Optimization Study for Hydrogen Control during Severe Accidents in KSNPP

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1. Introduction

During a postulated hypothetical severe accident, hydrogen control measures have been important design issues for the Korean Standard Nuclear Power Plant (KSNPP) to safeguard the containment against the potential threat of hydrogen explosion.

Continued studies of the hydrogen behavior and its control have been performed using MAAP [1], CONTAIN [2] and GOTHIC [3] codes for the five representative accident scenarios. The previous results showed that the local concentration as well as the global one could be well maintained below the limit of 10v/o by adopting the hydrogen control measure into the KSNPP.

The purpose of this study is to establish the analytical bases and locating criteria for optimizing the number of hydrogen control devices considering the previous results. Firstly, we did the base case runs with and without control mechanisms and then tried to minimize the number of hydrogen control devices by locating it only in the limited areas of hydrogen release points. Secondly, adverse effects of limited hydrogen control in specific areas on the other areas where there are no hydrogen control were evaluated to determine whether additional hydrogen control devices are required or not. The late recovery action for spray system expected in view of accident management was also considered during evaluation process. Finally, localization effects through elevation or horizontal distance were evaluated by 3-D GOTHIC code for the relatively restricted area in containment especially for the containment annular region or steam generator compartment which has large vertical height.

The study results gave us the very important insight that when using the optimization approach to minimize the number of hydrogen control devices, adverse effects of the controlled area on the non-controlled area with respect to the late spray recovery should be considered carefully. However, at the same time, it was also proved that with the limited number of hydrogen control devices in the hydrogen release areas excluding the large open spaces above the operating floor, the hydrogen concentration could be effectively controlled within the limit of licensing target of 10 v/o in the KSNPP.

2. Selection of Accident Scenarios

From the knowledge of PSA results and their contribution to hydrogen generation, five accident scenarios such as SBO, LBLOCA, MBLOCA, SBLOCA and TLOFW were selected since these scenarios are typical ones and have relatively high contribution to containment failure modes as well as significant hydrogen release.

3. Description of Analysis Case

MAAP 4.0 was used for system model, hydrogen generation and release estimates before the vessel breach for all cases in this study. The ex-vessel hydrogen generation by molten core concrete interaction (MCCI) was modeled by CONTAIN code. Base case runs for five candidate scenarios were analyzed by CONTAIN code without hydrogen control and containment spray. In addition, separate or combined cases between hydrogen burn and spray model were run by CONTAIN code with varying spray actuation time. Figure 1 shows the physical containment nodal model that was used in CONTAIN analysis. Cases for SBO and SBLOCA were analyzed by using the detailed 3-D model of GOTHIC code to understand the localization effects of hydrogen and to determine the proper locations of hydrogen control devices. These two cases were selected because of its specific location or showing high differences in hydrogen concentration between areas based on results of base case runs. The 3-D cell model applied to containment annulus is shown in figure 2. The analysis results for these cases are described in summary in the following section.

4. Hydrogen Control and its Local Effects

4.1 CONTAIN Analysis

A. BASE CASE RUNS WITHOUT OR WITH HYDROGEN CONTROL

The analysis results are summarized in table 1. The average concentration over the five candidate scenarios without hydrogen control is 6.82v/o and the average differential concentration between compartments is 1.97v/o except for the reactor cavity, which represents the inherently good mixing capability of the KSNPP with large containment free volume. However, certain accident scenarios like SBLOCA and LBLOCA showed high local concentrations specifically in reactor drain tank room, which are very close to the limit hydrogen concentration of 10v/o. For these cases the differential concentrations were more than 3v/o for which it could be judged as uncontrolled local hydrogen behavior. So, further consideration of the active hydrogen control was needed.

On the other hand, the analysis results in table 1 with hydrogen control in all compartments performed for the three accident scenarios, SBO, MBLOCA and TLOFW showed well controlled hydrogen behavior with average concentration below 6 v/o for each case and the maximum differential concentrations lower than 1v/o. The SBO case had the highest concentrations in both the average and differential.

Through the base case runs above, we became to know that the KSNPP might have some vulnerable regions to hydrogen threat. These include the reactor cavity and the reactor drain tank room, and the containment annulus region was revealed as a relatively weak area in view of hydrogen localization.

B. EFFECTIVENESS OF LOCAL HYDROGEN CONTROL

For the SBO and LBLOCA which are the typical cases for hydrogen release to containment annulus region and steam generator compartment, local hydrogen burn analyses were made to evaluate the capability of limited hydrogen control by using the hydrogen burn model in the hydrogen release compartments including the reactor cavity, reactor drain tank room and the steam generator compartment as noted in table 2.

