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Considerations for Developing Regulatory Guide for the Accident Analyses Employing Advanced Safety Features

Suk K. Sim [a*], Min Jeong Hwang [a], Young Seok Bang [b], Kap Kim [b], Sweng Woong Woo [b], Taesuk Hwang [b]
[a]*Environment & Energy Technology, Inc., 99 Gajeong-ro, Yuseng-gu, Daejeon, 305-804, Korea*
[b]*Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon, 305-338, Korea*
[*]*Corresponding author: sksim@en2t.com*

1. Introduction

Ever since the Korean Nuclear Industry imported nuclear power plants from abroad, evolutionary design improvements have been undertaken for the self-reliance of the nuclear power plant design and operational technology as well as for the enhancement of the nuclear safety and economics. Evolutionary development for the Nuclear Steam Supply System (NSSS) of the OPR1000 has included such advanced safety features as Direct Vessel Injection(DVI), Fluidic Device(FD), and POSRV for the APR1400 and Passive Auxiliary Feedwater System(PAFS), FD+ and ECC Bypass Barrel Duct(ECBD) for the APR+[1]. For the regulatory safety review of the new design features, it is important to develop a regulatory guide considering the design and operating characteristics of the new design features. Beneficial as well as adverse effects on the safety should be identified and verified.

Korea Institute of Nuclear Safety(KINS) has been evaluating the effects of these advanced safety features on the safety since 2012. As a result, KINS has been developing regulatory guide for the accident analyses employing the advanced safety features through the long-term nuclear safety R&D program.

Important factors and regulatory issues for the safety analyses employing the advanced safety features are discussed and considerations for developing regulatory guide are presented herein.

2. Regulatory Guide Development Strategy for the Advanced Safety Features

In principle, the safety evaluation of the advanced safety features should be performed based on the experimental data and best estimate safety analysis methodology. Above all, current regulatory evaluation practices of the safety analyses such as SRP and regulatory guides should be reviewed and then the new design features which are not considered in current regulatory safety review should be identified. System of regulatory guide is then determined and new regulatory guide is developed based on the premise that the effects on the safety of the advanced safety features are included in the safety analyses. After the evaluation methods and acceptance criteria are reviewed, the adequacy of new regulatory evaluation methods for the advanced safety features should be validated through the safety analyses or safety evaluation, if necessary. Developed regulatory guide is then implemented in the SRP after discussions among the experts.

3. Regulatory Issues for the Advanced Design Features of the APR+

APR+[2] has been developed from APR1400 through uprating the power and improving the safety systems. Total power was increased to 4,290 MWt and thus the NSSS design has been upgraded accordingly. Due to safety concerns of the Station Black-Out(SBO) after the Fukushima NPP accident in 2011, passive AFS has been adopted as new design features for ultimate heat sink instead of the active AFS of APR1400. Four train Safety Injection System (SIS) has been implemented in the new design with four Direct Vessel Injection(DVI) nozzles. ECC Bypass Barrel Duct(ECBD) has been adopted to reduce the ECC bypass to the break. Currently, APR+ has received standard design approval for the APR+ standard design[2] from the Korea Nuclear Safety and Security Commission (NSC). Advanced safety features as well as related safety issues are identified and the considerations in developing regulatory guide are discussed in this section.

3.1 SIT with Fluidic Device

APR+ design eliminated LPSI (Low pressure Safety Injection) pumps in the ECCS and instead relies on the four train HPSI (High Pressure Injection) pumps and four passive SITs equipped with FD+. SIT discharge flows are decreased during the low pressure blowdown phase of the Loss of Coolant Accident(LOCA) and thus, extend the blowdown time. During the full scale VAPOR SIT tests[2], it was found that the N_2 gas was entrained in the SIT discharge flow well before the SIT tank is fully drained as shown in Fig. 1. After the gas entrainment, the SIT discharge flow decreases and becomes unstable and thus may cause the instrument readings unreliable. The same phenomenon of gas entrainment is expected during the in-plant startup.

