CONTAIN ANALYSIS OF HYDROGEN DISTRIBUTION AND COMBUSTION IN PWR DRY CONTAINMENTS

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ABSTRACT

Hydrogen transport and combustion in a PWR dry containment are analyzed using the CONTAIN code for a multi-compartment model of the Zion plant. The analysis includes consideration of both degraded core and full core meltdown accidents initiated by a small break LOCA. The importance of intercell flow mixing on distributions of gas composition and temperature in various compartments are evaluated. Thermal stratification and combustion behavior are discussed.

1. INTRODUCTION

The hydrogen combustion during a full core meltdown accident (i.e. combustion associated with an extensive corium/concrete interaction) has been identified as one of the important issues affecting the PWR dry containment performance¹. The U.S. NRC also identified hydrogen control for PWR dry containments as a high priority generic issue, G.I. 121. This issue will address hydrogen combustion problems such as the distribution of hydrogen in large volumes and the potential for local detonations.

This paper presents a CONTAIN² analysis of the hydrogen transport and combustion behavior in a PWR large dry containment. Although G.I. 121 was established for degraded core accidents, the analysis and discussions presented in this paper include both degraded core and full core meltdown cases. For the degraded core case, in-vessel hydrogen generation equivalent to oxidation of 75% active cladding is assumed. Ex-vessel hydrogen generation during corium/concrete interaction is added for the full core meltdown case.

2. ANALYSIS

An analytical evaluation of hydrogen distribution and combustion has been performed for the Zion plant using a 14-cell nodalization model. The nodalization includes the reactor vessel, 12 containment compartments and the environment. A description of the compartments including volume size, elevation, height, and number of structures is given in Table 1. The steam generator compartment is divided into two parts with one part (Compartment A) containing the pressurizer. The 12 containment compartments are connected by 22 flow paths. The connection of the flow paths and all flow path areas, lengths and loss coefficients are important parameters which determine the intercell flow rates

and in turn control the hydrogen distribution in the containment. CONTAIN also models water flow through sumps. Condensate and sprays are collected in the sump of each compartment. The overflow from the sump in each compartment is delivered eventually to the reactor cavity region, where the molten core debris (corium) is located.

The accident sequence analyzed was a small break LOCA with the assumption of a 3-inch (0.0762 M) break size in the hot leg. The MARCH code³ was used to provide the in-vessel hydrogen release rate for the full core meltdown case. MARCH predicted hydrogen generation equivalent to 44% active cladding oxidation. This in-vessel hydrogen release, a boundary condition for the CONTAIN analysis, was ratioed up to reflect 75% active cladding oxidation as required by G.I. 121. The ex-vessel hydrogen generation was computed by the CORCON model of the CONTAIN code. Although the in-vessel release was obtained for full core meltdown case, it will also be used for the degraded core case for the purpose of demonstrating the effect of 75% active cladding oxidation.

2.1 Hydrogen Transport

For a small break LOCA sequence, hydrogen is released from the reactor vessel through a break to the steam generator compartment (i.e., cell 4) for a time period of 46 minutes (from 966 to 3700 s) as predicted by the MARCH code. For a full core meltdown accident, the release of gases from the corium/concrete interaction into the cavity compartment (cell 1) started at about 5000 seconds. With these mass sources entering the containment atmosphere, the corresponding intercell flow through 22 flowpaths between the 12 compartments is illustrated in Figure 1. During the in-vessel release period, the buoyancy driven flow initiated in the source compartment (cell 4) causes a strong flow circulation in the containment. An upward flow is induced from Cell 4 to Cell 10 (central polar crane compartment) and Cells 12 and 13 (upper dome). The flow then moves downward from the upper dome to Cell 11 (annular polar crane compartment) and to the lower containment regions (Cells 8, 7, 6 and 5). The CONTAIN predicted mass flow rates are in the range of 400 to 700 kg/s for the upward flow and are less than 100 kg/s for the downward flows as revealed in Figure 1. During the ex-vessel release period, the hot gases released from the concrete in the cavity region initiates the upward flow motion. The flow rate in general is relatively small. However, CONTAIN predicted a strong flow circulation between the upper dome and the crane compartments after a large amount of CO is generated from the corium/concrete interaction. The intercell flow promotes hydrogen mixing and increases the uniformity of gas composition among the various containment cells. Figure 2 illustrates the hydrogen and steam fractions in all containment cells. It is seen that, after the termination of in-vessel release at about 3700 seconds, hydrogen fractions in all cells, except Cells 1 and 2 where the intercell flow is relatively slow, vary by about 1% only. This variation is further diminished during the ex-vessel release period. At about 11,500 seconds, i.e., about 100 minutes after the initiation of corium/concrete interaction, the containment atmosphere achieved, practically, a uniform composition. Figure 2 also indicates that the containment is steam-inerted. In all cells, the steam and hydrogen concentrations are about 65% and 4.5%, respectively, after a stable condition is established. Hence, no hydrogen burn was predicted by the CONTAIN code due to steam-inerting.

