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Hydrogen Management Strategies Using the Igniters and Recombiners

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Abstract

Hydrogen, which is generated by cladding oxidation, can diffuse to all subcompartments in the containment so that high hydrogen concentration may be induced only locally. If the hydrogen concentration in containment reaches to the flammability limit and enough hydrogen is allowed to build up, the hydrogen can ignite and cause a spike in containment pressure that exceeds the containment ultimate design pressure, thereby failing the containment. It is thus important to analyze the accident sequence inducing high hydrogen concentration locally and to develop adequate control and management strategies. In this paper, a framework for evaluating hydrogen control and management strategies involving multiple decisions is presented. The compact influence diagrams including multiple decisions are constructed and evaluated with the MAAP4 calculations. Each decision variable, represented by a node in the influence diagrams, has an uncertainty distribution. Using the values from standard safety analysis report of the reference plant, Advanced Power Reactor 1400MWe (APR1400), the hydrogen control and accident management strategies are assessed. The strategies are ranked with respect to a new measure in terms of hydrogen concentration. The MAAP4 code calculations are performed to generate data for hydrogen concentrations and to identify the important severe accident phenomena in containment for the decision-making analysis as well. In this paper, a problem with two decisions is modeled for a simplistic illustration. One decision is whether or not to actuate the igniters at the time of core uncovery; another decision is to use the passive autocatalytic recombiners (PARs). We chose a small-break loss-of-coolant accident (LOCA) sequence, which was one of the dominant accident sequences in the reference plant, as the reference case. The framework ling of the decision problem by using the decision-making tools, data analysis, and the MAAP4 calculations. It is shown that the proposed framework with a new measure for assessing the hydrogen control and accident management strategies is very flexible in that it can be applied to any kind of accident management strategy for any accident sequence. The igniters are the fastest way of reducing the containment hydrogen concentration, whereas the PARs remove hydrogen at a slow rate.

1. Introduction

The objective of the accident management [1,2] is to prevent core uncovery and subsequent reactor vessel failure, to maintain containment integrity as long as possible, and finally to minimize any off-site release. Continuous burning will prevent hydrogen accumulation and will not result in a significant pressure spike in the containment building. The fastest way of reducing the containment hydrogen concentration is to intentionally burn the hydrogen with the igniters. Decision tree is used as a decision-making tool. To develop a decision-making path for using the hydrogen igniter and PAR is important because the results are different depending on whether the igniters and PAR are used or not and when the operation begins. Because the APR1400 containment event tree (CET) has containment failure probability pursuant to the containment response during the severe accident progression, there is a need to develop a particular event tree concerned with hydrogen behavior in the containment. Based on the decision tree and CET, a sample calculation framework for hydrogen is presented utilizing relevant control and management strategies.

The PARs do not require a source of power and draw an air-hydrogen mixture from the containment atmosphere and heat the mixture to the point where hydrogen and oxygen recombine to form water vapor. At low hydrogen concentrations, energy from the recombination of hydrogen with oxygen is released at a relatively slow but continuous rate into the containment. The heat produced creates strong buoyancy, which increases the influx of the surrounding gases to the recombiner. The natural convective flow currents promote mixing of combustible gases in the containment. The hydrogen recombiners are designed to maintain the containment hydrogen concentration below 4% following the design basis LOCA. The PARs ensure low hydrogen concentration control under the accident conditions, economical aspect, and passive safety improvement.

2. Strategy Implementation

One of the safety functions to prevent containment failure is to maintain pressure control because the combustible gas detonation mechanism can result in large pressure increases in a short period of time. Thus a strategy using the igniters is studied to cope with containment pressure spike in this paper. Figure 1 shows that containment rupture and leak cumulative probability versus the containment pressure. Another safety function is to maintain temperature control. A strategy to operate the containment spray system is considered to deal with containment temperature rise in this study. Reducing the hydrogen concentration in the containment during a severe accident will help mitigate a potential containment failure mechanism. In this paper, reducing containment hydrogen via an intentional hydrogen burn and recombiners strategy is used as an example strategy. Once the pressure and temperature spikes are over, however, there will be no more short-term challenges to the containment integrity.

