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The sensitivity analysis without credit to operator action for 30 minutes in the APR1000 PSA

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1. Introduction

The Probabilistic Safety Assessment (PSA) for the standard design of the APR1000 is performed as required in the EUR Rev.E Chapter 2.17. The purpose of this design phase PSA is to demonstrate that the APR1000 design meets the probabilistic target of Core Damage Frequency (CDF) and Large Release Frequency (LRF) set forth in the EUR by performing Level 1 and Level 2 PSA for all operating modes.

APR1000 has various advanced safety features which are very effective in the safety point of view.

Therefore, this paper discusses the design effectiveness by performing the sensitivity analyses without credit to operator action for 30minutes in the design phase Level 1 and 2 PSA. The scope of sensitivity analysis is the internal hazards during all operating modes including Spent Fuel Pool Risk. External hazards including seismic delineated in EUR 2.17 is qualitatively addressed or screened out according to EUR 2.17.2.5 in the design phase PSA of the APR1000.

2. Methodology of APR1000 Level 1 and 2 PSA

This section provides an overall Level 1 and 2 PSA methodology that complies with EUR 2.1.4.3 in support of the design phase PSA. The PSA is used to ensure that the Unit satisfies the following probabilistic requirements under all operational modes including shutdown states:

EUR requirements delineate as below;

- 2.1.3.5A.A: The cumulative Core Damage frequency (CDF) shall be lower than 10^{-5} per reactor year.
- 2.1.3.5A.C: Sequences potentially involving the early or delayed failure of the Primary Containment leading to Large Releases or Early Release shall have a cumulative frequency well below the target of 10^{-6} per reactor year.
- 2.17.3.5B.C: PSA shall at least include that probabilistic goals should be achieved also without credit to operator action for 30 minutes after initiating event occurs.

The design phase Level 1 PSA for internal events at power mode is basically done based on the technical requirements of ASME/ANS RA-Sa-2009 as endorsed by U.S. NRC RG 1.200. The Level 1 internal events PSA at power mode is modeled using conventional small event tree and large (or linking) fault tree approach in terms of a set of initiating events, event sequences composed of functions or system success or failure, and logic models that describe combinations of basic events that define the possible success and failure states.

The objective of the Level 2 PSA is to ascertain the likelihood, magnitude, and timing of radiological releases to the environment following a severe accident. The level 2 analysis includes evaluation of the physical processes and phenomena involved in the release of radiological material from the fuel during a severe accident, assessment of the transport and deposition of this material inside containment, determination of the potential containment failure modes, and identification of the phenomena contributing to the various failure modes. The approach of the at-power internal events Level 2 PSA is consistent with those of NUREG-1150, NUREG-1335, NUREG-1570, and the requirements of the ASME/ANS PRA Standard.

The internal events Level 1 and Level 2 PSA for low power and shutdown (LPSD) modes are performed based on NUREG/CR-6144 with similar methodologies of the at-power internal events PSA. In addition, EPRI TR-1003113 is reviewed to identify LPSD initiating events.

3. Engineered Safety Features of APR1000

The active safety systems in the APR1000 are designed to be four (4) trains to ensure additional redundancy considering Single Failure Criterion (SFC) and unavailability due to on-line maintenance, which means an N+2 concept. These systems can reach and maintain a controlled state and a safe shutdown state after a Design Basis Accident (DBA). Each train and its components of Safety Injection System (SIS), Shutdown Cooling System/Containment Spray System (SCS/CSS) and associated supporting systems are physically separated into four (4) quadrants to secure vital safety functions from malicious and natural hazards.

APR1000 has various advanced Engineered Safety Features (ESFs) to provide protection in the highly unlikely events of an accidental release of radioactive fission products for DBA and Design Extension Conditions (DEC-A). The main systems of ESFs are Safety Depressurization and Vent System (SDVS), In-containment Refueling Water Storage System (IWSS), Passive Auxiliary Feedwater System (PAFS) with Alternative Auxiliary Pump (AAP), Diverse Safety Features (DSF), and so on.

In particular, the PAFS provides an independent mean of passively returning condensate to the Steam Generator (SG) by using gravity force in the events where the Main Feedwater System (MFWS) is unavailable. When the PAFS is unavailable, AAP starts automatically upon the signal receipt of Diverse Protection System - Passive Auxiliary Feedwater Action System (DPS-PAFAS) and supports to remove the decay heat actively through the Steam Generator.

The Diverse Containment Spray System (DCSS), which is designed for the containment heat removal for DEC-B conditions, also provides a means of long-term cooling to maintain the plant in a safe state in the event of DEC-A when the SCS or its supporting systems such as Component Cooling Water System (CCWS) and Essential Service Water System (ESWS) are not available.

The Mid-loop Level Control System (MLCS) is adopted to reduce the risk of mid-loop operation during shutdown modes by automatic Reactor Coolant System (RCS) inventory control during mid-loop operation.

The Emergency Boration System (EBS) is designed to injects automatically highly concentrated borated water into the RCS following an Anticipated Transients Without Scram (ATWS), which the reactor cannot be tripped by the control rods to reach and maintain the reactor in a subcritical condition.

4. Sensitivity analysis in PSA

Sensitivity analysis is performed to measure the impact when the following operator actions to be taken within 30 minutes are not considered in the PSA model according to the EUR 2.17.3.5.