The resulting average concentrations for SBO and LBLOCA are 6.2v/o and 5.2v/o, respectively. The SBO case with limited hydrogen burn model resulted in lower average concentration than that of the base case without burn model, and slightly higher concentration compared to the same case with all cell burn model in table 1. Also, the maximum differential concentrations between cells for both cases were about 1.5v/o which is smaller than those of the corresponding base cases without burn model but larger than those with all cell burn model.

In general, the limited local hydrogen control can be estimated as adequate for both global and local hydrogen control and as good approach to minimize the number of hydrogen control devices. However in other aspects, it also addresses that with limited hydrogen control itself there could be localization problems occurred because of a considerable possibility of exceeding the design target value of 7v/o depending on the conditions of gas mixture and ESF system operation, which means loss of the active hydrogen control in reality even though the analysis results show the local concentrations for all cells, which are below the limit of licensing target value of 10v/o.

C. EFFECTS OF LATE SPRAY RECOVERY ON LOCAL HYDROGEN CONTROL

Figures 3 and 4 show the hydrogen transient behavior for LBLOCA and SBLOCA cases with limited local hydrogen control and the late spray operation. For these cases, it was assumed that the MCCI terminated at 33,000 seconds and 41,000 seconds respectively, which are the equivalent times to the 100% Zr oxidation of 820Kg hydrogen generation for each case. When the spray system was recovered at each of these times, rapid increase of local concentration occurred in the annulus region and the reactor drain tank room where no hydrogen control devices were located because of sudden steam condensing by cold spray initiation as seen in the above figures. The highest peak hydrogen concentration for LBLOCA reached 9.5v/o in the reactor drain tank room followed by the next of 9.0v/o in the annulus region. For SBLOCA case, it was 9.4v/o in the annulus region, which are 3.9v/o higher than the average concentration of 5.5v/o for this accident case. The maximum differential local concentration between the cells was more than 6.0v/o.

Through this case runs it was found out that we need to consider the consequential effects of hydrogen localization due to rapid steam condensation by late spray recovery in the relatively restricted areas where there are no hydrogen control devices.

4.2 GOTHIC Analysis

For the detailed understanding of the hydrogen behavior inside containment and finally to get knowledge about the proper locations for hydrogen control devices, the 3-D GOTHIC code was used. Case runs were made for the SBO and SBLOCA accident scenarios. Figure 5 shows the GOTHIC result for the horizontal distribution of hydrogen concentration of the containment annulus region for the SBO sequence, and figure 6 shows the flow pattern for the same region.

Through GOTHIC results we became to know that a strong circulating flow path is generating from the bottom of the hydrogen release point to the top of the annulus region during the short period after reactor drain tank rupture for the SBO or the vessel failure for SBLOCA. According to the results, relatively high localization, which is more than 5v/o in hydrogen concentration along the horizontal distance or the vertical height in the same region, was happened. The localization trend was such that the vertical peak occurred at the mid-top of the total length, but horizontally it was occurred where the strong flow path was developed.

5. Guideline for Hydrogen Control

From the analysis results done by CONTAIN and GOTHIC in this study, we could establish the following interim guidelines for area selection criteria for hydrogen control and locating criteria of hydrogen control devices.

<u>**SELECTION CRITERIA FOR HYDROGEN CONTROL**</u>

a. Large open areas above the operation floor need not be controlled.
b. Any compartments that belong to the direct hydrogen release points need to be locally controlled.
c. Any compartments that exceed 10v/o hydrogen concentration need to be locally controlled regardless the inert effects by high steam concentration.
d. Specific areas that are suspicious to have more than 3v/o higher local differential concentration compared to the average one need to be analyzed in details to determine whether or not the additional hydrogen control is required.

<u>**LOCATING CRITERIA OF HYDROGEN CONTROL DEVICES**</u>

a. Upper side of the flow junction between a neighborhood compartment and hydrogen release compartment where these compartments are horizontally aligned.
b. About 10 feet below the top elevation of a compartment which is upwardly neighbored with relatively large free volume.
c. Vicinity of the geometric center of cross-sections of horizontal and vertical flow paths.
d. Every 15 to 20 feet for vertical direction and every 40 to 50 feet for horizontal direction in region which constitutes a sufficiently large and long flow channel, but every 20 to 30 feet for the specific horizontal region that is blocked in horizontal direction.

e. Locating the hydrogen control device not to be overlapped on the same vertical axis to allow efficient upward hydrogen burn if more than two hydrogen control devices are required.
f. Other specific area needed by engineering judgement
g. Consideration of accessibility for Inspection and maintenance and equipment survivability of safe related components nearby hydrogen control devices.

6. Conclusion

The analysis results showed that the KSNPP is generally well designed for the mixing of hydrogen in nature. In addition, it addressed the possibility of localization problems under certain conditions when the local hydrogen control is to be applied for the limited locations of release points.

When considering the analysis results and insights gathered through this study, we can hopefully conclude that the KSNPP has sufficient capability to withstand hydrogen threats during severe accident with the limited hydrogen control in areas below the operating floor by following the guidelines established through this study.

