Effect of water injection on hydrogen generation during severe accident in PWR

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Abstract Effect of water injection on hydrogen generation during severe accident in a 1000 MWe pressurized water reactor was studied. The analyses were carried out with different water injection rates at different core damage stages. The core can be quenched and accident progression can be terminated by water injection at the time before cohesive core debris is formed at lower core region. Hydrogen generation rate decreases with water injection into the core at the peak core temperature of 1700 K, because the core is quenched and reflooded quickly. The water injection at the peak core temperature of 1900 K, the hydrogen generation rate increases at low injection rates of the water, as the core is quenched slowly and the core remains in uncovered condition at high temperatures for a longer time than the situation of high injection rate. At peak core temperature of 2100–2300 K, the Hydrogen generation rate increases significantly after water injection into the core at peak core temperature of 2500 K because of the steam serving to the high temperature steam-starved core. Hydrogen generation of the molten pool at the lower core region. However, hydrogen generation can be seen in base case after formation of the molten pool at the lower core region. However, hydrogen is generated if water is injected into the molten pool, because steam serves to the crust supporting the molten pool. Reactor coolant system (RCS) depressurization by opening power operated relief valves has important effect on hydrogen generation. Special attention should be paid to hydrogen generation enhancement caused by RCS depressurization.

Key words Pressurized water reactor (PWR), Severe accident, Core damage state, Depressurization, Water injection, Hydrogen generation, Steam starvation

1 Introduction

In a severe accident in a pressurized water reactor (PWR), water is systematically injected into the core to remove the decay heat and cool the core. However, consequences of such an injection at various core damage stages is yet to fully understood, on possibility of in-vessel corium retention, kinetics of hydrogen generation, reactor coolant system re-pressurization, impact on fission products release, etc^[1]. Answers for these uncertainties are required for accident management in the existing PWRs, and for safety analysis in designing a novel PWR.

Hydrogen generation during the in-vessel phase of a PWR severe accident is mainly due to oxidation of zircaloy and other structural materials. In some core damage stages, hydrogen generation is constrained by steam insufficiency, hence the need of water injection into the steam-starved core to ease the situation with the water evaporation. Thermal stress generated by rapid cooling of the injected water, however, may cause cracking and fragmentation in the ZrO₂ layer. The loss of this protective layer may expose the underlying zircaloy to the high temperature steam, giving rise to increased rate of the hydrogen generation^[2,3], along with increased heat generation from oxidation. Thus, water injection at different core damage stages may affect local hydrogen concentration in containment and power level of the core, and may have an impact on the hydrogen

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management and effectiveness of core cooling strategy, consequently.

For developing and implementing core cooling strategy, and evaluating the negative impacts properly, the effect of water injection on hydrogen generation in a hypothesized severe accident in a 1000 MWe PWR was studied.

2 Plant description and analysis assumptions

The plant is a 1000 MWe 3-loop PWR with a large dry containment. Assumptions for the accident analysis are as follows.

Hydrogen generation during water injection is pertinent to core damage stage and water injection rate. Various accident sequences, such as station blackout, coolant loss, steam generator tube rupture, feed water loss, etc, will result in similar core degradation progression if proper core cooling measures were not taken. Water is injected into the reactor coolant system by the emergency core cooling system that includes the high pressure injection system, accumulator and low pressure injection system. Actual water injection rate using the emergency core cooling system is depended on pressure of the reactor coolant system if sufficient water is available. It is also assumed that the reactor is running at its full power when the accident initiates. Referring to the accident sequence selection in the research of water injection in five US nuclear power plant^[4], this scenario causes station blackout plus loss of auxiliary feed water, a failure that is commonly referred as TMLB'.

Hypothetically, the following events are to happen to the fuel elements:

- (a) Fuel rod cladding ballooning and rupture at 1100–1500 K;
- (b) Rapid zircaloy oxidation at 1500-2100 K;
- (c) The cladding breaks at eutectic point of 2470K;
- (d) The ZrO₂ protective layer failed at 2500 K;
- (e) Cohesive debris bed and molten pool growing at ~2800 K;
- (f) UO_2 melts at 3120 K.

