XA9847565

CONSIDERATIONS OF SEVERE ACCIDENTS IN THE DESIGN OF KOREAN NEXT GENERATION REACTOR

DONG WOOK JERNG, CHOONG SUP BYUN
Korea Electric Power Research Institute,
Korea Electric Power Corporation,
Taejon, Republic of Korea

Abstract

The severe accident is one of the key issues in the design of Korean Next Generation Reactor (KNGR) which is an evolutionary type of pressurized water reactors. As IAEA recommends in TECDOC-801, the design objective of KNGR in regard with safety is to provide a sound technical basis by which an imminent off-site emergency response to any circumstance could be practically unnecessary. To implement this design objective, probabilistic safety goals were established and design requirements were developed for systems to mitigate severe accidents. The basic approach of KNGR to address severe accidents is firstly prevent severe accidents by reinforcing its capability to cope with the design basis accidents (DBA) and further with some accidents beyond DBAs caused by multiple failures, and secondly mitigate severe accidents to ensure the retention of radioactive materials in the containment by providing means to maintain the containment integrity. For severe accident mitigation, KNGR principally takes the concept of ex-vessel corium cooling. To implement this concept, KNGR is equipped with a large cavity and cavity flooding system connected to the in-containment refueling water storage tank. Other major systems incorporated in KNGR are hydrogen igniters and safety depressurization system. In addition, the KNGR containment is designed to withstand the pressure and temperature conditions expected during the course of severe accidents. In this paper, the design features and status of system designs related with severe accidents will be presented. Also, R&D activities related with severe accident mitigation system design will be briefly described.

1. INTRODUCTION

Korean Next Generation Reactor (KNGR) is an evolutionary type of pressurized water reactors with a rated capacity of 1350 MWe. As other ALWRs currently being developed in the world, KNGR also considers severe accidents in the design, following the fundamental safety principle of the defense-in-depth concept. Therefore, severe accidents are systematically addressed in the design by identifying the vulnerability of the current plant design and defining systems and equipment features or analysis works necessary for the safety enhancement.

In the KNGR design, severe accidents are considered in conjunction with safety goals. The KNGR design objective for safety is in the same track with the IAEA's safety objectives described in TECDOC-801. Thus, severe accidents are treated in the design to the extent that no significant radiological consequence to the vicinity of a nuclear power plant site can be technically assured. Whence, an immediate response outside of site boundary would be practically unnecessary for at least 24 hours after core melt occurs.

To practically implement the safety objective, probabilistic safety goals were established. As a safety goal to prevent severe accidents, the core damage frequency(CDF) shall be less than 1E(-5)/RY considering internal and external events except for seismic events which need to be dealt in a different way. For the mitigation goal, radiation release frequency which exceeds 10mSv(1 rem)/24 hours at the site boundary shall be less than 1E-6/RY. Further, a limit of the long-lived radioisotope release is required such that the frequency of accidents releasing more than 100 TBq of Cs-137 shall be less than 1E(-6)/RY to ensure the use of land around the plant site.

To meet the safety goals, specific design requirements have been developed[1,2]. For the prevention of severe accidents, increasing design margin and reinforcing the reliability of conventional engineered safety features (ESFs) are the major focus of requirements. For the mitigation of severe accidents, containment structural integrity under the severe accident conditions is almost important. To address the severe accident phenomena challenging the containment integrity, specific systems and their functional requirements were also developed. Especially, those phenomena challenging early containment failures, such as hydrogen detonation and high pressure core melt ejection, shall be explicitly considered in the design to virtually eliminate their threat to the containment.

In the next section, we will introduce the basic concept of KNGR to prevent and mitigate severe accidents. In Section 3, the system features and their design status for severe accident mitigation such as the containment general arrangement and cavity structure will be presented along with some of key design issues. In Section 4, R&D works related with severe accident mitigation to support the KNGR design will be briefly described and in Section 5, we will conclude the paper by presenting the results from preliminary probabilistic safety assessment of KNGR and future schedule.

2. DESIGN APPROACH OF KNGR TO DEAL WITH SEVERE ACCIDENTS

In this section, we will introduce the design approach of KNGR to cope with severe accidents in two steps: one for prevention and the other for mitigation.

2.1 Prevention of Severe Accidents

Preventing severe accidents generally means that the progression of initiating events is arrested in the category of design basis accidents(DBAs) so that the integrity of fuel can be maintained within the design limits. To prevent severe accidents, therefore, it is important to suppress accident initiators and ensure the proper function of engineering safety features.

Preventing severe accidents is implemented in the design by three steps: 1. increasing design margin to absorb abnormal transients, 2. enhancing the reliability of ESFs, and 3. extending ESF or other necessary system functions considering multiple failure conditions beyond DBAs. Table 1 summarizes the design improvements in KNGR to prevent severe accidents.