The APR1400 hydrogen mitigation strategy consists of these two systems as shown in Table 1. Twenty-one (21) PARs replaced off-site thermal recombiner, which is the existing hydrogen management system. Although igniters are the fastest way of reducing the containment hydrogen concentration, ten (10) igniters are installed in the APR1400 to maintain local hydrogen concentration. The hydrogen burn may briefly cause pressure and temperature spikes, which are the adverse effect of the strategy. In the sample case, a 7100Pa pressure spike occurred locally as shown in Fig. 2. But this pressure increase will not challenge the containment thus we neglect the adverse effect via hydrogen burn in the results. The hydrogen control system in the reference plant is equipped with the odd and even power channels. If the hydrogen concentration exceeds 4% by volume or the exit coolant temperature exceeds 644K, the hydrogen control system is actuated passively. In order to burn the hydrogen in the containment, ten (10) glow type hydrogen igniters are installed. Since the hydrogen igniter operates instantly, it can control the higher hydrogen generation rate as compared to the PAR, which is more suitable for control of sustained, steady release of hydrogen from the primary loop.

Table 1. APR1400 hydrogen mitigation system

Compartment	PAR	Igniter	
S/G (broken)	2	2	Hydrogen source compartment
S/G (unbroken)	2	2	Hydrogen source compartment
Annular	6	2	IRWST vent location needs igniter
Containment dome	4	2	DBA combined
Pressurizer	2	1	Hydrogen source compartment
Heat exchange room	1	-	Hydrogen built up area
IRWST	2	-	Hydrogen source compartment
Reactor cavity	2	1	Hydrogen source compartment
Total	21	10	

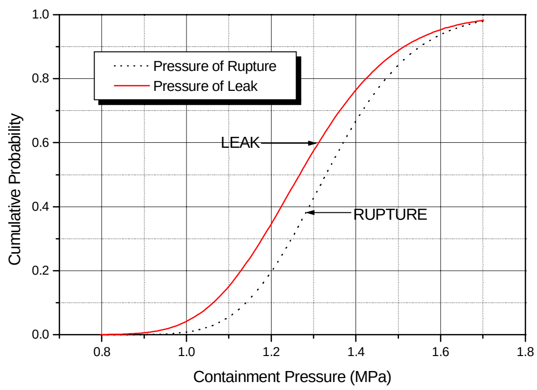

Fig. 1 Containment failure probability

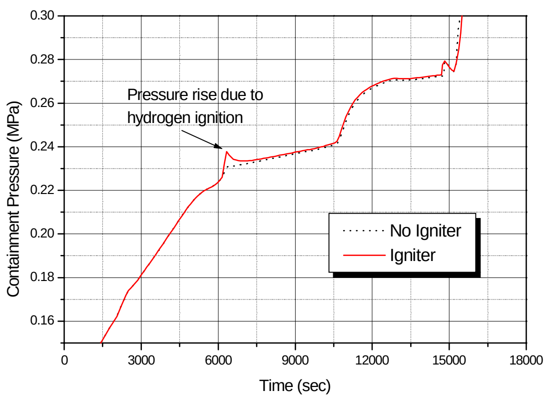

Fig. 2 Pressure rise due to hydrogen burn

3. Methodology

In this section we present a procedure to construct the decision tree for evaluating the hydrogen control. The criterion, which contains the cumulative hydrogen concentration, is used to assess the hydrogen control strategy feasibility. Hydrogen can diffuse to all the compartments and relatively high hydrogen mole fraction may be induced only locally. To analyze hydrogen behavior from a global point of view, however, we divided the containment into twelve compartments. The cold leg small-break LOCA with $0.00214m^2$ break area, which is one of the dominant accident sequences in the reference plant is selected as the example scenario. The reduced decision tree for the hydrogen control strategy is obtained and evaluated.

4. Decision Tree

The decision tree is a graphical and mathematical representation of a decision problem. It consists of two nodes and a branch. One of the nodes is the decision node and the other is the chance node. Each chance node has a probability and the flow of sequence leads to the final result. An advantage of the decision tree is the explicit representation of the decision structure, which directly shows the decision maker the value of each possible outcome, however, decision tree grows exponentially with problem size. An example decision tree for the hydrogen control follows. Since there are no top events exclusively relating to the hydrogen problem, we must first come up with a suitable event tree. Because the PAR is a passive system this turns out not to be a decision problem, but reducing the containment hydrogen via PAR is one of the hydrogen control and managements. It was thus supposed that the PAR operation is another decision node from the hydrogen management viewpoint. The sequences are divided into three groups. One group, which is concerned with the PARs only is presented in Fig. 3. Another group, which is concerned with igniters only is presented in Fig 4. The third group, which is combination of PARs and igniters is also presented in Fig. 5. The sequences of the three groups have different end point values, i.e. hydrogen concentrations. The important nodes in the reduced decision tree, which results in twenty-four (24) accident scenarios, involve the nodes of the safety injection system and containment spray system. In these figures the probability P1 and P1’ implies the feasibility of the hydrogen control strategies. P2 is the unavailability of the safety injection system and P3 is the unavailability of the containment spray system. Igniter decision is excluded in the PAR only decision tree because of the system unavailability or the adverse effect such as the pressure and temperature spike. The PAR decision is excluded in the igniter only decision tree because of performance degradation.