Containment temperatures shown in Figure 3 illustrate that the generation of hot gases in Cell 1 (cavity compartment) causes a thermally unstable situation

in the compartment. This unstable temperature distribution would help to promote intercell flow mixing and reduce variations in gas composition.

An analysis was also performed for the small break LOCA sequence in which the core is partially degraded and no reactor vessel breach was assumed. The CONTAIN predicted intercell flows, temperatures, and gas concentrations in all containment compartments are shown in Figures 4, 5, and 6, respectively. Comparisons with the above discussed full core meltdown case reveal several interesting points:

1. The hot gases released from the corium/concrete interactions in the cavity region (Cell 1) apparently serves as an effective driving force to enhance intercell flow mixing. Without this driving force, the intercell flows predicted for the degraded core case are nearly diminished in the regions below the central and annular polar crane compartments (Cells 10 and 11) immediately after the termination of the in-vessel release at about 3700 seconds. Intercell flows are predicted only between the polar crane compartment and the upper dome.
2. Without a strong intercell flow mixing in the containment, CONTAIN predicted a thermally stratified atmosphere for the degraded core case. Figure 5 shows that, after the termination of the in-vessel release, temperatures in the upper dome and the polar crane compartments are above 500K while temperatures in the central and lower compartments are below 450K. This thermally stable temperature distribution was not predicted for the full core meltdown case.
3. The high temperature predicted for the full core meltdown case tend to maintain a high steam concentration in the atmosphere. (The release of steam from the ablated concrete also contributes to the high steam content.) Hence, the atmosphere is inerted and no hydrogen burn was predicted. For the degraded core case, the lack of release of hot gases from the cavity results in a continuous decrease of atmosphere temperature and a gradual steam condensation. Eventually, the steam concentration is reduced to the level that the atmosphere is de-inerted as shown in Figure 6. After the atmosphere is de-inerted, CONTAIN predicted four hydrogen burns at about 15,000 seconds.
4. The thermally stratified atmosphere predicted for the degraded core case also exhibits a large variation of hydrogen concentration in the containment. At 25,000 seconds (2 hours and 40 minutes after the hydrogen burn), the hydrogen concentration is about 5% in the central and lower regions of the containment, in which the temperature is relatively low and the steam content is below 50%. In the upper regions of the containment, in which the temperature is high and the steam content is about 65%, the hydrogen concentration is reduced to 3.5%.

This comparison of the degraded core and full core meltdown accidents indicates the importance of the driven forces for the intercell flows, the interdependence of hydrogen and steam concentrations, and their effects on the potential hydrogen combustion.

2.2 Hydrogen Combustion

Hydrogen combustion analyses in a multi-compartment containment were performed with the CONTAIN code for full core meltdown sequence discussed in Section 2.1. The CONTAIN default combustion model was used in the analysis. It is noted that the CONTAIN combustion model is based on experimental data determined in steam-saturated air at relatively low temperatures and pressures. The lean ignition limit (7% of the combustible gases) used in the analysis is subject to uncertainty. Since the containment is steam-inerted, containment sprays were actuated to induce hydrogen burns. The refueling water storage tank served as the water source. Failure of recirculation was assumed to occur when the refueling water storage tank became depleted. This prevents further spray operation.

