Development of Reference Source Terms for EU-APR1400

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1. Introduction

According to the European Utility Requirements (EUR) [1], the Reference Source Term (RST) for severe accident shall be determined based on the plant design characteristics, realistic assumptions, and best estimate methods. But, so far either the TID-14844 [2] or the NUREG-1465 [3] source term has been used for accident analyses in the Korean NPP licensing applications. These source terms are developed for the typical U.S. NPP and do not reflect the design characteristics of EU-APR1400 (1,400 MWe PWR) which will be applied for the EUR certification in European countries.

The process of developing the RST for EU-APR1400 is to undergo a similar process that NUREG-1465 had gone through when it came out with its proposed source terms. The purpose of this study is to develop the EU-APR1400 design-specific RST complied with the EUR.

2. Methods and Assumptions

This section addresses the major methods and assumptions used to evaluate the design-specific RST.

2.1 EU-APR1400 Design Characteristics

The EU-APR1400 is designed to have a capability of rapid RCS depressurization through the Rapid Depressurization System (RDS) for prevention of high pressure melt ejection (HPME) and direct containment heating (DCH). The RDS is actuated after core exit temperature (CET) exceeds 649 ℃. Therefore, the EU-APR1400 RCS can be depressurized to be much less than 20 bars only with actuation of the RDS before occurrence of the reactor vessel breach during any core damage sequences. The EU-APR1400 low RCS pressure conditions during a severe accident perfectly follow the NUREG-1465 selection criteria.

However, one distinct design feature of the EU-APR1400 that was not considered in NUREG-1465 is the ex-vessel core catcher. The primary function of the ex-vessel core catcher is to retain and cool the corium debris drained out from the failed vessel. By the virtue of the ex-vessel core catcher design feature, the possibility of MCCI on the reactor cavity floor can be practically excluded. As a result, the ex-vessel release fractions of fission products proposed by NUREG-1465 can be considered unrealistic in EU-APR1400 severe accidents.

2.2 Selection of Accident Sequences

In terms of developing the representative source term, the type of severe accident considered when complying with the selection criteria of NUREG-1465 was limited to a series of low pressure severe accidents. A low pressure core melt scenario has a tendency of low retaining fission products in the reactor coolant system compared to a high pressure core melt scenario and thereby the fission products are much more easily released from the core into the containment atmosphere especially during the early in-vessel release phase.

However, to determine plant-specific source terms for EU-APR1400, the risk-significant accident sequences are selected based on core damage frequency (CDF) coming from the results of the Level 1 PRA which was done in EU-APR1400. For our analysis, the top 19 sequences which are more than 1% in terms of contribution to CDF were selected. The selected 19 sequences encompass almost all types of accident initiators, including ATWS, general transients, LOCA, SGTR, SBO, LOOP, MSLB, loss of DC power, and ISLOCA.

2.3 Uncertainty Quantification Method

Extensive MAAP [4] analyses are performed to quantify the EU-APR1400 specific source term characteristics. The final results are presented in terms of release fractions and release durations. These results are drawn from the 59 MAAP runs per sequence with a different combination set of parameter values which are selected by the Latin Hypercube Sampling (LHS) method over the selected risk-significant sequences. The number of MAAP runs per sequence is given by Wilks' formula. If 59 randomly sampled MAAP runs are performed per sequence there is a 95% confidence that the maximum code results do not exceed the 95th percentile of the distribution.

2.4 Assumptions

For our analysis, the following assumptions are considered because of the absence of specific evaluations and experimental data for EU-APR1400.

- Fission product elements were grouped into 8 major groups on the basis of similarity in chemical behavior in accordance with NUREG-1465 grouping.

- The onset of fission product release is mechanistically calculated by MAAP from the first fuel pin failure.
- A 5% release fraction for gap release phase is chosen for volatile fission product groups 1, 2, and 3 (noble gases, iodine, and cesium, respectively).
- Iodine entering the containment is 95% CsI with the remaining 4.85% as elemental iodine (I_2) and 0.15% as organic iodide (CH_3I).

3. Results

In order to determine the release fractions and durations of each fission product group, rather than evaluating the statistically processed values on a sequence-by-sequence basis, the results from all sequences (with 59 runs for each sequence) are processed (ordered) at the same time. The results are selected with CDF-weighted mean, the 50th percentile (median), the 75th percentile, and the 95th percentile of the cumulative CDF (CCDF).

In NUREG-1465 the mean values were used to represent the release of the volatile fission product groups 2, 3, and 4 because the uncertainty ranges were narrow. While the 75th percentile values were used to represent the release of the non-volatile fission product groups 5, 6, 7, and 8 because the simple mean values were much higher than the median in its samples due to the several order of magnitude spread in the results.

Comparing the CDF-weighted mean values to the CCDF 50th percentile values in our analysis, the release fractions are about the same for both values with the CCDF 50th percentiles yielding slightly higher release fractions by 2%~4% in the early in-vessel release fractions for fission product groups 2 and 3. For fission product groups 5 to 8, the early in-vessel release fraction is higher for the CDF-weighted mean. The similar results from the two approaches also confirm that there are no extreme outliers within the uncertainty ranges and that the samples are more or less symmetrically distributed over the uncertainty ranges. The larger value between the CDF-weighted mean and the CCDF 50th percentile value is considered to be the representation of best-estimate results.

The corresponding release durations are chosen based on whether the median or the CDF-weighted mean is chosen for the release fraction so that the selected release fractions and release durations are consistent. For the release of non-radioactive aerosols, the smaller value is chosen because smaller aerosol density is more conservative with respect to aerosol coagulation and sedimentation process.

The source term results in terms of release fractions and release durations for the major fission product group are presented in Table I.

Table I: EU-APR1400 RST (Group 1~4)

Release Phase	Fission Product Group			
	1	2	3	4
	Release Fraction			
Gap	0.05	0.05	0.05	-
In-vessel	0.95	0.413	0.356	0.339
Ex-vessel	-	0.015	0.0072	0.107
Late In-vessel	-	0.03	0.0126	0.0169
	Release Duration (hr)			
Gap	0.49	0.49	0.49	-
In-vessel	2.27	2.27	2.27	2.27
Ex-vessel	-	1.89	1.87	2.66
Late In-vessel	-	19.09	18.34	13.84
	Onset Time of First Release (hr)			
Gap	2.44	2.44	2.44	-
In-vessel	2.93	2.93	2.93	2.93

4. Conclusions

The Large LOCA is the reference sequence used in the NUREG-1465 evaluation, whereas the EU-APR1400 risk-significant sequences are dominated by small LOCA and non-LOCA sequences. Moreover, when considering the EU-APR1400 has many design features to mitigate the consequences of severe accident phenomena, it is not surprising that the aspects of both release fractions and durations are distinctly different from NUREG-1465.

This RST will be continuously updated to reflect to the design features of EU-APR1400, and then, be used as the reference for design purposes such as criteria satisfaction of radioactivity releases, equipment survivability, control room habitability for severe accident, and so on.

REFERENCES

[1] EUR, European Utility Requirements for LWR Nuclear Power Plants, Rev.D., 2012.
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[3] L. Soffer et al., Accident Source Terms for Light-Water Nuclear Power Plants, NUREG-1465, U.S. Nuclear Regulatory Commission, 1995.
[4] Fauske and Associates, QA Document for MAAP5 Code Revision 5.0.2 beta, 2013.