Table 1 includes design improvements for the prevention of containment bypass accidents which are another type of severe accidents. Prevention is more important for containment bypass accidents because they might result in unacceptable radiological consequences without core degradation. In KNGR, the Intersystem LOCA and multiple S/G tube rupture accident are explicitly considered in the design as noticed in Table 1.

2.2 Mitigation of Severe Accidents

If Engineered Safety Features(ESFs) fail to arrest the progress of accidents, the situation becomes severe accident conditions so that core degradation and successively reactor vessel failure could occur. The mitigation of severe accidents, therefore, are important measures to cool the degraded core and, thus, ensure the containment integrity.

Table 1 KNGR design improvements for severe accident prevention.

Category	Related Systems	Improved Features
Design Margin Increase	- Pressurizer	- PZR volume of 68 m^3(2400 ft^3){~0.017 m^3(0.62 ft^3)/MWth} - No PORV installed - No safety valve actuation for mild overpressure transient such as loss of load.
	- Steam Generator	- Dryout time of 30 minutes
	- Reactor Core	- Thermal margin of 10 ~ 15 %
ESF Reliability Enhancement	- SIS	- 4 Trains and dedicated system - No realignment of suction line with the use of IRWST
	- EFWS	- 2 EFW tanks and dedicated system - 2 Trains with 2 pumps per train
	- CSS	- Use of SCS pumps and Hx for back-up
ESF function extension/Other system reinforcement	- SIS and SDS with IRWST	- Feed and bleed cooling capability
	- SDS with IRWST	- Depressurization of RCS without containment contamination.
	- Reactor Protection System	- Use of a control grade alternate protection system for shutdown in case of ATWS
	- On-site Electrical Power	- Use of a gas turbine generator for AAC in case of SBO
Containment Bypass Prevention	- SCS and CVCS	- Higher piping design pressure for prevention of Intersystems LOCA
	- Steam Dump System	- No atmospheric dump in case of SGTR - Use of N-16 detectors for early detection of the S/G tube rupture - Higher reliability of steam dump valve operation

In the KNGR design, the principal approach to mitigation is the ex-vessel cooling by providing a large cavity and cooling system. Whence, the cavity shall be designed to capture the corium and an associated cavity cooling system shall be provided to cool it. This concept is based on the defense-in-depth principle because the corium can be retained in the cavity which acts like an additional container. For cavity cooling, KNGR takes the pre-flooding strategy principally. In case that pre-flooding fails, however, fusible plugs are provided to enable the post-flooding.

Though the principal approach for severe accident mitigation in KNGR is the ex-vessel cooling using the cavity and associated system, a concept of cooling the reactor vessel exterior is being carefully examined for the feasibility of indirect cooling of corium relocated to the vessel lower region. For the ex-vessel flooding, the possible maximum flooding level without a change of the current plant layout design is found to be about 2.7m(8.9 ft) from the bottom of the reactor vessel. This level is good enough to flood the lower head of the vessel. However, more studies such as critical heat flux at the surface of the vessel and in-vessel melt progression are necessary to finally determine whether to take this concept.

Severe accidents involve various phenomena which can be categorized as High Pressure Melt Ejection (HPME), Direct Containment Heating (DCH), Hydrogen Deflagration and Detonation, Ex-Vessel Steam Explosion(EVSE) and Molten Core-Concrete Interaction (MCCI). The mitigation systems in KNGR focus on how to effectively manage these phenomena and are basically to ensure the containment integrity. Table 2 summarizes these design features and Section 3 will further describe the system design in detail.

Table 2 KNGR design features for severe accident mitigation

System	Major Functions & Related Phenomena	Performance Requirements / Design Criteria
Hydrogen Igniter System	- Combustible Gas Control	- Maintaining H_2 concentration lower than 10% with 100 % oxidation of active fuel cladding material
Reactor Cavity and Cavity Cooling System	- Retention of core debris - Cooling of core debris to prevent MCCI and enable the long term cooling	- Sufficient area for core debris spreading ($0.02m^2/MWth$) - Enough structural strength for steam explosion and DCH load - Sufficient cooling water from IRWST
SDS and IRWST	- Rapid depressurization to prevent high pressure core melt ejection	- Depressurization capacity to 1.7 MPa (250 psig) before reactor vessel breach occurs
Containment	- Retention of radioactive materials under severe accident conditions	- ASME Factored Load Category as the ultimate structural capacity for the severe accidents

3. KNGR DESIGN STATUS FOR SEVERE ACCIDENT MITIGATION SYSTEMS

3.1 Containment and General Arrangement

The containment is ever more important for severe accident mitigation since it is the last barrier against the release of radioactive materials. A preliminary design of the KNGR containment and general arrangement was completed and described in Ref.3 in detail. The KNGR containment is a large dry type and designed considering the load conditions due to severe accidents. The pressure capacity is sufficient such that the containment structural integrity can be maintained below the ASME Factored Load Category during the first 24 hours after core melt.