5. Criteria

When an accident takes place, the operator must determine whether the hydrogen control system should be operated or not. In an accident management strategy assessment measure, three items are contained as follows. S represents the accident scenario, P the probability of the accident development, and X the accumulated hydrogen concentration in the containment. For the example case 1, the S_1 scenario is determined from the decision tree, P_1 is its probability, and X_1 is the hydrogen concentration. Only if the hydrogen concentration is calculated from the accident scenario, the hydrogen concentration curve can be obtained. At first, the hydrogen concentration should be placed in increasing order. Corresponding to the cumulative probability, hydrogen concentration curve is obtained as follows.

$$X_1 \le X_2 \le X_3 \le \Lambda \le X_N \quad (1)$$

In this example, the S_1 accident scenario has the lowest hydrogen concentration and the S_N accident scenario has the highest hydrogen concentration. The accident scenario including the cumulative probability is shown in Table 2. The hydrogen concentrations calculated by MAAP4 [3] are arranged in the order of increasing hydrogen concentration and added up from the bottom. The final level 1 probabilistic safety assessment [4] results for APR1400 are utilized in quantifying the decision tree.

Table2. Accident Management Assessment Criteria

Scenario	Probability	Hydrogen Concentration (Vol.%)	Cumulative Probability
S_1	P_1	X_1	$CP_1=P_1+P_2+\cdots+P_N$
S_2	P_2	X_2	$CP_2=P_2+\cdots+P_N$
S_N	P_N	X_N	$CP_N=P_N$

6. Results

We examined the broken loop steam generator compartment where the hydrogen may be released directly. The cladding oxidation rate did not exceed 100% by volume in all the cases.

