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An Effort for Resolving a Current Hydrogen Issue in APR1400 in case of a high-Pressure Severe Accident

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1. Introduction

For a loss of coolant accident (LOCA), most of the hydrogen generated in a reactor pressure vessel (RPV) is released through a cold-leg or hot-leg break. But in the case of a high-pressure accident such as a loss of feed water (LOFW) or station blackout accident in APR1400, the hydrogen in the RPV is expelled to a pressurizer. And it is released into the in-containment refueling water storage tank (IRWST) when a pilot-operated safety and relief valve (POSRV) is opened manually or automatically by an over-pressurization developed in the pressurizer. The IRWST in the APR1400 containment is a large annular compartment to store the refueling water. But if it is used as a release tank of the RCS de-pressurization, then the hydrogen behavior and its combustion characteristics in the IRWST are very important because an impulsive pressure load induced by the hydrogen combustion can threaten the structural integrity of the containment when it occurs.

Many studies [1, 2] have been conducted to evaluate the hydrogen behaviors and a possibility of a flame acceleration and a deflagration-to-detonation transition (DDT) in the IRWST of APR1400. In the studies, it was noted that there exits a possibility of flame acceleration in the IRWST when a dry hydrogen was released. Also, a research work conducted in FZK for an EPR nuclear power plant (NPP) revealed that a hydrogen release into the IRWST is a bad choice in view of a pressure load on the containment structure. In the current EPR, the hydrogen release location is changed to a pressurizer relief tank (PRT) which is installed near a reactor coolant pump. By doing this, the hydrogen mitigation strategy for the high-pressure accidents in EPR can be merged into the case of a LOCA. The hydrogen mitigation problem is more important in APR1400 than EPR because of the geometric aspects such as large aspect ratio of height to length and small vent area in the IRWST. These aspects can increase the possibility of DDT. In the SSAR of APR1400, it has four PARs (passive auto-catalytic recombiner) and two igniters installed to reduce the hydrogen concentration in the IRWST. In the authors' point of view, this design of the hydrogen mitigation in the IRWST is not satisfactory to remove a hydrogen hazard. Usually, the PAR is not used in an atmosphere with highly-concentrated hydrogen because it can act as an uncontrollable ignition source for hydrogen. The igniters can be inactive during a SBO accident, so it is useless as a hydrogen mitigation device without an electric power.

In this study, an effort was made to resolve a current hydrogen issue in APR1400 in the case of the high-pressure accidents.

2. Hydrogen Mitigation Strategies

A hydrogen mitigation strategy (HMS) proposed in the previous work was reviewed in this study. And two more strategies are proposed as a candidate for resolving the hydrogen issue in APR1400.

2.1 Partitioning of the IRWST

The APR1400 containment is designed to survive from a global burning of the hydrogen generated by full metal oxidation. The most simple and effective way to reduce the hydrogen concentration is mixing of hydrogen with steam released during an accident. When the steam from the pressurizer is released through the spargers immersed in the water of the IRWST, most of the steam is condensed and very dry hydrogen is accumulated in the free volume of the IRWST. In the paper [1], it was proposed to partition the IRWST in order to confine the water around the spargers. The main idea to do this is increasing the amount of uncondensed steam which can reduce the hydrogen concentration effectively. Unfortunately, this concept of the hydrogen mitigation for the IRWST failed to attract interest in a research group of the APR1400 safety. It is because of a design guide to limit the water temperature below saturation in the IRWST. It is still believed that pressure loads generated by rapid condensation of the steam sparged in the IRWST must be minimized by maintaining the refueling water subcooled. In currently-operating NPPS, steam sparging systems such as reactor drain tank (RDT) or PRT do the same work as the IRWST with spargers in APR1400 to relieve the RCS pressure. But in these RDT and PRT, the uncondensed steam release is allowed because the pressure loads from incomplete condensation of the steam is already considered in its structural design. In the same way, the partitioned volume of the IRWST including the spargers can be used as a PRT by reinforcing the partitioning walls. In this study, it is named ***PRT in IRWST*** for the hydrogen mitigation.