The KNGR containment is a double containment type as shown in Fig.1. The inner containment is a steel-lined, prestressed concrete cylinder with a hemispherical dome. The internal diameter of the inner containment is 45.7 m(150 ft). The nominal wall thickness is 1.2 m(4 ft) up to dome spring line elevation and the dome thickness is 1.1m(3.5 ft). The maximum containment height is 52.9 m(173.5 ft) above the operating floor. The 6 mm(1/4 in) thick steel liner plate is installed for leak tightness. The inner containment free volume excluding the volume of ICI cavity and drain sumps is 9.1E(4) m^3(3.2E(6) ft^3). The containment free volume is large enough not to exceed 13 v/o of hydrogen produced by 75% of the active fuel clad oxidation without any active countermeasure. The global hydrogen burning based on the adiabatic isochoric complete combustion model was found to result in the maximum containment pressure of 0.8 MPa(117 psia) with this free volume.

The outer containment is for biological shield and made of a reinforced concrete right cylinder with an inner diameter of 52.4 m(172 ft). The outer containment structure has sufficient strength for structural support and missile protection for which a local impact due to tornado-generated missiles is assumed. The KNGR containment and auxiliary building will be built on the common basemat. This provides an advantage for seismic design since it reduces the flexural shear loads in the auxiliary building shear walls and outer containment.

The annulus between the inner and outer containments is 2.1 m(7 ft) wide. The main function of the annulus is the collection of leakage from the inner containment. The leakage is filtered and recirculated back to the inner containment by the Annulus Ventilation System(AVS). The annulus also provides an access for installing, testing, inspecting, and tensioning the tendons. The annulus compartment is considered as a part of the penetration area. Thus, high energy lines in the annulus shall be enveloped by guide tubes or extended sleeves.

Fig.2 shows the general arrangement of the KNGR nuclear island in a plan view. The safety systems are located in the auxiliary building which surrounds the containment and the redundant trains of safety systems are physically separated by quadrant or symmetrical arrangement. As noticed in Fig.2, the SIS pumps are placed in each quadrant and the CSS pumps, EFWS tanks, and On-site Diesel Generators are symmetrically arranged. This arrangement is to prevent the propagation of external events such as fire and flood from one region to another. The containment internal arrangement was designed such that the mixing by natural circulation can be maximized and local accumulation of hydrogen can be prevented. Especially, the annular vent gap between the inner containment wall and operating floor was extended to 0.3 m(1 ft) for natural circulation from lower to upper compartments of the containment.

3.2 Reactor Cavity and Cavity Cooling System

The KNGR reactor cavity houses the reactor vessel and the in-core instrument(ICI) tubes. Additionally, the cavity has a role for the retention and cooling of core debris in case of severe accidents. The current cavity design considers pre-flooding strategy which fills the lower volume of the cavity before the reactor vessel failure occurs. Thus, the design issues of the cavity are:

1. the availability of the cooling water, 2. the cavity space enough to assure core debris spreading and coolability, and 3. the cavity structural strength to withstand the pressure load by steam explosion. The cooling water for the cavity is supplied from IRWST which is an enormous reservoir of cooling water. The pre-flooding strategy would ease the issue of core debris spreading and cooling due to the mixing effects by Fuel-Coolant Interaction. For pre-flooding strategy, it is considered that steam explosion is the most challenging issue. Accordingly, the cavity and reactor vessel support structural strength must consider the steam explosion load.

Fig.3 shows a schematic of the KNGR reactor cavity design along with the indication of vent path. The KNGR cavity has the approximately 84 m^2(906 ft^2) floor area which is about 0.021m^2 (0.23 ft^2)/MWth. To prevent direct containment heating due to the escape of core debris to the upper part of the containment, the cavity configuration is designed to minimize debris entrainment. Since there are seals around the reactor vessel head and ICI table in addition to the corbel and primary shield plugs which restrict the flow through the reactor vessel annulus, the steam and gases produced in the cavity escape mostly through the vent pathway as indicated in Fig.3. The vent pathway is designed to take many turns to knock off the entrained debris from the gas flow.

