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Severe Accident Mitigation Features in Korean Advanced NPP

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1. Introduction

The likelihood of a severe accident, which postulates reactor core meltdown beyond the scope of design basis accidents and consequently can lead to releases of large amounts of radionuclides into the environment, is extremely low. However, in view of the postulated severe damage to the reactor core, the social and economic consequences of such an accident can be very significant.

The Korean advanced Nuclear Power Plants (NPPs) are designed for the prevention and mitigation of severe accidents, based on in-depth phenomenological analyses that identify potential design and operational vulnerabilities and address them in a manner that minimizes the risk to the public and to the environment [1]. The design and construction of the severe accident prevention and mitigation features are in compliance with USNRC regulations. These design features comply with USNRC SECY-93-087, "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light Water Reactor (ALWR) Designs."[2] In principle, a series of potential phenomena which can threaten the integrity of the containment needs to be screened, reviewed and assessed, since various individual phenomena can occur under severe accident conditions depending upon the design characteristics of the plant.

This paper introduces what design principle and features of the severe accident mitigation systems employed in Korean advanced NPPs to comply with the requirements, in particular, related to keep the containment integrity during the severe accident.

2. Severe Accident Mitigation

If a severe accident cannot be prevented by the preventive design features, other following features mitigate the effects of a severe accident. Of particular importance are the containment design and the ability of mitigating equipment to survive severe accident conditions.

2.1 Containment Design

The containment is a pre-stressed concrete structure composed of a right circular cylinder with a hemispherical dome and is founded on safety-related common basemat. The containment encloses the reactor vessel, steam generators, reactor coolant loops, and portions of the auxiliary and engineered safety features systems. The containment provides reasonable assurance that leakage of radioactive material to the environment does not exceed the acceptable dose limit as defined in 10 CFR 50.34[3] even if a LOCA occurred.

The containment reinforcing consists primarily of hoop and meridional steel. Prestressing tendons are also arranged in hoop and meridional directions. The roof of the containment is a hemispherical dome. The buttresses are extended up to 48 degrees into the dome to provide anchorage for the dome hoop tendons. The 6.0 mm (0.25 in) in thickness steel liner plate is attached to inside of the dome and the cylindrical wall to provide leak-tightness.

The containment provides a large free volume with its internal structures arranged in a manner to (1) protect the inner containment from missile threats, (2) promote mixing throughout the containment atmosphere, and (3) accommodate condensable and non-condensable gas releases from design basis accident and severe accidents. The internal structures, which are made of reinforced concrete, enclose the reactor vessel and other primary system components. The internal structures provide radiation shielding for the containment interior and missile protection for the reactor vessel and containment shell.

In severe accident scenarios, the containment vessel is the last fission product barrier protecting the public from radiation release. Therefore, it is of paramount importance to provide a strong containment design to meet severe accident internal pressurization challenges.

The containment is designed in accordance with ASME Section III, Division 2 [4]. The containment is analyzed to determine all membrane, bending, and shear stresses resulting from the specified static and dynamic design loads given from the severe accident.

As stated in SECY 93-087, the conditional containment failure probability (CCFP) must be less than 0.1 or meet a deterministic containment performance goal that provides comparable protection so the following general criterion is met: The containment maintains its role as a reliable, leak-tight barrier by providing reasonable assurance that the containment factored load category (FLC) requirements are met for a period of approximately 24 hours following the onset of core damage, and following this 24-hour period, the containment continues to provide a barrier against the uncontrolled release of fission products. The Korean advanced NPP's containment meets the FLC requirement of ASME Section III, Division 2, Subarticle CC-3720.

2.2 Cavity Flooding System

The cavity flooding system (CFS) provides a means of flooding the reactor cavity during a severe accident to cool the core debris in the reactor cavity and to scrub fission product releases. The water delivery from the in-containment refueling water storage tank (IRWST) to the reactor cavity is accomplished by means of active components. The CFS is designed to provide an inexhaustible continuous supply of water to quench the core debris.

The components of the CFS include the IRWST, holdup volume tank (HVT), reactor cavity, connecting piping, valves, and associated power supplies as shown in Fig. 1. The CFS takes water from the IRWST and directs it to the reactor cavity. The water flows first into the HVT by way of the two HVT spillways and then into the reactor cavity by way of two reactor cavity spillways.

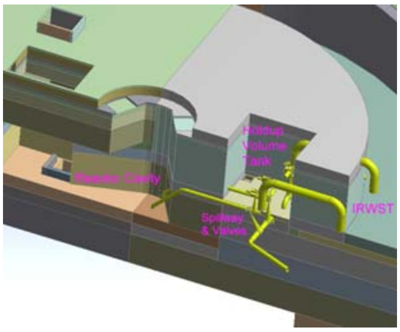

Figure 1. Configuration of the CFS

Once actuated, movement of the water from the IRWST to the cavity occurs passively due to the natural hydraulic driving heads of the system. Flooding ceases when water levels in the IRWST, HVT, and reactor cavity equalize at same elevation.

Flooding of the reactor cavity serves the following purposes in the strategy to mitigate the consequences of a severe accident:

- Minimize or eliminate corium-concrete attack
- Minimize the generation of combustible gases (hydrogen and carbon monoxide) and noncondensable gases
- Scrub fission products released due to corium-concrete interaction
- Remove heat from the core debris

It is currently believed that an acceptable stable state can be achieved ex-vessel as long as the CFS has been actuated prior to vessel breach (VB). Although providing water to the reactor cavity may not immediately terminate the concrete erosion, having a water-filled reactor cavity prior to VB can reduce and ultimately terminates the erosion, while simultaneously providing scrubbing of fission products released in the molten core-concrete interaction process.