2.2 Hydrogen release to HVT

APR1400 has a holdup volume tank (HVT) as a component of a recirculation system for a long-term cooling of the containment. It collects water on a floor flooded by an operation of a spray system or bleeding of the reactor coolant. It is located between the two steam generator (SG) compartments and at the same elevation as the SG pedestals. Here, it is proposed that the HVT is used as a hydrogen release location. This strategy is very similar to the EPR's HMS for the high-pressure accidents. The water, steam, and hydrogen from the POSRV are released through spargers installed in the HVT during a severe accident in this concept. Some part of the water and steam are expected to be well-mixed with the water in the HVT and condensed. But much of the uncondensed steam can be released and mixed with the hydrogen released through the sparger. In order to evaluate the hydrogen behaviors in the APR1400 containment during a TLOFW accident, a GASFLOW simulation was conducted. Fig. 1 shows the hydrogen and steam distributions in the containment after passing a maximum release time of the hydrogen. Compared to a large-break LOCA, the hydrogen is well-mixed with the steam. A possibility of a flame acceleration was not found during the accident progression by using $\sigma - \lambda$ criteria.

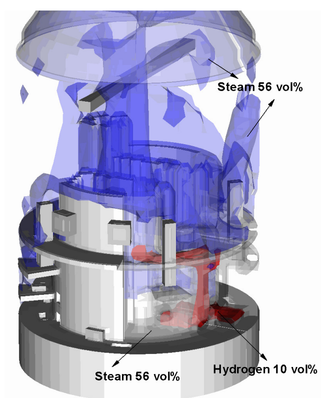

Fig. 1. Hydrogen and steam distributions in the APR1400 containment during a TLOFW accident

2.3 Hydrogen burning system

As said before, four PARs and two igniters are installed in the IRWST of APR1400. But, the possibility of the DDT occurrence in the IRWST still exists in the case of a dry hydrogen release. If the igniters are used as a hydrogen removal device by burning it in a confined long channel like the IRWST, care must be taken. Inappropriate installation and operation of the igniters can lead to a dangerous hydrogen explosion. When they are activated by a NPP operator in a bad situation such as a highly-concentrated hydrogen condition, the flame may be accelerated and become a detonation.

Here, a new design concept for a hydrogen removal system for the IRWST is proposed. This system is composed of sensors, control box, electric power device, and a cluster of spark igniters. The main idea of this system is based on a minimum run-up distance for DDT. If the distance between two igniters is sufficiently shorter than the run-up distance, the flames from the igniters can not be accelerated to DDT. Fig. 2 shows the run-up distance for a hydrogen-air mixture depending on a tube diameter. The hydraulic diameter D_h of the free space in the IRWST is about 2m in normal operation, so the run-up distance is 20 times of the D_h. This means that DDT can be excluded in the IRWST if the distance between the igniters is shorter than 40m (Factor 2 by counter-flames from the igniters is used for safety.). In this system, the electric power for the igniters can be generated by a water turbine. And the igniters are automatically activated by a flow from the sparger.

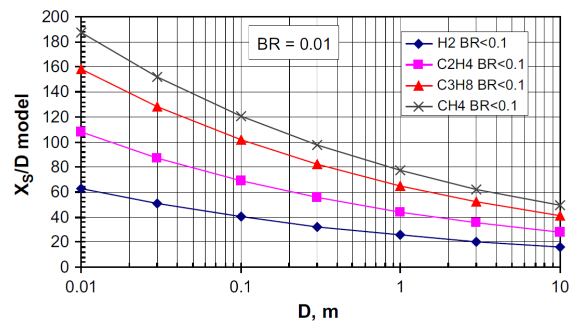

Fig. 2. Run-up distances over tube diameter as a function of tube diameter for BR[0.01 (model for BR $\leq$ 0.1). Ref. [3]

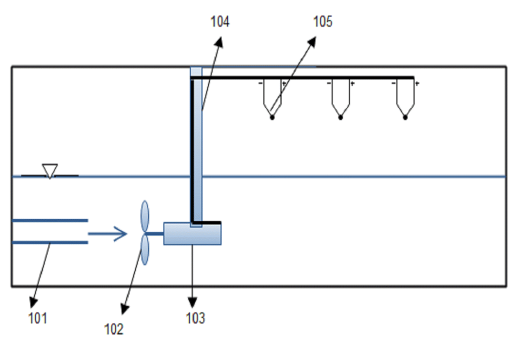

Fig. 3. Conceptual design of auto igniter-cluster, 101: sparger, 102: turbine, 103: generator, 104: support bar, 105: igniter

3. Conclusion

In this study, hydrogen mitigation strategies for resolving the current hydrogen safety issue in the IRWST of APR1400 were proposed. It is recommended to study experimentally the hydrogen burning system based on the run-up distance for DDT.

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