRVs. The results show that the change from SDS valves to POSRVs is insensitive to the core damage frequency. This is expected result since the availability of the depressurization function is dominated by the operator error probabilities.

The external, shutdown events were evaluated at the 2nd and 3rd evaluation. The major contributors to fire-induced core damage frequency were the fire in the auxiliary building and switchyard control building. The major contributor to the CDF during shutdown was loss of offsite power. The results of the containment performance analysis in terms of the conditional probability of containment failure and source terms indicate that KNGR design does not have any particular vulnerability to containment performances compared with other PWR plants. The effectiveness of new design features of containment system such as advanced design of cavity configuration, hydrogen mitigation system(HMS), cavity flooding system(CFS), and external containment spray backup system(ECSBS) are modeled in containment response analysis.

The KNGR cavity configuration allowed much less corium ejection out of cavity during high pressure melt ejection compared with conventional PWR. Hydrogen igniters and passive auto-catalytic recombiners could prevent hydrogen burn. Also, the CFS was very effective to mitigate corium-concrete interaction(CCI) and base melt-through, whereas the ECSBS plays ultimate heat sink of containment at late phase of accident. In the current KNGR containment design, there is a provision that the coolant from IRWST can flow into the caviity and provide external reactor vessel cooling, which is not credited in the analysis. According to sensitivity studies, this provision is somewhat effective to the containment performance if we removed the passive cavity flooding system.

In optimization design in phase III which are performed march, 2000, preliminary evaluation was performed to see the synopsis of PSCS removal and its alternative design. At this time, PSA considered the necessity of model change by independent reviews from experts as well as the reflection of design changes. In addition to the big change of PSCS and double containment system, some trivial design changes but affecting somewhat large on safety is reviewed. It is the control power supply to the auxiliary feedwater system enhancing the redundancy. And the common cause failures of check valve for safety injection and auxiliary feedwater system are changed to NUREG/CR-5497 data from EPRI URD data. It is because the newly recommended data is considered more appropriate and the latter is so conservative to apply system based unavailability evaluation comparing to that of existing plant.

Preliminary evaluation results and design changes from phase 2 KNGR PSA are transmitted to the betterment of Korean standard nuclear power plant plus(KSNP+) where the safety is not so impaired even though the design improvement is focused on the economics.

III. KNGR Design Optimization Review Process

As depicted in the Figure 1, The optimization comprised of three steps:

- Identification of issues (internal design team)
- Technical feasibility analyses (internal design team)
- Decision by the design review and evaluation committee (DREC) (high level managers and experts in and outside of KEPCO, in order to establish consensus among participants in the project)

In the identification stage, technical and/or economic issues that need detailed investigation are selected and categorized into several groups. Design feasibility analysis, licensing impact analysis, and cost/benefit analysis are then performed for these issues. The analysis results are reported to DREC for decision-making.

After a through review process, KEPCO has decided to remove some systems to improve the economic competitiveness. The changes do not increase safety losses. For example, while double containment and the

Passive Secondary Condensing System (PSCS) have been removed from the design, other hardware has been added; namely, diesel driven pump or alternative designs for backup of the auxiliary feedwater system and an in-vessel retention strategy (IVR) for severe accident mitigation.

There was a long debate about the mitigation of thirty minutes of steam generator dry-out time, which is one of KNGR top-tier requirements. The debate related to several factors, including safety, operational philosophy, manufacturing, and so on. In addition, KEPCO has reduced the length of steam generator tubes for the purpose of reducing the flow-induced vibration, while we increased steam generator radial size in order to achieve the increased 4000 MWth NSSS thermal power.

During this decision process, several sensitivity studies (including PSA and cost analyses) to evaluate the effects of the design changes on safety, operations, and commercial factors (including public acceptance effects) were made. With respect to the decision to use a single containment design, they performed the evaluation for containment failure frequency, offsite dose, and the impact of reinforcement on the severe accident mitigation facility. In evaluating removal of the passive secondary condensation system, the committee was concerned with meeting their internal goal of core damage frequency, which is a tighter goal than the top-tier one. Other alternative cost-effective options were reviewed for coping with core damage frequency and station blackout.

Among the issues considered, the replacement of Passive Secondary Condensing System (PSCS) required the extensive use of PSA, due to its impact on safety. Also, in a somewhat lesser degree, the use of double containment and its benefit requires examination in PSA domain. In the next section, we will discuss these two examples in detail.

III.1 Passive Secondary Condensing System

During the Phase 1 of the project, it was decided that it would be beneficial to enhance the safety against the total loss of feedwater event. For this purpose, KNGR developed Passive Secondary Condensing System. It is a passive system that condenses the steam from the steam generators by natural circulation cooling mechanism. Therefore, the system is simple and its reliability is much higher than that of active systems. In Phase 2, the basic design of the PSCS has been completed. Its operability has been examined as well. However, PSCS requires a large tank on top of the auxiliary building and it increases the cost substantially. Furthermore, PSCS has been designated as non-safety grade system. Hence, it can not replace the existing auxiliary feedwater system.

