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The sensitivity analysis for design effectiveness of Diverse CSS in the APR1400+ Level 2 PSA

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1. Introduction

The Probabilistic Safety Assessment (PSA) for the standard design of the APR1400+ is performed as required in the EUR Rev.E Chapter 2.17. The purpose of this design phase PSA is to demonstrate that the APR1400+ 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.

APR1400+ has various advanced safety features which are very effective in the safety point of view. This paper discusses the design effectiveness by performing the sensitivity analyses for the number of Diverse Containment Spray System (DCSS) trains in the design phase PSA of APR1400+. The scope of sensitivity analysis is the At-power internal event Level 2 PSA.

2. PSA Methodology of APR1400+

This section provides an overall Level 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 requirements under all operational modes including shutdown states:

Probabilistic Safety Requirements in delineated in EUR 2.1.3.5 and 2.1.2.5 will be met as follows:

- Probabilistic Safety Targets for cumulative LRF of 1.0E-6/ry (exceeding CLI) for the full scope of PSA at the detail design phase when a site is chosen
- Practical Elimination (PE) with extremely low frequency for each SA phenomena

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 PSA 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.

3. Engineered Safety Features of APR1400+

The active safety systems in the APR1400+ 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.

APR1400+ 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), Auxiliary Feedwater System (AFWS) with Motor Driven Pump (MDP) and Turbine Driven Pump (TDP), and so on.

The Severe Accident (SA) mitigation systems of APR1400+ are designed to limit offsite releases after accident with core melt. They consist of Emergency Reactor Depressurization System (ERDS) function, In-vessel retention & Cavity Flooding System (IVIS + CFS), Diverse Containment Spray System (DCSS), Hydrogen Mitigation System (HMS), and Containment Isolation System (CIS) which are described as follows:

- The EDRS is independent from the SDVS and rapidly depressurizes the RCS to eliminate a High Pressure Melt Ejection (HPME) under all DEC-B conditions
- The IVIS + CFS design to inject cooling water into the reactor vessel to guarantee the in-vessel retention. It also floods the reactor cavity in order to facilitate the cooling and stabilization of the debris to mitigate late containment failure after Reactor Vessel failure
- The DCSS is provided to decrease containment pressure and temperature during DEC-B conditions by condensing the steam generated in the containment and to reduce the potential for further pressure increase by removing decay heat from the containment atmosphere and from the core debris in the reactor cavity.

- The HMS is designed to control combustible gas inside the containment within the acceptable limits by Passive Autocatalytic Recombiners (PAR) in consideration of hydrogen generation during the DEC-B conditions.
- The containment isolation system (CIS) is designed to confine the release of any radioactivity from the containment following an accident.

4. Sensitivity analysis in PSA

Sensitivity analysis is performed to assess the potential on the At-power internal event Level 2 PSA according to the number of DCSS Train for SA during the standard design phase.

4.1 Requirements for sensitivity analysis of DCSS

The requirements for single failure criterion in DEC for sensitivity analysis of DCSS as follows:

- EUR 2.1 5.1.5: Compliance with the single failure criterion is not required in DEC
- IAEA (TECDOC-1791), Czech Decree: safety features for DECs are not required to be designed to meet the single failure criterion
- Finland (YVL): ~ the diversity principle shall satisfy the (N+1) failure criterion

Only Finland (YVL) requires the diversity principle for DEC to satisfy single failure criterion.

4.2 The number of DCSS for sensitivity

The number of DCSS considered for sensitivity analysis are as below;

- Base Case
  - 2 Trains of DCSS are available
- Sensitivity Case01
  - Only 1 Train of DCSS is available
- Sensitivity Case02
  - DCSS is not available (No DCSS)

4.3 Results for sensitivity analysis

The design effectiveness to be taken in terms of the risk is evaluated by the sensitivity analysis regarding the number of DCSS as presented in Table I.

In terms of Sensitivity Case01 with only 1 DCSS, CF due to containment over-pressurization, 7^{th} PE, is slightly increased compared to Base Case. Therefore, total LRF (%) is also slightly increased and No CF is just over 90%.

In terms of Sensitivity Case02 without DCSS, CF due to containment over-pressurization, 7^{th} PE, is a lot increased compared to Base Case. Therefore, total LRF (%) is also a lot changed and No CF is less than 80%.

As a results, both total LRF and CF due to 7^{th} PE in the sensitivity Case01 are slightly increased compared to Base Case. But on the other hand, those in the sensitivity Case 02 are a lot increased. So, the sensitivity analysis results indicate that DCSS with at least one train is very effective design feature to mitigate SA like containment over-pressurization of 7^{th} PE.

Table I: Analysis results for sensitivity

Phenomena for PE Demonstration	Provisions	DSA (Deterministic)	PSA (Base) (2 DCSS)	PSA (1 DCSS)	PSA (No DCSS)
1. Hydrogen Detonation	PAR	No DDT	≒ 1.0E-09	Same with Base	Same with Base
2. Large Steam Explosion	PECS	No failure of cavity structure	Not applicable	Not applicable	Not applicable
3. Direct Containment Heating	ERDS	RCS Pressure (〈 20 bar)	〈 1.0E-09	Same with Base	Same with Base
4. Large Reactivity Insertion	Prevention	Subcriticality	Not applicable	Not applicable	Not applicable
5. Rupture of Major Pressure Components	Robust Design	〈 1.0E-07 (No rupture)	Not applicable	Not applicable	Not applicable
6. Failure of Spent Fuel Storage	DSFPCS, Makeup	No heatup of fuel	≒ 5.0E-09	Same with Base	Same with Base
7. Containment Over-pressurization	DCSS	P 〈 FLC Pressure	**≒ 5.0E-09**	**〈 1.0E-08**	〈 1.0E-07
8. Basemat Melt-Through	PECS	MCCI prevention	≒ 1.0E-10	Same with Base	Same with Base
9. SA with Containment Bypass	CIS, SG Isolation	Not applicable	≒ 3.0E-08	Same with Base	Same with Base
10. SA during Shutdown with Open Containment	SAMG, E/H	Not applicable	Deterministic PE	Deterministic PE	Deterministic PE
NoCF (LRF) (%) of At-Power Internal Events	-	-	**〉90%**	**≒ 90%**	**〈 80%**

5. Conclusion

This paper provides the design effectiveness and achieving safety goals delineated in EUR by performing the sensitivity analysis for the number of DCSS trains in the standard design phase Level 2 PSA of APR1400+.

According to the results, the Sensitivity Case02 with No DCSS can affect containment integrity due to containment over-pressurization, but both Base Case with 2 Trains DCSS and Sensitivity Case01 with 1 Train DCSS have similar design effectiveness, which is 7^{th} phenomenon for 10 phenomena of Practical Elimination.

It is expected that not only Base Case but also Sensitivity Case01 will be met EUR requirements such as PE and probabilistic safety targets with enough margin for the full scope of PSA at the detail design phase when a site is chosen.

Therefore, the single failure criterion for DCSS in DEC may not be necessary to be met safety targets of cumulative LRF of 1.0E-6/ry (exceeding CLI).

In the future, more sensitivity analyses need to be performed to evaluate the design effectiveness of the other diverse safety features such as Emergency Boration System (EBS), Diverse Protection System (DPS), Diverse Spent Fuel Cooling System (DSFPCS), and so on.

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