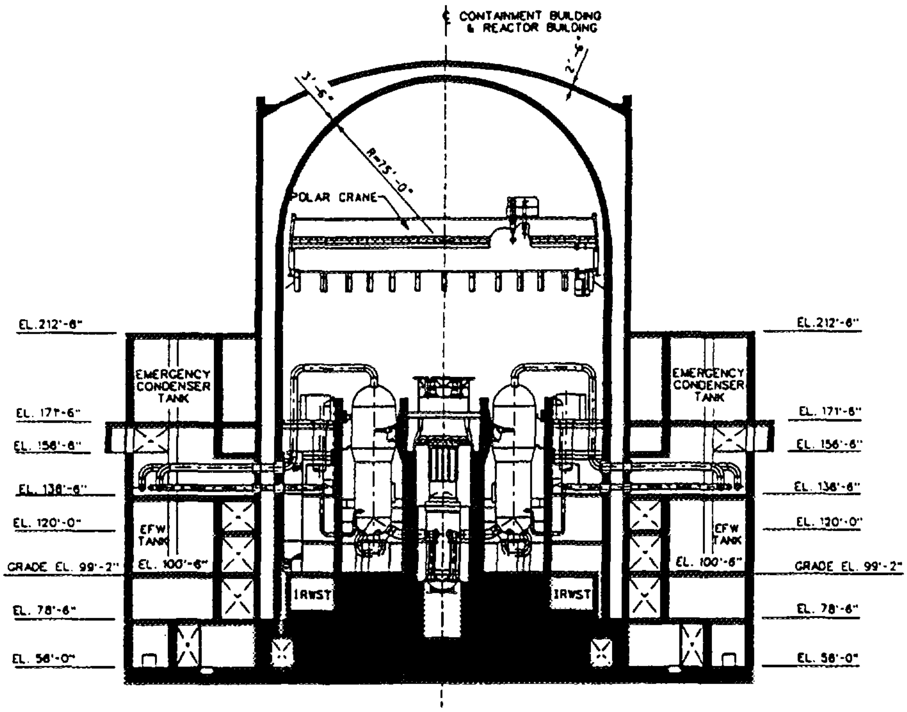

Figure 1 A cross-section of the KNGR containment in the vertical direction

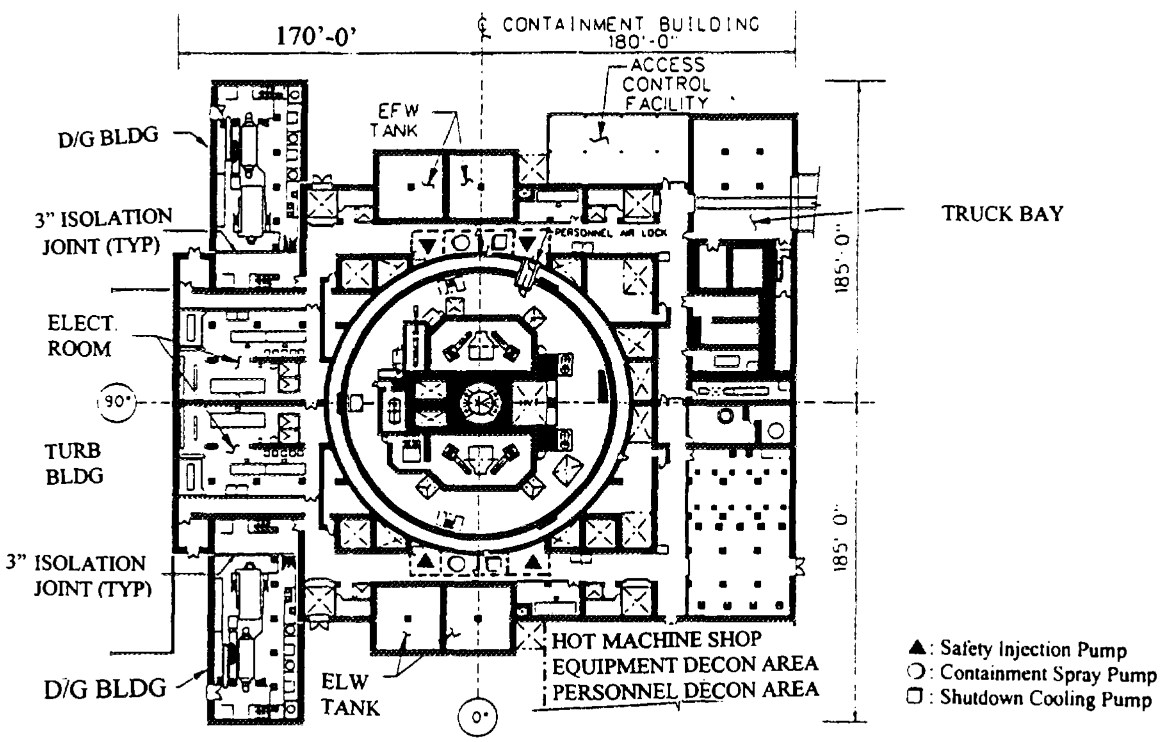

Figure 2 A cross-section of the KNGR containment in the horizontal direction

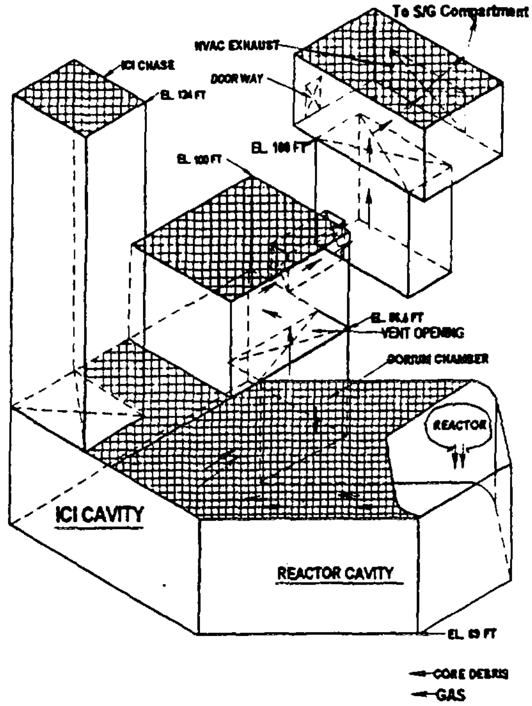

Figure 3 Schematic of the cavity configuration and vent pathway(Not in scale)

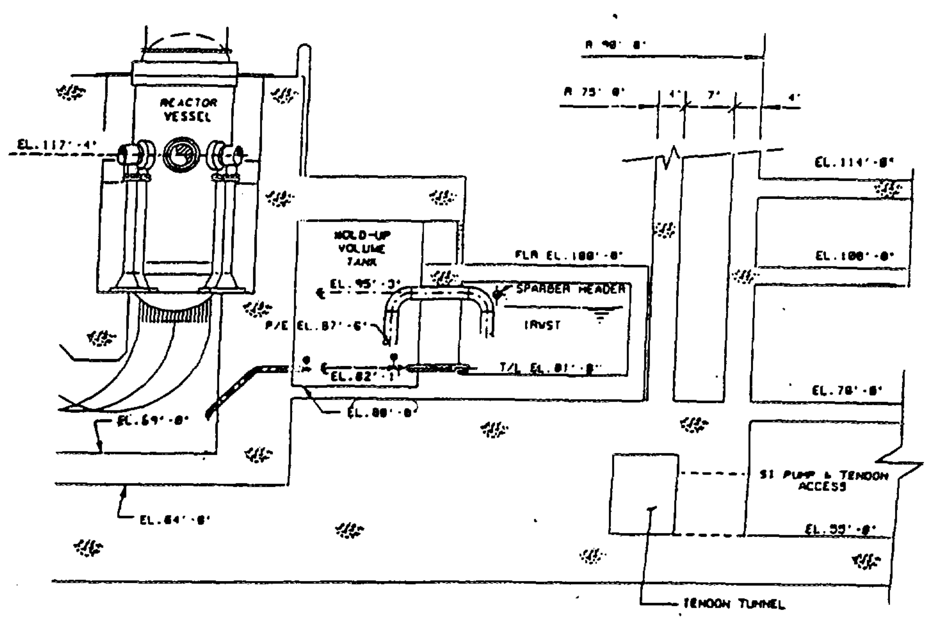

Figure 4 Cavity water supply path

The cavity floor has an approximately 0.9m(3 ft) thickness sacrificial layer above the containment liner plate. The sacrificial layer is for the Molten Core-Concrete Interaction(MCCI) which will occur before a stable cooling of corium is established. The material for this layer needs to be highly resistant to MCCI without producing a large amount of non-condensible gases.

The cavity is associated with the Cavity Flooding System(CFS) to perform its function during severe accidents. Since KNGR takes pre-flooding strategy in principle, the cavity flooding starts by opening motor operated valves(MOV) manually when the core uncovery is detected. The core uncovery is determined by the core exit temperature and reactor vessel level monitors. Additionally, an abrupt change of neutron flux level may be used as an indicator.

The water supply path to the cavity is illustrated in Fig. 4. The water flows first into the Hold-up Volume Tank through the two 35.6 cm(14 in) diameter HVT spillways and then into the reactor cavity through the 25.4 cm(10 in) diameter reactor cavity spillways by gravity. The flow stops when the water level in the cavity equalizes to that in the IRWST. The equilibrium level shall be below the ICI plate under the reactor vessel lower head so that the contact of water with the ICI tube by inadvertent opening of MOVs can be excluded. In case that MOVs fails, the CFS can deliver water through two pipes with the fusible plugs. The fusible plugs are designed to melt due to the heat from the corium accumulated in the dry cavity so that the cavity flooding can start in a passive way.

3.3 In-Containment Refueling Water Storage Tank(IRWST)

The IRWST contains water for refueling operation and more importantly it plays many roles for accident mitigation. The IRWST provides water source for the safety injection and containment spray systems. It becomes a heat sink for the RCS inventory discharged from the pressurizer safety valves or safety depressurization system, and supplies water for cavity flooding. The water inventory shall be sufficient to perform these functions as well as refueling operation.

