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A study on hydrogen burn due to the operation of containment spray system

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ABSTRACT: The bounding calculation for inflammable gas combustion due to the steam condensation by the operation of the containment spray system was performed. Sensitivity study was performed for two initiating events, i.e. station blackout and loss of coolant accident. The parameters for sensitivity study are the condition of cavity, i.e., wet or dry, and the timing of operation of the containment spray system. It is shown, based on MAAP4 analyses, that: (1) for dry cavity, auto-ignition burn and hydrogen laden jet burn due to the high temperature in the reactor cavity consumes large amount of burnable gas in the containment and reduces the peak pressure at the global burn by flammability criteria (2) for wet cavity, large amount of hydrogen and carbon monoxide are generated after dryout of the reactor cavity, but burn is prohibited due to the low gas temperature in the reactor cavity and the high concentration of the steam. The late operation of the containment spray system condenses the steam rapidly, which results in the global burn at high concentration of burnable gas in the containment. The containment peak pressure from this burn is determined to be high enough to threaten the containment integrity significantly.

1. INTRODUCTION

The purpose of this study is (1)to calculate the peak pressure from the inflammable gas combustion due to the steam condensation by the operation of containment spray in the PWR large dry containment building, and (2)to predict the type of inflammable gas combustion which may depend on the reactor cavity condition, wet or dry. The possibility of hydrogen (including carbon monoxide) burn depends on the gas temperature, the mole fraction of steam or hydrogen in each compartment of the containment building. The source of steam would be water inventory in the reactor coolant system, water supplied by emergency core cooling systems (ECCSs) including safety injection tanks (SITs), and cavity flooding system which injects water into the reactor cavity directly.

Hydrogen is generated from zircaloy oxidation in the reactor core and from molten corium-concrete interaction in the reactor cavity or at the containment floor. Because this study places a focus on the late hydrogen burn due to the steam condensation by the operation of containment spray system, the sensitivity study for in-vessel hydrogen generation was not performed. Instead, the sensitivity study for the timing of containment spray system operation has been performed. The timing of containment spray system operation affect the amount of gases generated from molten core-concrete interaction, the type of gas combustion and the subsequent containment peak pressure.

Chemical reactions between concrete off-gas and core debris are important because they provide a source of combustible gases (hydrogen and carbon monoxide). A chemical equilibrium model is used for reactions. While equilibrium allows all reactions to proceed in parallel, the equilibrium constants of some important oxidation reactions lead to nearly serial oxidation of the major metallic pool constituents. Followings are the major reactions. Reactions with zircaloy and steam or carbon dioxide which oxidize the metal, proceed nearly to completion:

(1) $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$

(2) $Zr + 2CO_2 \rightarrow ZrO_2 + C$

If free carbon is produced, it will react with steam or carbon dioxide after the zircaloy depletion and become carbon monoxide.

(3) $C + H_2O \rightarrow 2CO + H_2$

(4) $C + CO_2 \rightarrow 2CO$

2 ANALYSIS METHOD

Station blackout and loss of coolant accident (3 inch diameter equivalent) were selected as initiating events. It is assumed that the ECCSs except SITs are not available. The availability of SITs determines the condition of reactor cavity. If the inventory of four SITs injected into the reactor cavity via reactor vessel, then the reactor cavity became wet (flooded). Otherwise, it became dry. The inventory of SITs eventually vaporizes into containment atmosphere and increases steam mole fraction. Cases to be analyzed are as following:

1) station blackout without SITs (Case1)
2) station blackout with SITs (Case2)
3) loss of coolant accident without SITs (Case3)
4) loss of coolant accident with SITs (Case4).

The timing of containment spray system operation was varied for each case to find out its effect on the peak containment pressure.

The severe accident analysis program MAAP4 (Electric Power Research Institute 1994) was used to simulate the entire accident progression including hydrogen burn. Two general types of combustion processes are important in the severe accident analysis, deflagration and detonation. Deflagration is defined as a combustion process for which the combustion front moves at subsonic velocity with respect to the unburned gas, while detonation process is defined as sonic or supersonic propagation of the combustion front. Detonation is not considered in this analysis.

MAAP4 has three types of burn model, i.e. auto-ignition burn, hydrogen laden jet burn and burn by a flammability criterion. All of these were considered in this analysis. A complete hydrogen burn will occur in a region if the gas temperature exceeds auto-ignition temperature, regardless of the hydrogen concentration in the region (auto-ignition burn). Temperature of 983 K was assigned to the onset of auto-ignition (Fauske and Associates, Incorporated 1991). If hot and hydrogen-rich gases are transported into cool and oxygen-rich regions, hydrogen laden jet burn is possible without an ignition source for gas temperature of 1060 K or greater (Fauske and Associates, Incorporated 1991) (hydrogen laden jet burn). Finally hydrogen burn is modeled by the flammability criteria for a given compartment. A flammability criteria is defined as a function of composition of gas mixture at a given temperature and pressure.

