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Regulatory Considerations for the Long Term Cooling Safe Shutdown Requirements of the Passive Residual Heat Removal Systems in Advanced Reactors

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1. Introduction

Ever since the TMI-2 accident in 1979, passive safety systems are introduced to the Advanced Light Water Reactor(ALWR) designs to enhance the safety of the Nuclear Power Plant(NPP) using various inherent passive safety systems. During the development of the AP600 and SBWR in the U.S.A., EPRI proposed safe shutdown requirements for the passive Residual Heat Removal System(RHRS) compared to the cold shutdown required by General Design Criteria(GDC) - 34 for the active RHRS so that it can remove residual heat from the core without exceeding Specified Acceptable Fuel Design Limits(SAFDLs), i.e., no fuel failures[1]. EPRI's contention is based on the belief that it is not necessary to achieve cold shutdown due to inherently long-term reliability of the passive RHRS. EPRI also defined safe shutdown as 215.6 ^{o}C. USNRC approved safe shutdown at 215.6 ^{o}C for a safe and long term cooling state for the redundant passive RHRSs by SECY-94-084[2]. USNRC issued COLA(Combined Construction and Operating License) for the Levy County NP Unit-1/2 for the AP1000 passive RHRSs in 2014[3]. Korea Hydro and Nuclear Power(KHNP) is developing APR+[4] and adopted Passive Auxiliary Feedwater System(PAFS) as a new passive RHRS design.

Korea Institute of Nuclear Safety(KINS) has been developing regulatory guides for the advanced safety design features of the advanced ALWRs which has plan to construct in near future in Korea[5].

Safety and regulatory issues as well as the safe shut down requirements of the passive RHRS are discussed[6,7] and considerations in developing regulatory guides for the passive RHRS are presented herein.

2. Long Term Cooling Safe Shutdown Evaluation of the APR+ PAFS

Preliminary benchmark performance evaluation of the APR+ PAFS Long Term Cooling(LTC) safe shutdown requirements was performed using MARS-KS code. Design basis event was selected for the PAFS LTC safe shutdown performance evaluation. PAFS LTC safe shutdown performance was evaluated against the USNRC safe shutdown requirements used as COLA for the Levy NP Unit-1/2[3] and regulatory considerations were identified.

2.1 PAFS Design Features

APR+ PAFS replaces Auxiliary Feedwater System(AFS) of the APR1400 to passively remove the core residual heat. 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 steam-supply and condensate return lines are connected to the upstream of the MSIV and downstream of the MFIV, respectively. Each train of PAFSs is actuated by each Steam Generator(SG) low Wide Range(WR) level signal.

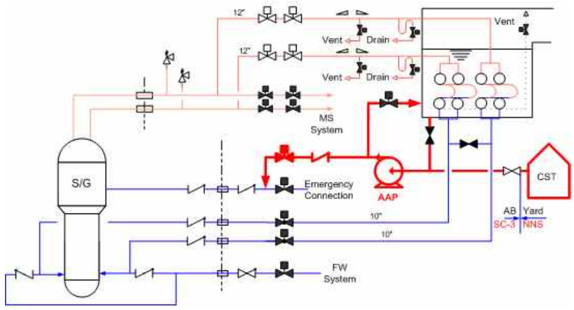

Fig. 1. APR+ PAFS Design Configuration[5]

2.2 PAFS Long Term Cooling Safe Shutdown Performance Evaluation

MARS-KS best estimate regulatory safety evaluation code[8] was used for the APR+ PAFS LTC safe shutdown performance evaluation analysis.

2.2.1 Design Basis and Acceptance Criteria

Loss Of Offsite Power(LOOP) was determined as the design basis event for the PAFS LTC safe shutdown performance analysis. Since there is no nuclear plant operating nor under construction with passive RHRS in Korea, currently, there is no regulatory guides for the passive RHRS. Thus, the same LTC safe shutdown requirements were used for the PAFS LTC safe shutdown requirements as the USNRC safe shutdown requirements used for the Levy County NP Unit-1/2 COLA licensing[3]. The acceptance criteria requires that the core average temperature reach 215.6 °C within 36 hours after the accident initiation and remain below 215.6 °C for 72 hours.