Two analyses were performed: early sprays and late sprays. For the case of early containment sprays, the spray duration was from 250 seconds to 3235 seconds. The sprays were terminated at about 8 minutes prior to reactor vessel breach. The analysis predicted eight hydrogen burns during a time period of 6.5 minutes as given in Figure 7. Four burns occurred in the source compartment (Cell 4) during the period when a large quantity of hydrogen was released from the break area. Another four burns occurred in the upper region of the containment (Cells 10-13) as a result of intercell flow. A total of 246 Kg of hydrogen was reacted, mostly in the source compartment as shown in Figure 7. Containment spray operation resulted in the collection of water in the reactor cavity region, where the corium is located. The corium/water interaction produced steam which re-inerted the atmosphere once the sprays were terminated.

For the sequence with late containment sprays, it was assumed that the sprays were actuated at about 10,000 seconds, i.e., 105 minutes after the reactor vessel breach. The accumulation of a large quantity of hydrogen in the containment resulted in 41 burns over a period of 30 minutes as given in Figure 8. The burn pattern appears different than the other case. Hydrogen burns occurred repetitively in the cavity region (Cell 1) and the flame propagated upward repetitively to the nozzle compartment (Cell 2). In many burns, the amount of hydrogen reacted was on the order of 1 Kg, and for some burns only 0.1 Kg of hydrogen was reacted. In these cases the oxygen is depleted after each burn. Among the 41 hydrogen burns, only a few burns occurred in the upper region of the containment. In these regions the atmosphere is rich in oxygen and the few burns involved a larger quantity of hydrogen. The largest burn occurred early in the upper dome (Cell 13) and consumed 313 Kg of hydrogen.

The four hydrogen burns predicted for the degraded core sequence were caused by the natural condensation of steam. (No sprays were applied.) The burn was initiated in Cell 6 at about three hours after the termination of the in-vessel release. Within about 50 seconds, the flame was propagated upward to Cells 5, 8, and 4. The quantity of hydrogen consumed in these four cells are 25, 37, 21, and 7 Kg, respectively. At the time of hydrogen burn, the oxygen and steam concentrations in these compartments are approximately 11% and 40%, respectively.

Based on these multi-cell CONTAIN analyses, it can be concluded that the intercell flow distribution and local steam condensation rate have a significant influence on the local gas fractions in each compartment. When the ignition and propagation criteria are met, repetitive burns can occur in many compartments.

2.3 Maximum Hydrogen Concentration

In the above hydrogen combustion analysis, it was assumed that ignition sources are available when hydrogen concentration is increased to the lean ignition limit. However, there are situations in which the ignition sources may be initially unavailable and, hence, a large quantity of hydrogen can be accumulated in the containment. The hydrogen concentration may reach the detonable range when the ignition sources are recovered later during an accident. Such a potential for local detonation was investigated by CONTAIN analysis. In the analysis, the hydrogen concentration was increased through forced steam condensation by containment sprays. The CONTAIN burn model was not activated in order to simulate the situation in which igniters were not available. This assumption maximizes the hydrogen concentration that can exist in the containment.

For the full core meltdown case, the containment sprays were initiated late during the accident (i.e. 10,000 seconds) when a large quantity of hydrogen has accumulated in the containment. The sprays were terminated in 50 minutes when the refueling water storage tank is depleted. The results show that activation of containment sprays for 50 minutes reduced the steam concentration in all containment compartments from about 70% to 10%. With the removal of steam, the atmosphere is hydrogen and oxygen rich. The maximum hydrogen concentrations shown in Table 2 are above 11% for all compartments. These concentrations are near the detonable level as given in the National Research Council Report⁴. The hydrogen concentration would have increased further if the containment spray operation had been extended over a longer time period.

For the degraded core case, the containment sprays were initiated at 250 seconds and were terminated in 50 minutes. The time period of spray operation coincides with the time period of in-vessel release. The predicted maximum hydrogen concentrations are slightly above 8% for all compartments except the source compartment (Cell 4) as given in Table 2. Based on these results, it appears that a local detonation is unlikely during the degraded core accident analyzed.

