Analysis of Hydrogen Risk Mitigation System for Severe Accidents of EU-APR1400 Using MAAP4 code

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1. Introduction

According to the EUR (European Utility Requirements for LWR Nuclear Power Plants) [1], it is mandatory that the HMS (Hydrogen Mitigation System) of the Eu-APR1400 should be equipped with a passive or automatic hydrogen control system. Considering this requirement, a PAR (Passive Autocatalytic Recombiner) system was adopted for the HMS of the Eu-APR1400. This passive HMS should be evaluated carefully in order to ensure that the HMS has adequate capacity to control hydrogen concentrations during severe accident conditions and to show that the system can satisfy the design requirements of the EUR.

In this paper, analyses were carried out to examine the effectiveness of the HMS incorporated into the Eu-APR1400 design. These analyses were performed using the MAAP (Modular Accident Analysis Program) 4 code[2]. in order to identify whether the HMS could control the average hydrogen concentrations in the containment, such that the concentration would not exceed 10 percent by volume; the analyses also considered whether there was the possibility of inadvertent hydrogen combustion in such processes as FA (Flame Acceleration) and DDT (Deflagration to Detonation Transition).

2. Methodology

The MAAP4 code was used to evaluate the quantities of in-vessel and ex-vessel hydrogen generation. MAAP4 calculation was run to the time at which an amount of the hydrogen becomes equivalent to that provided by 100% of MWR (Metal Water Reaction) in compliance with the criteria of the EUR and YVL (nuclear regulatory guides of Finland)[3].

2.1 Criteria of EUR and YVL

The criteria, EUR 2.9 3.1.7.5 C and YVL 2.2 4.1.6, prescribe the amount of hydrogen to be considered to resolve hydrogen issues under severe accident conditions. These criterions are as follows.

- EUR 2.9 3.1.7.5 C : To provide additional margin against hydrogen detonation, that, assuming a hydrogen production equivalent to 100% of active fuel cladding/water interaction and a realistic production rate, then the average hydrogen concentration in the containment will not exceed 10% by volume in dry conditions, giving credit to hydrogen control measures such as recombiners and/or igniters.

- YVL 2.2 4.1.6 : In analysing the pressure behavior of the containment, non-condensable gases have to be taken into account. When estimating the amount of released hydrogen in particular, it shall be assumed that 100% of easily oxidising material in the area of the reactor core reacts with water.

2.2 Calculation of Hydrogen Distribution

The hydrogen distribution analysis for the Eu-APR1400 containment was performed through MAAP4 calculations for accident sequences such as SBO, SGTR, TLOCCW, SLOCA, LLOCA and TLOFW. For those accident sequences, it was evaluated whether the hydrogen concentrations of the containment compartments would exceed 10 vol%.

2.3 Calculation of Hydrogen Depletion by PARs

MAAP version 4.07 has a PAR model that is based on those developed by the EPRI-ALWR program. For the calculation of the hydrogen depletion by PARs, the hydrogen depletion rate correlation for NIS PAR units was utilized.

2.4 Evaluation Methodology for Hydrogen Risk

For each accident sequence, it is examined whether compartments were found in which the hydrogen concentration exceeded the value of 10 vol%. In addition, for those cases, the risk of FA was assessed by the "sigma" (σ) criterion and, also, based on the "7 lambda" (7λ) criterion, the risk of DDT was evaluated.

The definition of DDT and FA phenomena are described as follows:

- FA : If the flow path area is decreased by obstacles, the flame can accelerate and DDT can occur by the acceleration of flame. The flame acceleration is a prerequisite condition for occurrence of DDT.
- DDT : It is a rapid transition phenomenon from deflagration to detonation when the degree of deflagration becomes strong. And the pressure load resulting from this phenomenon causes the serious damage to the containment integrity.

The criteria for evaluation of FA potential ("σ-Criterion") and DDT potential ("7λ-Criterion") represent necessary but not sufficient conditions for FA/DDT. Therefore, it may be possible that FA and DDT will not occur due to other reasons, even though the criteria are met. However, if the criteria are not met, it is certain that FA and DDT will not occur.

3. Results

3.1 Calculation of Hydrogen Generation

The numerical simulations for the selected accident 7 scenarios were performed using the MAAP4 code.

In-vessel hydrogen generation begins when the fuel element has been uncovered or damaged due to the decrease of coolant inventory. The continuing of the core melt progression accompanying core material interactions accelerates the hydrogen generation and, then, violent generation continues until the corium causes the core support plate to fail.

The quantities correspond approximately to 27% ~ 63% of the 100% MWR equivalence. The hydrogen generated in-vessel and ex-vessel can be released into containment compartments at specific release rates. For all the accident sequences considered, the expected hydrogen release locations are the RCS break point and the reactor cavity compartments. And, the hydrogen in each compartment can be depleted by PARs. Analyses were performed to evaluate the hydrogen concentrations in the containment using the MAAP4 code and the Eu-APR1400 HMS was determined to be composed of 31 full-size PARs.

3.2 Calculation of Hydrogen Depletion by PARs

The PARs distributed over all the containment remove hydrogen even at very low concentrations regardless of the steam concentration.

The hydrogen depletion rates depend on the hydrogen concentration. The averaged hydrogen concentration exceeds 10 vol% for most of the accident sequences except the SGTR-S28 sequence. However, the hydrogen components generated in-vessel and ex-vessel were controlled well by the PARs installed in the containment, so that the volumetric averaged hydrogen concentrations in dry condition did not exceed 10 vol%.

Although the hydrogen was generated also in the reactor cavity by the MCCI (Molten Corium-Concrete Interaction) phenomenon, the averaged hydrogen concentration in the containment did not increase continuously due to the mild hydrogen generation rate by the MCCI.

3.3 Evaluation of Hydrogen Risk

For the assessment of the hydrogen risk of the compartments, the possibility of FA and DDT phenomena were evaluated using the calculated gas concentration, temperature and pressure distribution. In all the cases, there were no compartments found to yield an FA index exceeding 1.0 and this shows that the possibility of an FA occurrence might be negligible.

Considering that FA is a prerequisite for DDT, it can be thought that there is only a slight possibility of DDT occurrence in all compartments. According to the results of DDT evaluation, it was found that the DDT index was much smaller than 1.0 in all compartments.

4. Conclusions

For seven (7) accident sequences, peak and final hydrogen concentrations inside the containment and the hydrogen risk of FA and DDT were evaluated to identify the HMS performance. The averaged hydrogen concentration in the containment did not exceed the value of 10 vol% in dry condition. Also, the peak values of hydrogen concentration in all compartments were less than 10 vol%. And, the values of the FA/DDT indexes were below 1.0.

The evaluation results show that the possibility of an FA occurrence and DDT phenomenon are probably negligible for all compartments of the Eu-APR1400 containment.

REFERENCES

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