2.2.2 MARS-KS Nodalization and Initial & Boundary Conditions

Fig. 2 shows APR+ MARS-KS nodalization including two trains of the PAFS. PAFS PCCT and corresponding piping and U-tube heat exchangers are also modeled as shown in Fig. 2

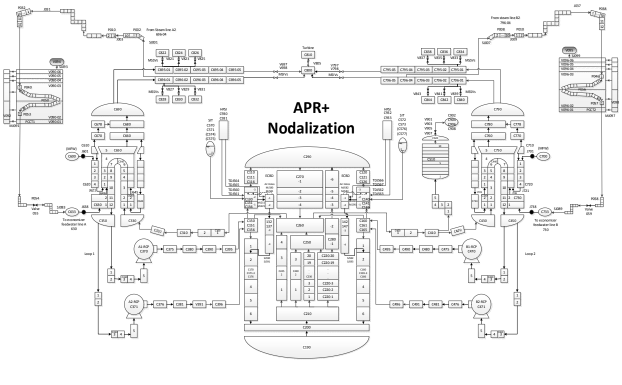

Fig. 2. APR+ MARS-KS Nodalization with 2 PAFS Trains

Full power condition was assumed as initial condition and LOOP was initiated at full power condition as shown in Table 1. APR+ PAFS design data[5] were used for the boundary conditions.

Table 1 : Boundary and Initial Conditions[4, 5]

Design Parameter	Design Data	MARS-KS
Initial core power	4290 MWt	4290 MWt
Initial core inlet temperature	559.3 K – 572.6 K (286.1 °C - 299.4 °C)	561.8 K (288.6 °C)
Initial core outlet temperature	-	599.25 K (326.1 °C)
Initial pressurizer pressure	6.03 MPa – 15 MPa	16 MPa
Initial steam generator dome pressure	-	7.03 MPa
Initial steam generator level	-	93.0 m
PCCT water average temperature	-	321.0 K (47.9 °C)
PCCT water level	-	9.32 m

2.2.3 Evaluation of the APR+ PAFS LTC Safe Shutdown Performance

Preliminary APR+ PAFS LTC safe shutdown performance analysis was performed using MARS-KS code. LOOP was initiated at full power as an initiating event. Single failure assumption was applied for the PAFS performance analysis due to non-safety component failures of the PAFS. Thus, two PAFS sensitivity cases were analyzed as follows,

- Case 1 : Two trains of PAFS actuated
- Case 2 : One train of PAFS B actuated (Single Failure)

Table 2 shows the sequence of the event for both cases.

Table 2. Sequence of Event of LOOP Accident

Events	MARS-KS Case 1	MARS-KS Case 2	Setpoint or Value
	Time (sec)		
LOOP	0.0	0.0	-
RCP Coastdown, MFIV close	0.0	0.0	-
Rx Trip Setpoint reached	1.2	1.2	RCP low flow (80 % of nominal RCP flow)
Rx Trip Signal	1.2	1.2	
Rx Trip	1.4	1.4	Rx Trip Signal +0.2 s
Turbine Trip	1.4	1.4	Rx Trip Signal +0.2 s
MSIV close	1.4	1.4	Rx Trip Signal +0.2 s
SG B 28.4% WRL reached	1172.0	1172.0	-
SG A 28.4% WRL reached	1175.0	-	-
PAFS start (SG B)	1217	1,217	SG B level 5 % WRL + 45.0 s
PAFS start (SG A)	1220	-	SG A level 5 % WRL + 45.0 s
Safety Shutdown Condition reached	9,585	-	215 °C, 6.9 Mpa
PAFS Hx uncovered	PCCT A - 103,953 PCCT B - 105,386	PCCT B - 44,547	2.1 m

For the Case 1 of two PAFS actuation, primary pressure and core temperature decrease gradually due to core heat removal by natural circulation of both PAFS. However, for Case 2 of one PAFS actuation, primary pressure and core temperature rapidly increase at about 44,000 sec due to excessive core heat removal by one PAFS, as shown in Figs. 3 and 4, respectively. With two trains of PAFS actuation, core temperature reaches safe shutdown condition of 488.6 K at 20,000 sec(5.5 hours), thus satisfies the LTC safe shutdown requirements.