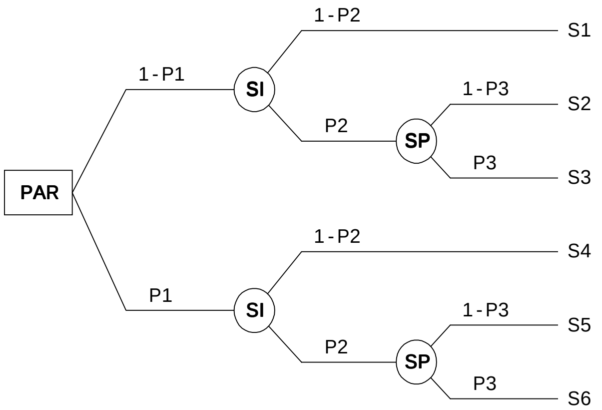

Fig. 3 PAR only case

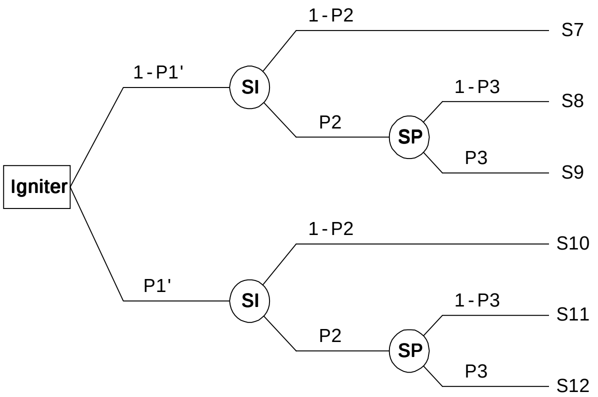

Fig. 4 Igniter only case

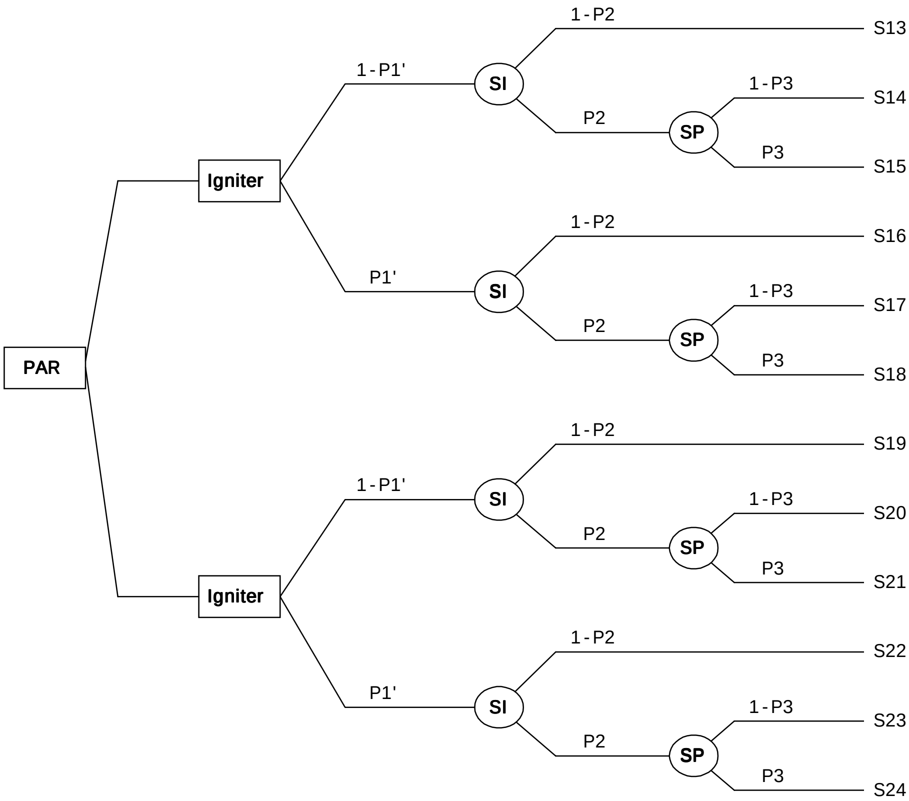

Fig. 5 PAR and igniter combination case

Figure 6 shows the mass of hydrogen, hich is generated in the core. After the core uncovery hydrogen generation is drastically accelerated by cladding oxidation during about 2000secs resulting in the oxidation rate of 45%. We considered the two decisions including the igniters and the PARs. Since the thermal glow plug igniters were effective in burning the gases as the mixtures became marginally flammable [5], the igniters may operate normally even if the containment spray comes in. The containment spray is not a direct hydrogen control system, but increases the relative mole fraction of hydrogen by condensing the steam as shown in Fig. 7. Thus the hydrogen concentration rises by about 1.5%. For the potential containment hydrogen concentrations expected following a severe accident PARs are not expected to last very long since they can overheat due to the exothermic hydrogen-oxygen reaction. Figure 8, on the other hand shows that the temperature increase is negligible due to the exothermal reaction. As shown in Fig. 9, when the igniters operate, the hydrogen mole fraction can be reduced by about 0.3%. But about 7000Pa pressure spike occurs in each case and this pressure increase is also negligible. Figure 10 shows the hydrogen concentration comparison for the two cases. One is the best case in which both the PARs and the igniters are operating. The worst case is that there is no hydrogen control system. Figure 11 shows the cumulative probability versus the hydrogen concentration. We selected three groups from the twenty-four (24) accident scenarios. Although the case of the PARs and the igniters combination has the low hydrogen concentration probability relative to the case of the PARs only, the difference is only minor. But the igniters only case has relatively high hydrogen concentration probability. The PARs will not work rapidly at the time of hydrogen generation, in which case the igniters can reduce the local hydrogen concentration. After the short-term challenge due to the local hydrogen burn is removed, the PARs will reduce the hydrogen continuously. From this result we can obtain the best case using the accident management assessment criteria.