The IRWST locates below the basement floor slab and between the secondary shield and inner containment walls as shown in Figs. 1 and 5. In Fig. 5, the SDS discharge lines to IRWST and sparger locations are also illustrated. The SDS discharge lines are not so symmetrically arranged due to the restriction of the pressurizer location. However, the sparger lines are symmetrically installed to promote uniform mixing of discharged flow in the IRWST. There are two sparger headers and each header has six spargers. The cross sectional view and dimension of the IRWST is shown in Fig. 6 with the sparger location in the IRWST. The spargers shall be adequately submerged in the water to condense the discharged steam and properly located away from the IRWST wall in order to avoid high impact to the wall during the discharge. The normal water level of the IRWST is 3.7 m(12 ft) from the bottom, and with this level the water inventory is 2.54E(6) L(669,800 gallons). The minimum water level in the IRWST is designed to be no less than 1.75 m(5.75 ft), because the net positive suction head shall be maintained for the SIS and CSS pump operation.

There is approximately 1.2 m(4 ft) of freeboard space above the water surface in the IRWST. The freeboard space is to alleviate pressure in the containment and hydrogen buildup in the IRWST during DBAs and severe accidents as well as normal operation. During refueling operation, the containment low volume purge connections are used to remove hydrogen in the IRWST. For hydrogen control during DBAs, there are two connections to the hydrogen recombiner. Additionally, igniters will be installed in the IRWST for hydrogen control during severe accidents. Since the IRWST could be overpressurized when the RCS inventory is

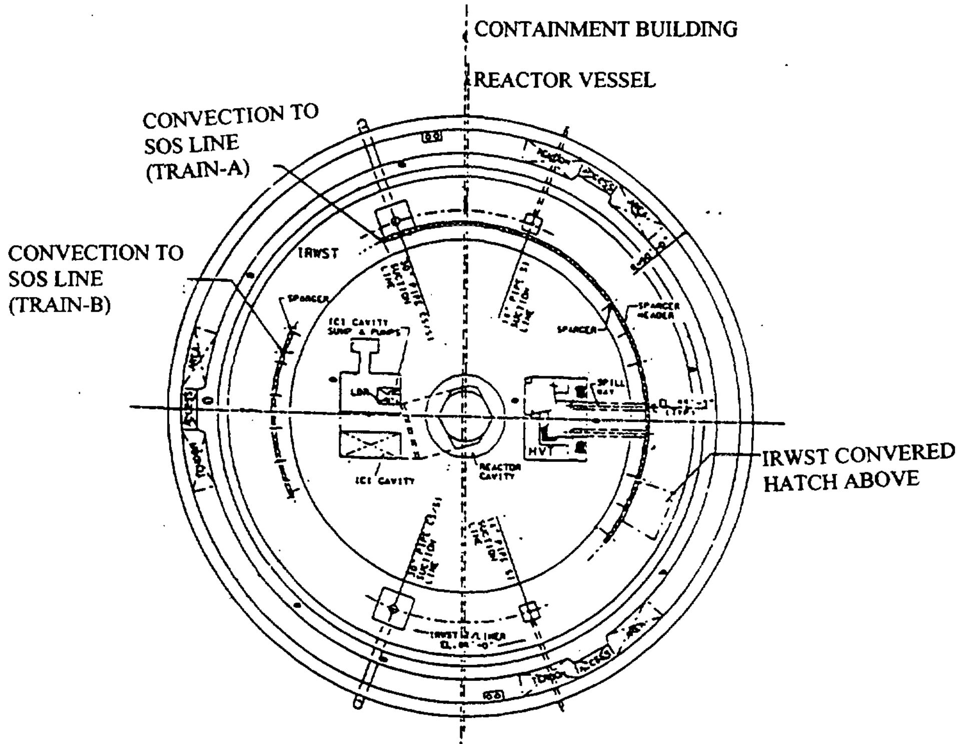

Figure 5 A cross-sectional view of IRWST with a sparger line in the horizontal direction