There are uncertainties in the estimation of gas combustion and gas distribution. There exist no data for the flammability criteria for which two or more inertants are mixed (i.e., steam plus carbon dioxide) and for which more than one combustible

Table 1 Data of reference plant

Description	Value
Reactor power	2815 MWth
Containment volume	$7.73*10^4$ m^3
Cavity volume	251 m^3
Cavity area	62.5 m^2
Total water mass of safety injection tanks	$2.07*10^5$ kg
Total water mass of reactor coolant system	$2.12*10^5$ kg

Table 2 Concrete composition

Concrete Species	Value ($^w/o$)	Concrete Species	Value ($^w/o$)
SiO_2	35.8	$MgO+MnO+TiO_2$	0.69
CaO	31.3	Fe_2O_3	1.44
Al_2O_3	3.6	Cr_2O_3	1.014
K_2O	1.22	H_2O	4.7
Na_2O	0.082	CO_2	21.15

gases are mixed (i.e., hydrogen and carbon monoxide). Arbitrary averaging methods are adopted to determine flammability criteria for these cases. Another limitation is nodalization of the containment building. Containment is divided into five compartments in this analysis. This small number of nodalization can not predict local high concentration of hydrogen precisely, but it is sufficient to catch up the general behavior of hydrogen burn.

The maximum containment peak pressure due to the global gas combustion resulted from sudden steam condensation was predicted in this analysis. The major assumption employed in this analysis is that once any compartment has reached to condition of burn by flammability criteria, the remaining combustible gas would burn completely, which is intended for a bounding calculation. To maximize in-core hydrogen generation, the core blockage model was not used.

The reference plant was a 2815 MWth PWR with large dry containment and plant data are summarized in Table 1. The composition of concrete in the reactor cavity was assumed to be typical limestone/common sand concrete (Cole, Kelly and Ellis 1984) and its composition is shown in Table 2.

3. RESULTS AND DISCUSSIONS

The calculation results are summarized in table 3.

Case1 (station blackout without SITs): Reactor vessel failed at 5 hours after the initiation of accident. In-vessel oxidation reached 67.8% of cladding equivalent and corresponding hydrogen mass generated was 562 kg. Since the cavity was dry, the molten corium interacted with basemat concrete and generated combustible gases. The gas temperature in the reactor cavity increases as time goes on and reached to an auto-ignition temperature about 5 hours after the reactor vessel failure. If the containment spray system operates at more than 5 hours after reactor vessel failure (sequence# SB3-SB9 in table 3), large amount of combustible gases are generated by the molten corium concrete interactions but peak containment pressure due to the global burn by flammability criteria is not high enough to threaten the integrity of containment because auto-ignition and hydrogen laden jet burn occurred in the reactor cavity and in the lower compartment prior to global burn by flammability criteria and consumed a lot of combustible gases.

Case2 (station blackout with SITs): Since the inventory of SITs would be injected after reactor vessel failure, the accident progression up to the reactor vessel failure

Table 3 MAAP calculation results

Case	Sequ_ ence#	Vessel failure time (hr)	Spray start time (hr)(*)	Generated hydrogen mass (kg)			Auto burn mass (kg) (**)	Jet burn mass (kg) (**)	Burn by flammability criteria (kg)(**)		Peak pressure at burn time(**) (MPa)	Clad oxid- ation (%)
				in core	in cavity	total			time (hr)	mass (kg)		
SBO Dry cavity	SB-1	5	0	562	44	606	0	0	5.64	626	0.363	67.8
	SB-2		3	562	179	741	0	0	8.75	741	0.417	
	SB-3		5	562	290	852	49	64	10.47	840	0.525	
	SB-4		6	562	454	1015	92	102	11.56	843	0.556	
	SB-5		7	562	540	1101	151	156	12.70	807	0.532	
	SB-6		9	562	667	1228	253	290	19.82	705	0.462	
	SB-7		10	562	723	1285	292	348	N/A	0	N/A	
	SB-8		12	562	823	1385	349	464	N/A	0	N/A	
	SB-9		18	562	1080	1641	420	543	N/A	0	N/A	
SBO Wet cavity	SB-10	5	0	562	44	606	0	0	5.64	626	0.363	67.8
	SB-11		3	562	85.3	647	0	0	9.18	667	0.390	
	SB-12		6	562	85.3	647	0	0	14.05	668	0.387	
	SB-13		12	562	85.3	647	0	0	20.86	652	0.389	
	SB-14		18	562	125	687	0	0	27.15	693	0.409	
	SB-15		24	562	535	1097	0	0	31.32	1096	0.696	
	SB-16		30	562	744	1305	0	0	36.98	1301	1.027	
	SB-17		36	562	930	1491	0	0	43.28	1261	1.160	
	SB-18		42	562	1089	1650	0	0	49.61	1145	1.206	
	SB-19		48	562	1229	1791	0	0	55.96	1067	1.231	
LOCA Dry cavity	LO-1	3.19	0	258	191	449	0	0	N/A	0	N/A	31.2
	LO-2		3	258	225	483	0	0	N/A	0	N/A	
	LO-3		5	258	381	639	0	0	8.87	677	0.407	
	LO-4		6	258	476	734	0	0	9.80	793	0.502	
	LO-5		9	258	735	993	165	158	16.75	691	0.506	
	LO-6		10	258	803	1061	214	220	19.29	649	0.481	
	LO-7		12	258	929	1187	270	355	N/A	0	N/A	
	LO-8		18	258	1234	1492	299	463	N/A	0	N/A	
LOCA Wet cavity	LO-9	13.5	6	545	100	645	0	0	22.96	709	0.414	65.8
	LO-10		12	545	130	675	0	0	29.38	738	0.427	
	LO-11		18	545	513	1058	0	0	33.96	1120	0.663	
	LO-12		24	545	758	1303	0	0	39.59	1364	0.980	
	LO-13		30	545	957	1502	0	0	45.84	1341	1.147	
	LO-14		36	545	1139	1684	0	0	52.14	1202	1.201	
	LO-15		42	545	1293	1838	0	0	58.47	1109	1.233	
	LO-16		48	545	1442	1988	0	0	64.80	1043	1.252	