3 Accident progression analysis (Base case)

The core degradation progression, in-vessel severe accident and H_2 generation was analyzed without any mitigation measures. But a comparison was made between the situations with and without water injection as a mitigation measure. The results are shown in Fig.1 for pressure of the reactor coolant system, water level of the reactor pressure vessel, core temperature and hydrogen generation rate.



Fig.1 Simulation results for a hypothetical PWR accident. (a) pressure of the reactor coolant system (RCS); (b) water level of the reactor pressure vessel (RPV); (c) H_2 generation rates and core temperatures.

As auxiliary feed water is not available in a TMLB' accident, the core decay heat cannot be removed by the secondary circulation, and the steam generators will dry out at about 3200 s. when pressure of the reactor coolant system begins to rise, ultimately challenging power operated relief valves of the pressurizer. The reactor coolant system is then having a pressure at which the power operated valves cycling open and close between its open and close set points, hence causing a coolant loss from the relief valves. The cladding temperature starts to rise sharply due to core uncovery at about 6400 s. Before the formation of debris bed at lower core region under much lower temperatures, rapid zircaloy oxidation occurs, with the generation of large amount of heat and hydrogen. Formation of cohesive debris bed and molten pool can be seen at about 8800 s, when zircaloy oxidation rate decreased due to a large reduction in surface area, with reduced heat and hydrogen generation rates. Eventually molten core slumps into the lower head of the pressure vessel, which is damaged due to high mechanical and thermal loads. The accident generates a total amount of 374 kg hydrogen. Most of the hydrogen is generated during the period from the core temperature reaching about 1500 K to molten pool formation at the lower core region.

4 Effect of water injection on hydrogen generation

Effect of the water injection on hydrogen generation was studied with water injections at the time when the core temperature reaches 1500, 1700, 1900, 2100, 2500, and 2800 K.

The reactor coolant system remains at a pressure when the power-operated relief valves are set somewhere in between their open and closet points, if depressurization measures are not taken. The condition corresponds to very low injection rate, as water can only be injected into the reactor coolant system by high pressure injection system. However, opening the relief valves is usually taken as depressurization measures of the reactor coolant system in high pressure sequences in PWR so as to^[5]: (1) avoid high pressure melt ejection and containment failure in early time caused by direct containment heating; (2) ensure water injection into the reactor coolant system by pumps at high flow rate to quench the high temperature core as quickly as possible; (3) ensure injection of water in accumulators into the reactor coolant system if available; (4) remove core decay heat by the reactor coolant system feed and bleed; and (5) reduce the mechanical loads imposed on lower head of the reactor pressure vessel.

Thus, the reactor coolant system depressurization by opening the relief valves is assumed.

There are three pumps for high pressure injection and three pumps for low pressure injection in this plant. Two pumps in each group can be used simultaneously, and we assume that the two high pressure pumps and two low pressure pumps work simultaneously to inject water into the core, corresponding to high injection rate; and that one high pressure pump and one low pressure pump are used to injected water into the core, corresponding to the lowest water injection rate.

The analysis results are shown in Fig.2. The accident progression can be terminated by water injection before the core temperature reaches 2500 K, which is designated as fuel cladding failure temperature. After failure of the fuel cladding, relocation of Zr-U-O eutectic mixture occurrs, with a gradual formation of the debris bed at the lower core region. Then the core cannot be cooled by injected water due to limited interface area between the debris and water. The hydrogen generation rate and other key parameters are summarized in Table 1. The hydrogen generation rate in base case was compared with those at the same core temperatures after the water injection. Special attention should pay to the time period when the hydrogen generation rate remains at high level, because the hydrogen concentration in the compartment of the pressurizer is decided by this time period if the power-operated relief valves are open.

At a high water injection rate, the core is quenched quickly and no noticeable hydrogen is generated; while at a low water injection rate, the core temperature increases at beginning of the water injection, with a peak core temperature of 2215 K. However, the hydrogen generation rate decreases as the core remains in uncovered condition at higher temperature for a short time.