As a part of the optimization study, we examined whether there are other alternatives. The PSA was used as a major tool in deciding whether the optimization was needed in the PSCS design. Because it was a safety significant system in previous safety evaluation, we were concerned about the safety loss due to its removal. So, we have reviewed the several related factors such as technical feasibility, offsite radiation goal, adverse effect by undesired operation and cost effectiveness in addition to core damage frequency for alternative design options. The alternative design options considered are upgrading of the system which is ultimately replacing the AFWS(Option 1), simply removing the system(Option 2), and addition of the alternate system(Option 3).

Table 1 showed that the cost-benefit is very competitive for option 3 and the other two options are almost the same. However, the two options are very different if we considered licensing and performance issues because option 1 is a very innovative concept not embodied in previous ALWR designs. From the safety perspective, the current design is the best solution. However, the associated cost is the highest as well. It is clear that Option 3 has a cost advantage over the other two options. With this analysis and detailed consideration of other safety goals, the decision to add one diesel driven pump of non-safety grade, which is backup to the auxiliary feedwater system was made.

Table 1. The safety-cost impact of PSCS design alternatives

Contents	Basic Design	Option 1	Option 2	Option 3
CDF(Correlated)	1.00	1.60	3.0	1.68
Cost	25 M$	22 M$(-3)	14.8 M$(-10.2)	16.6M$(-8.4)
Remarks	AFWS + Non Safety PSCS (50%)	Safety grade PSCS(100%)	AFWS + Removal of PSCS	AFWS + Removal of PSCS + DDP

III.2 Double Containment

It was decided in phase 1 to have a double containment to enhance the safety and to increase the public confidence on KNGR. The double containment consists of pre-stressed inner containment with reinforced outer containment. During the phase 2 of KNGR development, we examined the possibility of removing containment liner. However, we concluded to keep the liner since its removal will increase the licensing risk. With the liner in place, the benefit on radiation release has been reduced. The operation and construction crews raised questions on the constructibility and maintainability of annulus region of in and outside of containment. So the expert consultation from existing plant construction members were elicited in the review process.

For the optimization of outer containment, we have to show the safety standard could be maintained by reviewing the containment integrity and the radiation release goals. The sensitivity analysis showed that the addition of severe accident mitigation features such as the external cooling of reactor pressure vessel (RPV) is more beneficial than the addition of the outer containment from the containment integrity perspective: The containment integrity could be increased by more than 20% by adoption of IVR strategy(option 2) which would offset the loss by single containment(option 1) as shown in table 2. To satisfy the limit of off-site radiation and site boundary goals, the design leakage rate was tightened to 0.2 v/o/day. The penalty by the adoption of single containment is that the site boundary be extended to as far as 700 m. With the double containment, the site boundary can be set at 500 m. The design leakage rate of 0.2 v/o/day is the same as that of existing Korean standard nuclear power plants and it wouldn’ t be difficult to meet with a single containment with a liner.

Table 2. The safety comparison of double with single containment with IVR

Contents	Basic Design	Option 1	Option 2
Containment Failure Frequency(Correlated)	1.0	1.1	0.9
Conditional CF Probability(%)	10.6	11.7	9.6
Remarks	Double Containment	Single Containment	Single Containment + IVR

III.3 Optimization Results

There were more than twenty optimized items, including the following major items:

- Electric power up-rating by turbine system
- NSSS design optimization for performance enhancement
- NSSS and BOP safety system optimization
- Fuel and core design optimization for thermal margin and fuel performance
- Containment and severe accident mitigation system optimization
- General arrangement (GA) and building structure optimization for construction and maintenance convenience.

Table 3 shows the optimized design and its determining factors related to safety, operational and cost impacts. It indicates that the removal of PSCS and double containment is cost-effective. The monetary benefit for the removal of double containment is more than 10 million dollars, considering only direct cost savings without a large impact to safety.

One of the lessons we learned is that it is important to examine the overall impact of the various optimization options in PSA as well as cost estimate. Even though PSCS and double containment play somewhat different roles in the safety such as prevention and mitigation, they are closely related to the ultimate public safety goal. So, when we tried to remove each system, we have to review the systems integrally. 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.