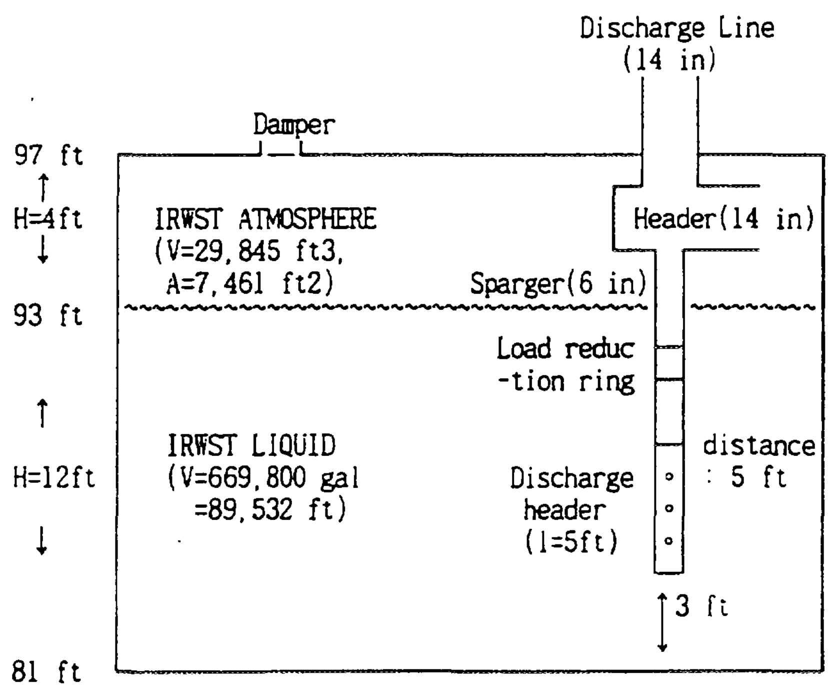

Figure 6 A cross-sectional view of IRWST with a sparger line in the vertical direction

discharged into it, four relief dampers are installed at the IRWST ceiling to relieve steam and gases built in the IRWST. Also, hydrogen accumulated in the IRWST can exhaust through these dampers.

Due to the IRWST, the re-alignment of the SIS and CSS suction line to the containment sump is no more necessary for accident management. The water escaped from the RCS or sprayed by the CSS is collected on the basement floor slab and routed to the holdup volume tank. The water accumulates in the holdup volume tank before it begins to spill back into the IRWST through spillways in the tank wall.

4. R&D PROGRAMS FOR SEVERE ACCIDENT ANALYSIS AND SYSTEM DESIGN

In this section, some of the R&D works associated with the KNGR development for severe accident mitigation will be briefly outlined.

4.1 Conceptual study of an in-core catcher for the reactor pressure vessel protection

This R&D work has interests in the prevention of the reactor vessel breach by cooling the corium inside the reactor vessel. In severe accidents, the core may melt and relocate down to the vessel lower head. In this scenario, direct contact with molten core will heat up and deform the reactor vessel lower head, resulting in the rupture. The structure of the in-core catcher creates an engineered gap which will prevent the molten core from the direct contact with the inner surface of the vessel. Therefore, it is anticipated that the in-core catcher could firstly prevent rapid heating of the reactor vessel lower head and secondly help secure water cooling through the gap and hence prevent the failure of the reactor vessel lower head. The objective of this study is a conceptual design of the in-core catcher which is suitable to create the engineered gap under the core melt conditions.

4.2 Development of analysis method for core debris cooling

This R&D project consists of following subjects: 1. development of a heat transfer model for the core debris cooling in the cavity, and 2. experimental investigations of heat transfer mechanism of the reactor internal gap cooling and reactor vessel external flooding.

For the first subject, an analytical model is being developed to simulate heat transfer mechanism between core debris and cooling water dealing core debris like a porous medium. The experiments for the second subject focus on the critical heat fluxes in the two different situations. One is the critical heat flux attainable for a gap which is stipulated to form between the reactor vessel interior and molten core crust. The other is the critical heat flux on the surface of the reactor vessel in case that the reactor vessel exterior is cooled by flooding the reactor vessel.

4.3 Development of a 3-D mechanistic model for hydrogen mixing and deflagrations.

During severe accidents, a large amount of hydrogen generates by the oxidation of cladding material and Molten Core-Concrete Interaction. Therefore, it is important to control hydrogen concentration below a detonable level unless otherwise hydrogen detonation might occur and result in a containment failure.

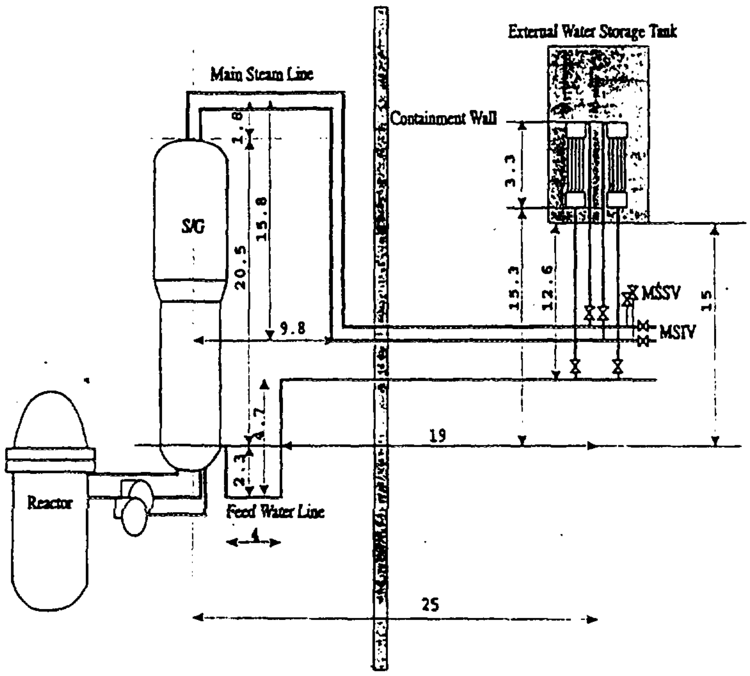

Figure 7 Schematic of passive secondary cooling system(unit in meter)