2.3 Hydrogen Mitigation System

During a degraded core accident, hydrogen is generated at a greater rate than that of the design basis LOCA. The containment hydrogen control system is designed to accommodate the hydrogen generation from a metal-water reaction of 100 percent of the active fuel cladding and limit the average hydrogen concentration in containment to 10 percent consistent with 10 CFR 50.34(f) and 10 CFR 50.44 [5] for a degraded core accident. These limits are imposed to preclude detonations in containment that might jeopardize containment integrity or damage essential equipment.

The containment hydrogen control system (HG) consists of a system of passive autocatalytic recombiners (PARs) complemented by glow plug igniters installed within the containment, as shown in Fig. 2. The PARs are capable of controlling hydrogen in all accident sequences with moderate hydrogen release rates, and are located throughout the containment. The igniters supplement PARs for accidents in which rapid hydrogen release rates are expected, and are placed near anticipated source locations to promote the combustion of hydrogen in a controlled manner.

(a) PAR (b) Igniter

Figure 2. Typical Shape of PAR and Igniter

The PARs are self-actuated and require no electric power. Therefore, no operator action is required. The igniters, which supplement PARs, are intended to control hydrogen concentration within containment once the operator confirms that an extended core uncovery is in progress. Therefore, the HG system prevents hydrogen from accumulating to the point where a destructive hydrogen detonation might occur within the containment.

2.4 Rapid Depressurization Function

The rapid depressurization (RD) function is a multi-purpose dedicated system designed to serve important roles in severe accident prevention and mitigation.

The pilot operated safety and relief valves (POSRVs) or emergency reactor depressurization valves (ERDVs) are designed to allow for depressurization of the reactor coolant system (RCS) below the cutoff pressure for high pressure melt ejection (HPME) to occur. The RD function is initiated by operator action as part of the severe accident management strategy.

The RD function design requirement related to severe accident mitigation is the capability to depressurize the RCS from approximately 175.8 kg/cm^2 (2,500 psia) to approximately 17.6 kg/cm^2 (250 psia) prior to reactor vessel breach. The target pressure of the RD function is determined on the basis of DOE/ID-10271 [6].

The RD function also serves an important role in severe accident mitigation. In the event a high pressure meltdown scenario develops and the feed portion of feed and bleed cannot be established due to unavailability of the SI pumps, the RD function can be used to depressurize the RCS and prevent HPME following a VB.

2.5 Reactor Cavity Design

The reactor cavity is configured to promote retention of, and heat removal from, the postulated core debris during a severe accident, thus serving several roles in accident mitigation. The large cavity floor area allows for spreading of the core debris, enhancing its coolability within the reactor cavity region.

The large free volume of the reactor cavity is a benefit when cavity pressurization issues are considered. Large, vented volumes are not prone to significant pressurization resulting from vessel breach or during corium quench processes.

The reactor cavity is designed to maximize the unobstructed floor area available for the spreading of core debris. Uniform distribution of the corium debris within the reactor cavity results in a relatively shallow debris bed and consequently, effective debris cooling is expected in the reactor cavity with the supporting of CFS. The containment liner plate in reactor cavity area is embedded 0.91 m (3 ft.) below from the cavity floor at the minimum.

Corium retention in the core debris chamber virtually eliminates the potential for significant direct containment heating (DCH) induced containment loadings.

2.6 Emergency Containment Spray Backup System

For a provision against a beyond-design-basis accident where either two shutdown cooling pumps and two containment spray pumps or the IRWST is unavailable, the emergency containment spray backup system (ECSBS) is provided as an alternative to the containment spray system (CSS). The ECSBS is designed to protect the containment integrity against overpressure and prevent the uncontrollable release of radioactive materials into the environment. The emergency containment spray flow path is from external water sources (the raw water tank of seismic category 1), through the mobile pump truck, to the ECSBS line emergency connection located at ground level near the auxiliary building. The designed flow rate of ECSBS provides sufficient heat removal to prevent containment pressure from exceeding the severe accident load used for FLC consequently secures the containment integrity even in the CSS unavailable situation.

3. Conclusions

The preventive and mitigative design features implemented in the design of Korean advanced NPPs include the HG, CFS, ECSBS, and structural designs of the containment and reactor cavity for severe accident loads to meet the requirement for the containment integrity under the severe accident.

The containment has features of large free volume and robust strength against overpressurization due to the hydrogen deflagration and/or steam production. The structural design of the reactor cavity is intended to control the ex-vessel accident progression. In particular, the reactor cavity was designed to meet the requirements for prevention and mitigation of phenomena such as HPME/ DCH, steam explosion and molten core concrete interaction. The main design characteristics include a core debris chamber inside the reactor cavity, a convoluted gas vent path, large floor area, and the CFS.

The Korean advanced NPPs are designed for safety functionality even during a very unlikely severe accident scenario. The design includes accident prevention and mitigation features that are based on the analyses of severe accidents. Sufficient robustness is provided in the design so that ample time exists for operator action to mitigate the consequences of a severe accident and minimize the radiological releases into the environment.

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