Regulatory evaluation should review the initiation time of the gas entrainment as well as the SIT startup test guidelines and acceptance criteria as specified in the plant startup test requirements including the measurement uncertainties. LOCA analysis should address the cause and effect of the gas entrainment on the accident behavior using best estimate plus uncertainty analysis method including measurement uncertainties. LOCA analyses should be reviewed in this respect and confirm the acceptance criteria during the regulatory evaluation.

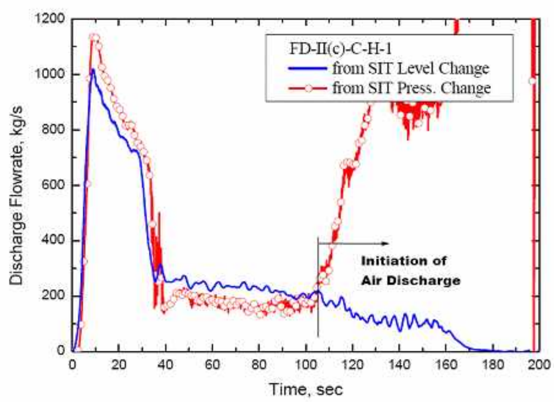

Fig. 1. VAPOR Discharge Flow and Air Discharge Time[2]

3.2 ECCS with ECBD

APR+ has adopted ECBD as a new design feature in the four train SIT. Each ECBD is welded to the core barrel at the opposite side of the downcomer from each DVI nozzle to reduce the ECC bypass to the break during the LOCA as shown in Fig. 2.

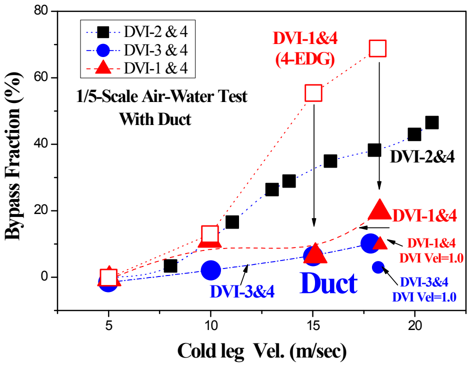

Fig. 2. ECC Bypass Fraction[2]

Each ECBD is designed in the form of 26" wide, 155" long and 0.2" thick duct attached to the core barrel. Since the ECBD channel depth, 2.2"(56mm), is almost one quarter of the downcomer gap, this ECBD is thus expected to affect the steady state downcomer and possibly core inlet flow distribution compared to the OPR1000 and APR1400 designs without ECBD. Also, during reflood phase of the LOCA, the SI jet flow from the DVI nozzle impinges on the ECBD and breaks up into droplets. Good fraction of these breakup droplets probably bypasses to the break causing multi-dimensional and multi-field flow distribution in the downcomer. Since the depth of the ECBD flow channel is only 2.2"(56mm), good portion of the impinging jet is expected to flow outside of the ECBD due to high impinging jet velocity and interferences caused by the rising steam flow inside the ECBD. ECBD also influences the downcomer boiling from the barrel wall heat transfer to the SI jets. Due to the restricted flow area of the ECBD and high temperature of the barrel wall, boiling of the injected SI water in the ECBD is expected to be increased compared to the downcomer without ECBD. However, this rising steam through the ECBD may block the incoming SI jet water by the CCFL(Counter-Current Flow Limit). This multi-dimensional flow distribution in the ECBD as well as in the downcomer should be further investigated and the models in the safety analysis system code should be validated through the proto-type experiments. .

Following safety issues of the SIS with new ECBD design shall be reviewed during the regulatory evaluation of the APR+,

- Effect of ECBD on the steady state flow distribution in the downcomer and core inlet
- DVI jet impingement on the ECBD, jet breakup and ECC bypass
- SI jet water boiling in the ECBD and downcomer , and its effect on the downcomer flow distribution
- Best estimate plus uncertainty LBLOCA analysis methodology for the ECC bypass
- Effect of the ECBD on the Chapter 15 non-LOCA safety analyses.