4.1 The operator actions for sensitivity

The operator actions considered for sensitivity analysis are as below;

- At-power Level 1 PSA
  - To initiate Emergency Boration by CVCS (CVOPH-S-BORATION)
  - Aggressive secondary cooling for SLOCA (MSOPH-S-ASC-SLOCA)
  - To operate PAFAS and AAP (PYOPV-S-PAFAS , PYOPH-AAP-FW)
  - To manually initiate reactor trip (RPOPV-S-RTRIP)
  - To load AAC DG following SBO initiator (DAOPH-S-AACDG)
  - To align for RCP seal by charging and auxiliary charging pump (CVOPH-S-RCPSEAL)
- LPSD Level 1 PSA
  - To make up RCS inventory during reduced inventory operation (HR-MI-IEP05/P11)
  - To start Diverse CSS/SCS to recover shutdown cooling (HR-RS-IEP05/P11)
- At-power and LPSD Level 2 PSA
  - To operate 3-way valve to convert release point from IRWST to atmosphere (H-3WAY, HR-RP-IE-LP)
  - To do rapid RCS depression (RDOPH-S-ERDS, HR-RD-IE-LP)

4.2 Safety Features related to operator actions

The following Table Ⅰ presents the safety features for operator actions considered for sensitivity analysis. Most of the operator actions are recovery action after failure of automatic initiation to control, mitigate, or terminate accidents. Some operator actions are to operate diverse system to mitigate or terminate DEC-A. In addition, severe accident mitigation systems including 3-way valves and Emergency Reactor Depressurization System (ERDS) are considered to mitigate DEC-B events by operator.

Table I: Safety Features for operation actions

Item	Operator Action	Description
At-power L1 PSA	CVOPH-S-BORATION	After the failure of automatic initiation of EBS
	MSOPH-S-ASC-SLOCA	After the failure of automatic initiation of PAFS
	PYOPV-S-PAFAS , PYOPH-AAP-FW	After the failure of automatic initiation of PAFS and AAP
	RPOPV-S-RTRIP	After failure of automatic reactor trip initiation
	DAOPH-S-AACDG	To operate independent train from 4 trains EDGs to cope with SBO
	CVOPH-S-RCPSEAL	To cope with RCP seal LOCA
LPSD L1 PSA	HR-MI-IEP05/P11	After failure of automatic initiation of safety injection by MLCS
	HR-RS-IEP05/P11	To operate independent train to cope with DEC-A such as Loss of Ultimate Heat Sink (LOUHS) and SBO
L2 PSA	H-3WAY, HR-RP-IE-LP	After failure of automatic conversion form RCS to containment atmosphere to prevent H2 burn in IRWST area
	RDOPH-S-ERDS, HR-RD-IE-LP	To prevent DCH/HPME during severe accidents by rapid RCS depressurization

4.3 Results for sensitivity analysis

The design effectiveness to be taken in terms of the risk is evaluated by the sensitivity analysis without credit to operator actions for 30 minutes as presented in Table Ⅱ.

As a results, the total CDF and LRF of sensitivity analysis in the Level 1 and 2 PSA except for external hazards are increased to 66% and 35%, respectively. The CDF for Internal events, internal fire and internal flooding in at-power PSA are increased to 119%, 102% and 111%, respectively. In case of LPSD PSA, the CDF for them are increased to 8%, 10% and 108%, respectively.

The sensitivity analysis results indicate that the impact to the total CDF and LRF are not significant. Because advanced APR1000 ESFs are very effective to control, mitigate, or terminate accidents, which include PAFS, Diverse features, MLCS, four (4) trains to ensure additional redundancy, and so on.

The CDF and LRF of the base case are well below the EUR safety targets of 1.0E-5/yr and 1.0E-6/yr, respectively. The PSA results of base case indicate that the APR1000 design results in a low level of risk and meet the requirements presented in EUR 2.1.3.5. Also, it is expected that the probabilistic goals presented in EUR 2.17.3.5 are achieved without credit to operator action for 30 minutes after initiating event occurs.

Table Ⅱ: Analysis results for sensitivity

Events	Sensitivity Analysis without credit to operator actions for 30 minutes (CDF/LRF comparing to Base)			
	CDF		LRF	
	At-power	LPSD	At-power	LPSD
Internal Events	119%	8%	159%	13%
Internal Fire Events	102%	10%	17%	0.5%
Internal Flood Events	111%	108%	26%	9%
SFP Internal Events	0%		0%	
SFP Internal Fire Events	0%		0%	
SFP Internal Flood Events	0%		0%	
Seismic Events	PSA Based Seismic Margin Analysis (SMA) (Qualitative)			
Other Internal and External Hazards	Screened Out or Not considered in PSA according to EUR 2.17.2.5.A1			
Sum	66%		35%	

5. Conclusion

This paper provides the design effectiveness and achieving safety goals delineated in EUR 2.17.3.5 by performing the sensitivity analysis without credit to operator actions for 30 minutes in the design phase Level 1 and 2 PSA.

According to the results, the cumulative total CDF and LRF of sensitivity analysis in the Level 1 and 2 PSA except for external hazards are increased to 66% and 35%, respectively and the impact to the risk is minor. Therefore, it is expected that the probabilistic goals delineated in EUR 2.17.3.5 are achieved due to advanced ESFs of APR1000.

By developing Level 1 and 2 PSA using the methodology defined in the EUR, it is possible to provide insights and the effectiveness of safety features to address safety requirements including the cumulative CDF, LRF and Practical Elimination of severe accidents on the basis of IAEA, TECDOC-1791 and EUR Rev.E.

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