(*) The time interval between reactor vessel failure and spray injection start.

(**)This table does not show burned mass of CO, however the containment peak pressure was calculated based on burned mass of H2 and CO.

(cladding oxidation, hydrogen generation, reactor vessel failure time) be same as Case1. After the reactor vessel failed, the inventory of SITs injected into the reactor cavity via the reactor vessel. The combustible gases will be generated as the molten corium interacts with basemat concrete. In MAAP code, the molten corium-concrete interaction does not occur as long as the water exists in the reactor cavity. Since it takes about 15 hours to dryout the water in the reactor cavity, the concrete-off gases are generated from about 20 hours after the initiation of accident (SB15-SB19). No auto ignition burn occurred in the reactor cavity due to relatively low gas temperature. (sequence# SB10-SB19). The later the timing of the containment spray system operation, the higher the containment peak pressure because more combustible gases are generated from molten core-concrete interactions and neither auto ignition nor jet burn occurred (SB10-SB19). This bounding calculation shows that the later operation of the containment spray system(24 hours after RV failure, SB15-SB19) could threaten the containment integrity seriously.

Case3 (loss of coolant accident without SITs) : Reactor vessel failed at 3.2 hours after the initiation of accident. In-vessel oxidation reached 31.2 % of cladding equivalent and corresponding hydrogen mass generated was 258 kg. Since the reactor cavity was dry, the gas temperature increased to an auto-ignition temperature. For cases that the containment spray system operated at 9 hours or more after reactor vessel failure (sequence# LO5-LO8), auto-ignition and hydrogen laden jet burn occurred in the reactor cavity and in the lower compartment. If the containment spray system operated at 12 hours after the reactor vessel failure (LO7-LO8), the global burn by flammability criteria does not occur because a large amount of hydrogen is consumed by auto- ignition and hydrogen laden jet burn.

Case4 (loss of coolant accident with SITs) : Cycled injection of water into the reactor vessel from SITs prevented the reactor vessel failure for a while. Reactor vessel failed at 13.5 hours after the initiation of accident. This late failure of reactor vessel results in high oxidation of cladding (65.8%) and more hydrogen generation (545 kg) in the reactor vessel. The significant corium concrete interaction occurs about 15 hours after reactor vessel failure. No auto-ignition burn occurs in the cavity due to relatively low gas temperature (sequence# LO9-LO16). The later the timing of containment spray system operation, the higher the peak containment pressure, because much combustible gas was generated from the molten core-concrete interaction but no combustible gases were consumed from auto-ignition burn or and jet burn. As shown in Table 3, the late operation of containment spray system (24 hours after reactor vessel failure, LO12-LO16) could threaten the containment integrity significantly.

4 CONCLUSIONS

Based on MAAP4 analyses, it is observed that the amount of ex-vessel gas generation and the behavior of combustion be dependent on the cavity condition. For dry cavity, even though a large amount of hydrogen and carbon monoxide are generated in the reactor cavity, auto-ignition burn and hydrogen laden jet burn due to the high temperature in the reactor cavity prevents the accumulation of burnable gas in the containment and reduces the peak pressure at the global burn by flammability criteria. For wet cavity, a large amount of hydrogen and carbon monoxide are generated in the reactor cavity after dryout of the reactor cavity, but auto-ignition burn is prohibited due to the low gas temperature and the high concentration of the steam. The late operation of the containment spray system condenses the steam and increases the concentration of burnable gas rapidly, which results in the global burn at high concentration of burnable gases in the containment. The containment peak pressure from this burn is determined to be high enough to threaten the containment integrity significantly.

It is recommended that if the core is damaged and no continuous supply of water into the reactor vessel is provided, then the valves at SITs should be closed before reactor vessel failure, in the aspects of hydrogen burn, to reduce the possibility of the containment failure. If it has failed to close valves at SITs before reactor vessel failure, the containment spray system should not be operated to reduce the containment pressure. The operation of spray system may result in the rupture of containment building due to the hydrogen burn.

REFERENCES

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