3. Summary

CONTAIN analyses for the Zion plant using a multi-compartment model for full core meltdown accidents initiated by a small break LOCA show that the containment atmosphere is steam-inerted and there is a variation of hydrogen concentrations initially among its various containment compartments. The containment was predicted to achieve virtually a uniform hydrogen distribution due to the intercell flow mixing at about two hours after the termination of hydrogen release from the reactor vessel. The hot gases released during corium/concrete interaction in the cavity region serves as a driving force to promote the intercell flow mixing. With steam removal by containment sprays and the assumption of no deflagration, the peak hydrogen fraction in many compartments could be above 11% which is near the detonability limit.

Combustion analyses for the full core meltdown case indicate that steam removal by sprays could result in repetitive hydrogen burns in many compartment. The burns are characterized by the reaction of a small quantity of hydrogen during each burn. This localized and limited deflagration appears to have no significant impact on containment loading.

CONTAIN predicted different intercell flow mixing for a degraded core accident in which the core debris was assumed to be retained in the reactor vessel. With no corium/concrete interaction to release hot gases into the containment, the intercell flow mixing is noticeably diminished due to the lack of a driving force. Hence, CONTAIN predicted a thermally stratified atmosphere in the containment. The upper region of the containment possesses a high temperature atmosphere and a large steam content. The atmosphere is predicted to be inert. In the central and lower regions of the containment, the atmosphere is at a relatively lower temperature which permits steam condensation, and hydrogen burns were predicted.

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Figure 1 Intercell flows for the full core meltdown sequence

Figure 2 Hydrogen and steam fractions for the full core meltdown sequence

Figure 4 Intercell flows for the degraded core sequence

Figure 3 Containment temperatures for the full core meltdown sequence

Figure 5 Containment temperatures for the degraded core sequence

Figure 6 Hydrogen and steam fractions for the degraded core sequence

Figure 7 Hydrogen burned for the full core meltdown sequence with early containment sprays

Figure 8 Hydrogen burned for the full core meltdown sequence with late containment sprays

Table 1 Zion 14 Cell Compartment Description

Cell#	Description	Volume (m ³)	Elevation(m)	Height(m)	No. of Structures
1	Reactor Cavity & instr. tunnel	260.75	4.038	8.07	6
2	Neutron detector & nozzle comp.	103.87	12.71	6.7	4
3	Primary vessel & system	---	13.88	---	---
4	Steam generator, comp A	3324.6	14.790	14.93	20
5	Steam generator, comp B	3297.4	14.79	14.93	16
6	Blowdown compartment	2034.2	11.58	14.93	14
7	Comp. between piping volumes	901.76	11.58	6.17	11
8	Unit cooler comp.	3456	18.7	8.23	9
9	Refueling room	1148.6	18.7	7.71	6
10	Central polar crane comp.	15424.5	35.6	20.26	8
11	Annular polar crane comp.	12345	35.6	20.26	3
12	Upper dome, comp A	16696	56.33	39.83	4
13	Upper dome, comp B	16696	56.33	39.83	4
14	Environment	---	---	---	---

Elevations are referenced to cavity floor level and correspond to the cell centers.

Table 2 Summary of Maximum Hydrogen Concentrations
for the Small Break LOCA Sequence

Cell	Case A		Case B	
	Time, s	Max. H ₂ , %	Time, s	Max. H ₂ , %
1	9800	8.2	12651	13
2	23900	8.2	12651	12
4	2285	10.3	13011	11
5	7400	8.7	13011	12
6	7200	8.6	13011	11
7	10800	8.8	13011	11
8	9800	8.7	13011	12
9	24500	8.2	12651	11
10	3210	8.2	13011	12
11	3210	8.4	13011	12
12	3210	8.5	12961	12
13	3210	8.3	12961	12

Case A: 1. Degraded core accident.
2. In all cells except Cell 4: O₂, % = 14~15, steam, % = 20~26.
3. Cell 4 (source cell): O₂, % = 10, steam, % = 40.

Case B: 1. Full core meltdown accident.
2. All cells: O₂, % = 12~15, steam, % = 12~20.

Oxygen and steam concentrations correspond to time at which the maximum hydrogen concentration occurs.