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Quantitative Safety Impact of Severe Accident Management Systems for EU-APR during Low Power Shutdown Operation

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1. Introduction

In order to enlarge and to diversify the export market of APR1400, the EU-APR design was developed based on the APR1400 design to comply with the latest version of the European Utility Requirements (EUR) revision D.

The EU-APR design has the distinguished and advanced severe accident management systems taken from the APR1400 to obtain a containment integrity for the beyond design basis accident, such as the Passive Ex-vessel retaining and Cooling System (PECS), the Severe Accident Containment Spray System (SACSS) and the Containment Filtered Vent System (CFVS).

The risk associated with the nuclear power plant can be identified through the Probabilistic Safety Assessment (PSA). In the EUR chapter 1 and 17 of volume 2, the Criteria for Limited Impact (CLI) should be applied to the Level 2 PSA as a risk metrics.

Hence this paper discusses the impact of the severe accident management systems for the EU-APR by using CLI as a risk metrics during Low Power and Shut-Down (LPSD) operation.

2. Methods and Results

2.1 Severe Accident Management Systems for the EU-APR

Generally, to prevent release of radioactive material, the severe accident management systems are installed in a nuclear power plant. For the EU-APR, which is based on APR1400, the several severe accident management systems are designed to mitigate severe accident.

Firstly, the PECS consists of the core catcher, cooling channel, sacrificial material and monitoring system. It is placed inside the reactor cavity under the reactor vessel. The PECS can retain the core debris to prevent both the molten corium-concrete interaction and basemat melt-through.

Secondly, the SACSS has the dedicated component cooling water system and essential service water system. It consists of two redundant trains for the SACSS pump and heat exchanger. The SACSS can prevent the containment failure for the over-pressurization and remove fission products in the containment atmosphere.

The last one is the CFVS. The CFVS consists of pre-filter and after-filter in the design stage. This system also can prevent the containment failure for over-pressurization.

2.2 LPSD Level 2 PSA for the EU-APR

In a case of the EU-APR analysis, the cumulative frequency of exceeding CLI is required as a risk metrics of the safety target instead of the large early release frequency. The CLI is defined in EUR Volume 2 Chapter 1 appendix B [2]. It involves following four design targets.

- No emergency protection action beyond 800 m from the reactor,
- No delayed action at any time beyond about 3 km from the reactor,
- No long term action at any distance beyond 800 m from the reactor,
- Limited economic impact out of the plant.

For PSA during LPSD operation, the Plant Operation State (POS) was defined into 15 POSs. The definition of each POS is described in NUREG/CR-6144 [1]. The LPSD level 2 PSA model was based on the LPSD level 1 PSA model to maintain a consistency of the level 1 PSA criteria. POS 1,2,14 and 15 have a similar severe accident progression with at-power except for the initial decay heat. So, a fraction of exceeding CLI for POS 1,2,14 and 15 was simply calculated by multiplying a conditional probability of large release, derived from the at-power Level 2 PSA results, with the Core Damage Frequency (CDF) from the LPSD level 1 PSA.

The EU-APR LPSD PSA model was constructed by using the SAREX 1.3 code. Plant Damage State Event Trees (PDS ETs) were quantified by using the FTREX quantification engine. The COUPE quantification engine was used to quantify the level 2 PSA model.

For the POS 3 to 13, PDS ETs for every initial event were constructed based on the LPSD level 1 event trees. These extended sequences were defined and grouped into plant damage states by the plant damage state logic diagram.

The next step is construction of the Containment Event Tree (CET) which evaluates the containment failure probability. To avoid complicated CET structure, Decomposition Event Trees (DETs) support the CET. The end points of the CET were grouped into the

Source Term Category (STC) by the source term category logic diagram.

To check whether each STC exceeds the CLI or not, the representative sequences are selected from each STC; and the source term was evaluated by the MAAP5 code.

The cumulative frequency of exceeding CLI for EU-APR during LPSD operation was calculated as 4.52% of the CDF.

2.3 Sensitivity Analysis

Individual or entire severe accident management systems for EU-APR are assessed by changing the PDS categorization logic. For example when sensitivity analysis for the PECS is performed, success logic for the PECS parameter is changed to fail logic and re-quantifies the level 2 PSA model.

The results of sensitivity analysis for the cumulative probability of exceeding CLI are shown in Table I.

- Case 1: Base Case
- Case 2: PECS Unavailable
- Case 3: SACSS Unavailable
- Case 4: CFVS Unavailable
- Case 5: PECS/SACSS/CFVS Unavailable

Table I: The Fraction and Increase Rate of Exceeding CLI

CASE	Fraction of CDF (%)	Increase Rate
Case 1	4.52	-
Case 2	54.18	11.97
Case 3	89.74	19.83
Case 4	21.32	4.71
Case 5	100.00	23.54

If the PECS is not credited as the severe accident management system, the fraction of exceeding CLI is calculated as 54.18% of the CDF. The possibility of the basemat melt-through is increased significantly, and radioactive materials exceeding CLI would be released to environment in this containment failure mode. This result shows that the PECS is one of the important safety systems to mitigate the release of fission products to the environment.

If the SACSS is not credited as a severe accident management system, the fraction of exceeding CLI is calculated as 89.74% of the CDF. The possibilities of the late containment failure and the containment failure before reactor vessel breach are increased significantly. The SACSS can control the containment pressure and temperature in the severe accident condition. This function prevents the containment failure for the over-pressurization. This sensitivity analysis result shows that the SACSS is the most important safety system against large release of radioactive materials.

If the CFVS is not credited as the severe accident management system, the fraction of exceeding CLI is calculated as 21.32% of the CDF. This system alleviates containment pressure and prevents the late containment failure for the over-pressurization. The result shows that the CFVS is less important safety system than the SACSS even though this system prevents the containment over-pressurization.

When above three severe accident management systems are not credited, the fraction of exceeding CLI is calculated as 100% of the CDF. It means every core damage sequence releases the radioactive materials exceeding CLI to the environment.

3. Conclusions

The fraction of exceeding CLI for the EU-APR during LPSD operation was calculated as 4.52% of the CDF under the condition that all severe accident management systems are credited. The PECS, SACSS and CFVS are considered as the severe accident management system which is EU-APR dedicated system. The exemption of each system leads to increase the fraction of exceeding CLI to 54.18%, 89.74% and 21.32% respectively. In case if all these systems are unavailable, the fraction of exceeding CLI is increased to 100%. The most effective system is the SACSS that the system reduces containment pressure and temperature.

According to the results of this study that applies the cumulative frequency of CLI as risk metrics, the newly designed severe accident management systems are effective to mitigate severe accident progression and prevent the radioactive material release to environment exceeding CLI.

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