This R&D project develops a mechanistic model which can simulate the hydrogen mixing and distribution in the containment, and performs experiments to validate the model. The model will be implemented in the MAAP code if successfully validated. Also, appropriate energy levels for hydrogen ignition are experimentally investigated. The hydrogen ignition energy level depends on the igniter types and composition of hydrogen and steam in the air. If energy level is too high, it might cause a detonation. If it is too low, ignition may fail. Therefore, the ignition energy level is important for the hydrogen igniter system design.

4.4 Conceptual Development of Passive Secondary Cooling System(PSCS)

The PSCS consists of a water pool and heat exchanger located outside of the containment. This system is to back up the Emergency Feedwater System(EFWS). When the EFWS fails, the steam from the steam generator bypasses into the heat exchanger of the PSCS and is condensed by the cold water in the water pool. This condensed water is returned by gravity into the steam generator through the main feed water line. A schematic of the PSCS in conjunction with the S/G is shown in Fig. 7.

The scope of the conceptual development includes a system performance analysis using a system simulation code and large scale experiments, and separate small scale experiments focusing on the heat exchanger design. The main functional purpose of PSCS is to cope with total-loss-of-feedwater accidents and steam generator tube rupture events. However, we are examining a possibility to extend its function especially for severe accident mitigation, since it could be available for the water source to cool the containment.

5. Concluding Remarks

The KNGR design is currently in the second phase of which objective is to produce design details sufficient to confirm its safety. According to the current design schedule, the analysis and

Table 3 Preliminary PSA Level 1 results of KNGR and comparison with YGN 3 PSA results.

Initiator	KNGR(a)	YGN 3(b)	Percent Reduction (%) |b-a|/b*100
LOCA	1.35E-06	2.68E-06	49.6
SGTR	2.33E-07	7.05E-07	66.9
ISLOCA	3.01E-09	3.39E-08	91.1
LOFW	4.82E-07	1.25E-06	61.4
Loss of Electric Power including SBO	4.46E-08	2.01E-06	97.8
LSSB	2.09E-09	1.31E-07	98.4
ATWS	5.15E-08	3.87E-07	86.7
Other Transient	3.84E-07	6.23E-07	38.4
Total	2.55E-06	7.82E-06	67.4

system design for severe accidents will be completed by early 1999 when the standard safety analysis report is submitted to the regulatory authority for review. After that, more detailed analysis will be performed as necessary.

As mentioned in the introduction, the system improvements for severe accidents are related with the safety goal. The system improvements for severe accident prevention and mitigation are directly related with the core damage and large radiation release frequency goals respectively. According to the preliminary PSA Level 1 results[4], the CDF of KNGR due to internal events is about 2.55E-6/RY. Table 3 shows a comparison of the contribution of initiating events on the CDF between KNGR and Younggawang 3(YGN 3) which is a current standard design in Korea. As noticed in Table 3, contributions on the CDF from LOOP and LOFW events which were significant in YGN 3 were greatly reduced due to the use of AAC and dedicated EFWS as well as feed-and-bleed cooling capability in KNGR. For the CDF due to LOCA was also decreased remarkably, because the SIS reliability was greatly enhanced. The CDF by other events like SGTR, ISLOCA, LSSB, and ATWS was also significantly reduced due to the design improvements listed in Table 1. As the PSA level 2 analysis progresses, the effectiveness of the mitigation systems will be evaluated and accordingly accident management guideline will be developed.

In parallel with the design works, the R&D projects described in Section 4 will be reviewed for practical application to the design. If it turns out to be desirable and feasible to incorporate such features from both technical and economical point of views, their introduction will be considered in the detailed design phase.

REFERENCES

[1] Y. S Choi, B. S. Kim, and H. D. Kim " The KNGR Design Features and Analysis Methodology for Severe Accidents", Technical Committee Meeting on Identification of Severe Accidents for the Design of Future NPPs, IAEA, Vienna, Austria, October, 1995.
[2] D.W.Jerng, and S.J.Cho, "Research Activities and Design Requirements for the Next Generation Reactor in Korea", International Workshop for Future Reactors, Institute of Applied Energy, Tokyo, July, 1995.
[3] "Preliminary General Arrangements of KNGR" , Korea Electric Power Corporation, November, 1995.
[4] "Preliminary PSA of the KNGR design", Internal Report, Korea Electric Power Research Institute, July, 1996