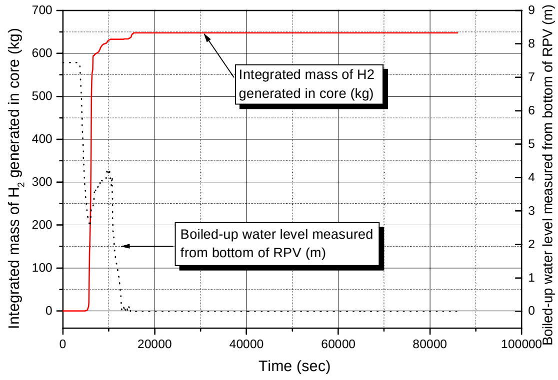

Fig. 6 H_2 generation in core and water level

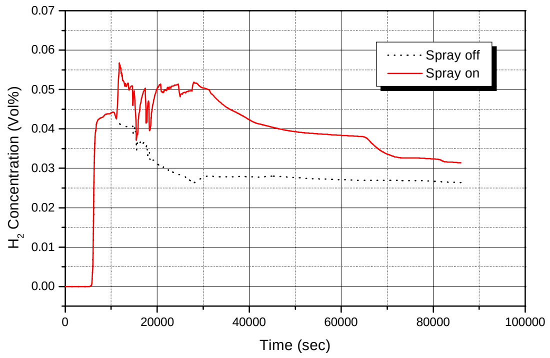

Fig. 7 H_2 concentration increase due to spray

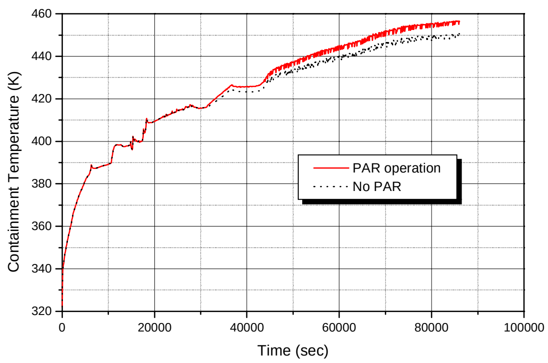

Fig. 8 Containment temperature increase due to PAR

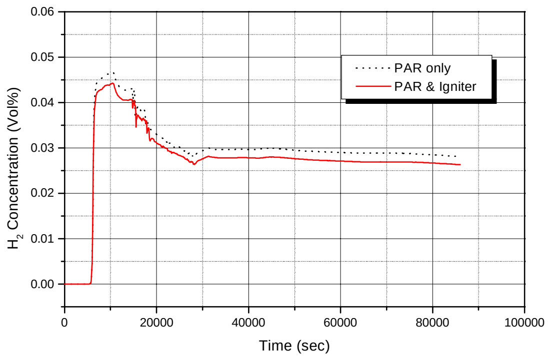

Fig. 9 H_2 concentration trend

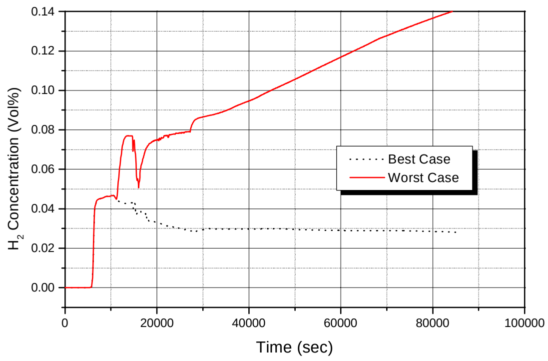

Fig. 10 H_2 concentration comparison

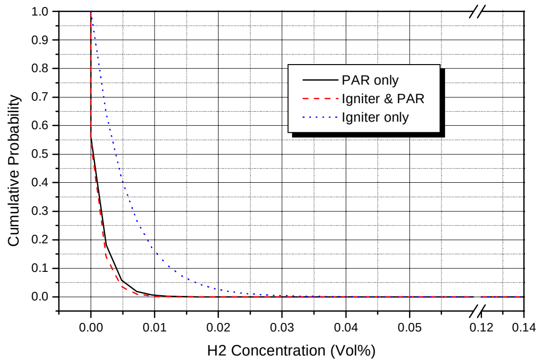

Fig. 11 Cumulative probability of H_2 concentration

7. Conclusion

In this paper, a framework as well as a new measure for evaluating the hydrogen control and management strategies was developed and applied to a small-break LOCA sequence. The UCN 3&4 is used as the reference plant for illustrating the feasibility of the proposed framework. The framework involves the development of the decision trees, data analysis, and the MAAP4 calculations. It is shown that the proposed framework with a new measure for assessing the hydrogen control is flexible enough to be applied to various accident management strategies.

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