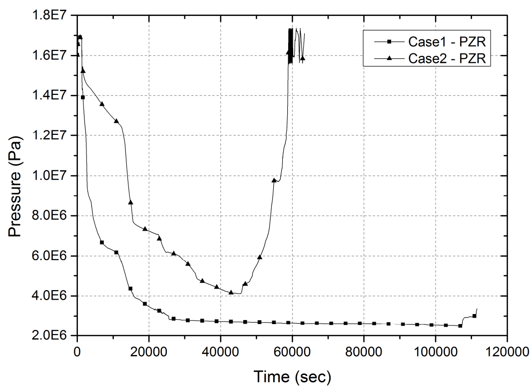

Fig. 3. Primary Pressure

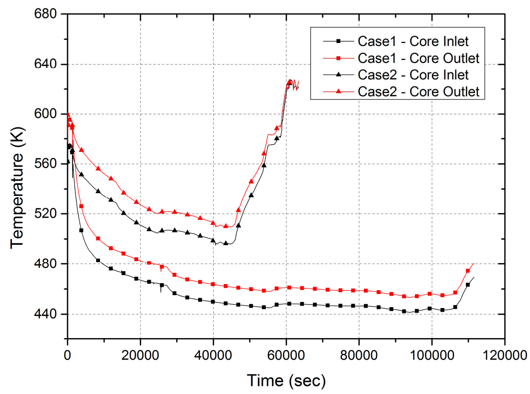

Fig. 4. Core Inlet and Outlet Temperatures

Fig. 5 shows the PAFS flow rates. For the Case 1, PAFS natural circulation flow decreases gradually as the core cools down, however, for the Case 2, higher PAFS flow of the actuating loop gradually decreases and then rapidly decreases as the core temperature increases. This is due to excessive heat removal by one PAFS. Fig. 6 shows the PCCT water level. As expected, for the Case 1 of two trains of PAFS actuation, PCCT water level deceases gradually, while for the Case 2 of one PAFS actuation, PCCT level maintained constant for the PCCT of failed PAFS. However, PCCT water level of the actuating PAFS decreases rapidly due to excessive heat removal by one train of PAFS.

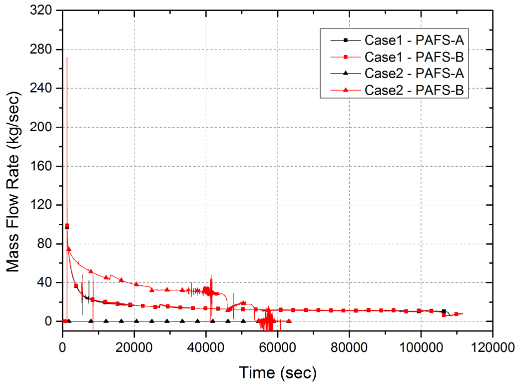

Fig. 5. PAFS Flow

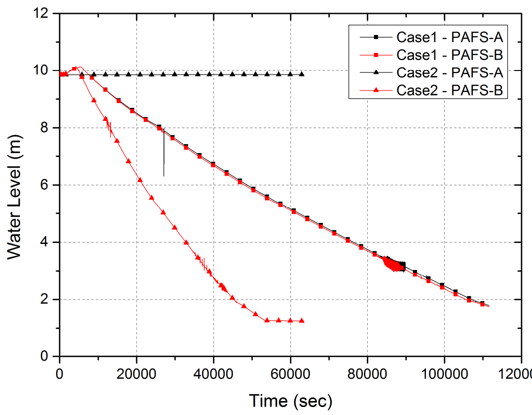

Fig. 6. PAFS PCCT Water Level

APR+ PAFS design should require one PAFS remove core residual heat considering single failure assumption. Based on the present calculation, detailed APR+ PAFS LTC safe shutdown performance analysis is required by the utility.

2.2.4 Regulatory Considerations of the APR+ PAFS Safe Shutdown Performance

Currently, active AFS is a sole safety core residual heat removal system and no operating reactors nor reactors under construction in Korea equipped with passive RHRS. Since the advanced reactors such as APR+ and SMART under development in Korea have adopted passive RHRS, regulatory guides for the safe stable shutdown condition using passive RHRS are needed. Following regulatory issues shall be addressed in developing regulatory guides and during regulatory evaluation of the LTC safe shutdown design and safety analysis of the passive PRHRS such as APR+ PAFS and SMART PRHRS,

- LTC safe shutdown definition and requirements
- Regulatory treatment of non-safety and active non-safety system failures
- Single Failure in passive RHRS
- Probabilistic Reliability Analysis including events initiated from the safe shutdown condition
- LTC safe shutdown performance analysis using passive RHRS
- Availability of shutdown cooling system

3. Conclusions

Recently, passive RHRSs have been introduced as new safety design features for the advanced reactors under development in Korea. These passive RHRSs have potential advantages over existing active RHRS, however, their functions are limited due to inherent ability of passive heat removal processes. It is high time to evaluate the performance of the passive PRHRs and develop regulatory guides for the safety as well as the performance analyses of the passive RHRS.

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