Fig.2 Initiation of water injection at different core temperatures.

 Table 1
 Hydrogen generation rate and other key parameters

Initiation of	Accident		PCT after water H ₂ generation			
water injection	termination		injection/K		rate	
(Corresponding	Н	L	Н	L	Н	L
PCT/K)						
1500	yes	yes	1550	1607	_	_
1700	yes	yes	1770	2215	_	_
1900	yes	yes	2300	2310	_	+
2100	yes	yes	2268	2300	+	+
2300	yes	yes	2321	2403	+	+
2500	yes	yes	2724	2813	++	++
2800	no	no	3200	3200	+	+

Notes: PCT, peak core temperature; H denotes high water injection rate; L denotes low water injection rate; + denotes increased hydrogen generation rate; "++" denotes even more increased hydrogen generation rate; - denotes reduced hydrogen generation rate.

When water injection rate is high, hydrogen generation rate drops as the core is quenched and reflooded quickly. However, at low injection rates of the water, the hydrogen generation rate increases as the core is quenched slowly and remains in uncovered condition at high temperatures for a longer time.

The hydrogen generation rate increases with the steam volume, by the high temperature steam-starved core. The rates are nearly the same at any water injection rate, due to Zr oxidation constrained by available cladding without ZrO₂ protective layer. The situation was similar to what happens after water injection into the core at peak core temperature of 2100 K.

The hydrogen generation rate increases significantly with the steam volume serving to the relocating Zr-U-O mixture. The core can be quenched eventually, but molten pool formation can be seen at the lower core region. Increased hydrogen generation rate can be seen even before water injection into the core as steam flow rate through the core increases due to reactor coolant system depressurization by opening the power-operated relief valves.

The core cannot be cooled by injected water, because cooling of the core is constrained by the crust supporting the molten pool, which eventually slumps into the lower head of the reactor pressurized vessel, hence the hydrogen generation by the steam serving to the steam-starved crust. However, almost no hydrogen generation can be observed in base case after the molten pool formation at the lower core region. Before the water is injected into the core, hydrogen generation rate increases, too, for the same reason mentioned above.

Steam starvation conditions occur on fuel rod surfaces during the accident progression due to dry-out of the reactor core and blockage formation. Recent experiments at FZK^[6] revealed the formation of α -Zr(O) precipitates distributed quasi homogeneously inside the oxide layer and the development of metallic scale on the outer surface of the oxide layer. This resulted in thickness reduction of outside ZrO₂ protective layer and exposed more metallic Zr to steam with the water injection into the core, hence enhanced oxidation and hydrogen generation. Such a situation was not considered in this analysis. Thus, oxidation and hydrogen generation during core quenching was under-estimated to some extent.

5 Conclusion

Effect of water injection on hydrogen generation during TMLB' accident was analyzed in a 1000 MWe PWR, and the following conclusions could be drawn:

The core can be quenched and accident progression can be terminated by water injection at the time before the formation of cohesive core debris at lower core region.

Hydrogen generation rate decreases with water injection into the core at the peak core temperature of 1700 K, because the core is quenched and reflooded quickly. The water injection at the peak core temperature of 1900 K, the hydrogen generation rate increases at low injection rates of the water, as the core is guenched slowly and the core remains in uncovered condition at high temperatures for a longer time than the situation of high injection rate. At peak core temperature of 2100-2300 K, the Hydrogen generation rate increases by water injection because of the steam serving to the high temperature steam-starved core. Hydrogen generation rate increases significantly after water injection into the core at peak core temperature of 2500 K because of the steam serving to the relocating Zr-U-O mixture. Almost no hydrogen generation can be seen in base case after formation of the molten pool at the lower core region. However, hydrogen is generated if water is injected into the molten pool, because steam serves to the crust supporting the molten pool.

During high pressure severe accident sequences in PWR, reactor coolant system is usually depressurized by opening the power-operated relief valves. However, this is accompanied with increased hydrogen generation rate even without the water injection, with increased steam flow rate through the core due to the depressurization. Special attention should be paid to this hydrogen generation enhancement.

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