3.3 PAFS and Passive Systems

Passive system designs have been evolved since the TMI-2 accident in 1979 to enhance the safety as well as the design simplification of the NPPs. As the passive safety systems introduced in the DC(Design Certification) applications, USNRC issued SECY-93-087[3] for the regulatory issues of the passive designs such as the availability of the active non-safety systems in passive designs, single failure of passive components and safe shutdown requirements. USNRC issued SECY-94-084[4] and approved AP1000 safe shutdown requirements during the Levy NP Unit-1/2 licensing review for the PRHRS (Passive Heat Residual Heat Removal System). Accordingly, USNRC revised SRP 15.2.1-15.2.5 Rev03(2007) for the non-safety systems during transients and accidents. Similar issue has been raised by the KINNS for the check valve failures of the MSSV during PSAR regulatory review for the SKN Unit 5/6[5].

APR+ PAFS replaces AFW of the APR1400 to passively remove the core residual heat during the SBO accident. The PAFS consists of horizontal u-tube heat exchanger, Passive Condensation Cooling Water Tank (PCCT), check valves and isolation valves powered by the batteries, piping, instrumentation and control systems. The stem supply line and the condensate return line are connected to the upstream of the MSIV and downstream of the MFIV, respectively as shown in Figure 3.

KHNP and KAERI modified the ATLAS integral effect test facility for the PAFS and performed various tests to evaluate the heat removal capability and the performance of the PAFS during the accidents. Key accidents including MSLB, FLB and SBO were analyzed for the PAFS using best estimate system code. The heat transfer models used in the safety analysis system code for the horizontal u-tube heat exchanger in the PCCT should be validated including the bundle effects.

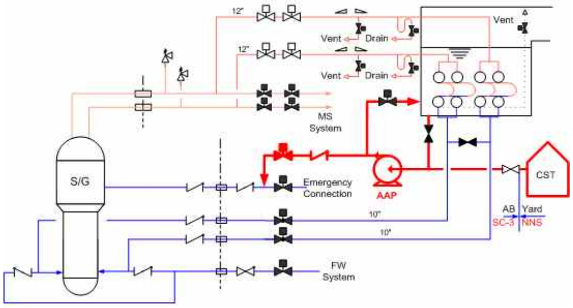

Fig. 3. PAFS Design Configuration of APR+[2]

Following safety issues shall be reviewed during the regulatory evaluation of the PAFS,

- Non-safety system failures of the PAFS
- Single failure of the FAFS and thus the heat removal capacity
- Safe shutdown requirements for non-LOCA events using PAFS
- Safe shutdown performance during LOCA using PAFS
- Long term cooling requirements using PAFS
- ITTAC requirements of the PAFS
- Chapter 15 design basis accident analyses extended for 72 hours to achieve safe and stable conditions using PAFS

4. Conclusions

The safety and regulatory issues were discussed for the advanced safety features of the APR+ standard design and regulatory guide development strategy for new safety design features was proposed.

The N_2 gas entrainment at the low discharge flow conditions of the SIT with FD+ should be further investigated for its cause and effects on the SI discharge flow. The startup test requirements should address this gas entrainment and its acceptance criteria should be validated during the startup tests including measurement uncertainties. Acceptance criteria should be confirmed during the regulatory review for the medium and large break LOCA safety analyses.

The regulatory safety evaluation should address the following safety issues related to the new safety design features of the APR+,

1. The effect of N_2 gas entrainment on the SI discharge flow at low flow conditions during SIT/FD discharge
2. The effect of ECBD on the normal plant operation and non-LOCA safety analyses as well as on the ECC bypass during LOCA.
3. PAFS and its non-safety components should be reviewed for their performance and the non-safety system failures should be considered in the safety analyses. Safe shutdown and long term cooling requirements using PAFS should be developed as regulatory guides and its acceptance criteria should be confirmed by the startup tests as well as the safety analyses.

Regulatory guide as well as the acceptance criteria for the APR+ advanced safety features should be developed for the licensing review of the APR+ and implemented in the KINS Safety Review Plan.

REFERENCES

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[5] SKN Units 5 and 6 PSAR Regulatory Review, PSAR-15.2.3-1-K4, KINS, 2015.