IV. Conclusions

This paper has presented examples of risk management and its integration into standard design of new plant to manage risks. It is shown here that balanced safety, operations, and cost considerations can provide for efficient NPP design, as demonstrated in KNGR design. The KNGR design is considered to have been optimized by this process,

- because it reflects the design, construction, and operating experience of Korean nuclear power plants;
- enabling it to be economically competitive even though the commercial energy environment is constantly changing;
- due to consensus among experts inside and outside the industries for balanced design of KNGR

Although the presence of passive system such as PSCS showed a significant safety enhancement to the design, it turned out to be less cost effective. Thanks to implementing the design optimization, the KNGR will be economically sound and unimpaired in safety and is expected to represent the future standard model for nuclear power plants.

The review process affirms the need to examine the impact on the plant level integrity. PSA is proved to be a useful tool for risk management.

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Table 3. Optimization Results by Each Design Alternatives

Plant Power Level	Electrical power Up rating (3931→ 4000 MWth)	- 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 -In-vessel Retention (IVR) -Cavity Flooding System(CFS) -Hydrogen Mitigation System	- Removal of Double Containment - 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 and addition of Diesel Driven Pump	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

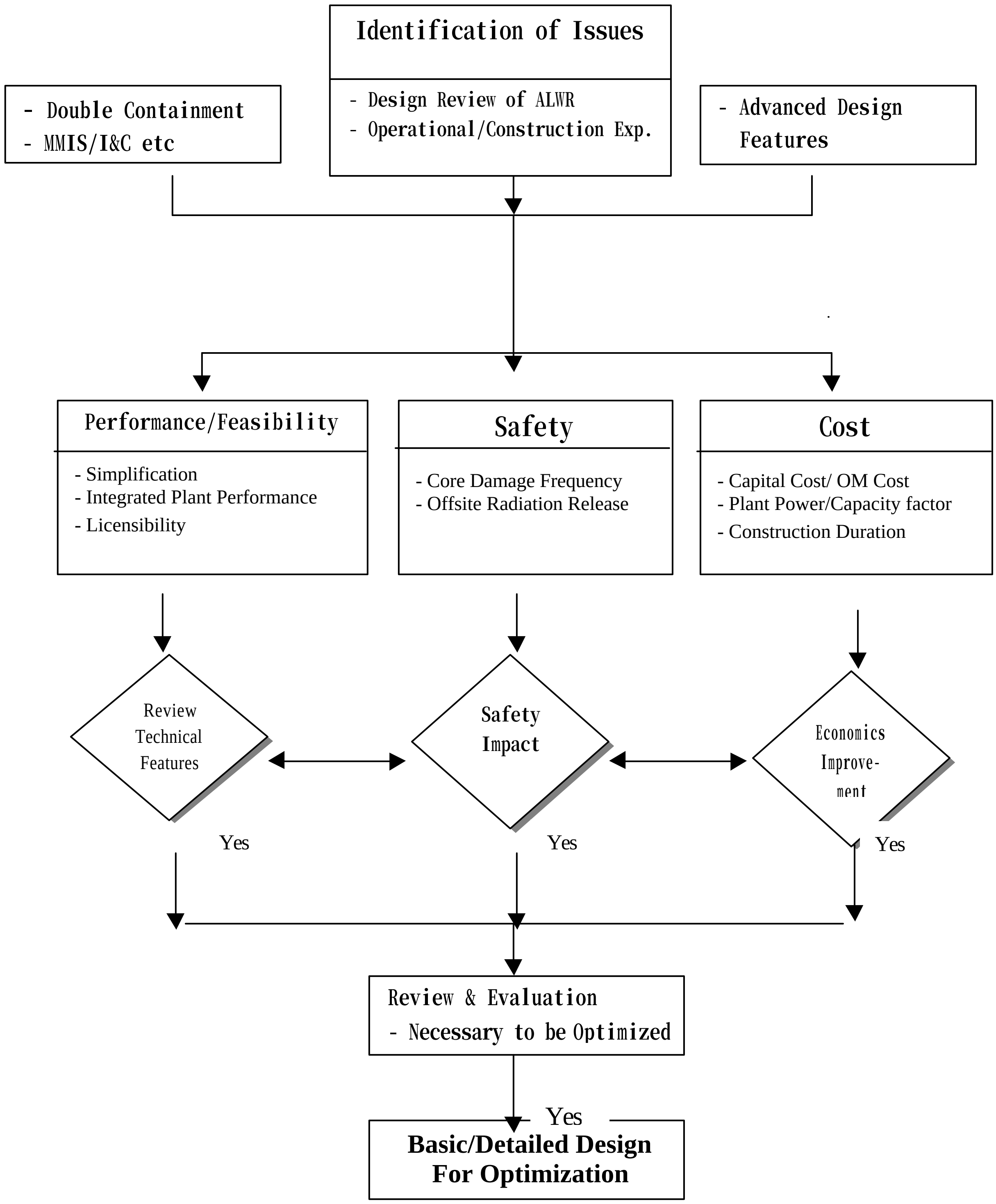

Figure 1. Schematic of the KNGR Design Optimization Process