However, since the limited local hydrogen control could result in adverse effects of rapid increase in the other regions, further detailed study which is specific to the accident scenarios, containment geometry or the operating procedure related to the mitigation system might be necessary before the final application of this approach to real design.

References

1. R.E.Henry, et al., "MAAP4.0 - Modular Accident Analysis Program for LWR Power Plants," Computer Code Manual, Fauske & Associates, Inc., May. (1994)
2. K.K.Murata et al., "User's manual for CONTAIN 1.1 : A Computer Code for Severe Nuclear Reactor Accident Containment Analysis," NUREG/CR-5026, SAND87-2309, Sandia National Laboratory, Nov. (1989)
3. Thomas L. George et al., "CONTAINMENT ANALYSIS PACKAGE USER MANUAL FOR GOTHIC V5.0," NAI 8907-02, Numerical Applications, Inc., (1995)

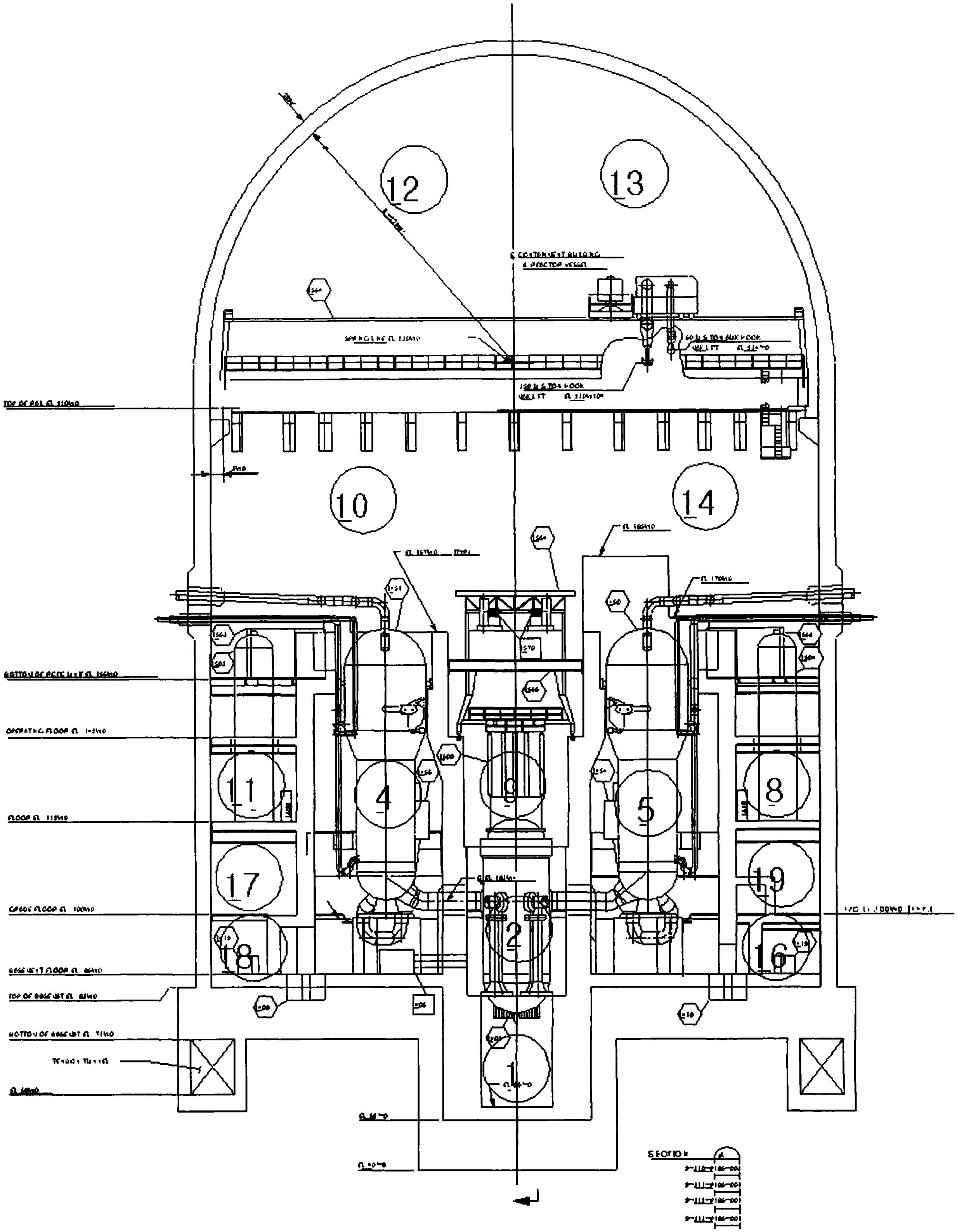
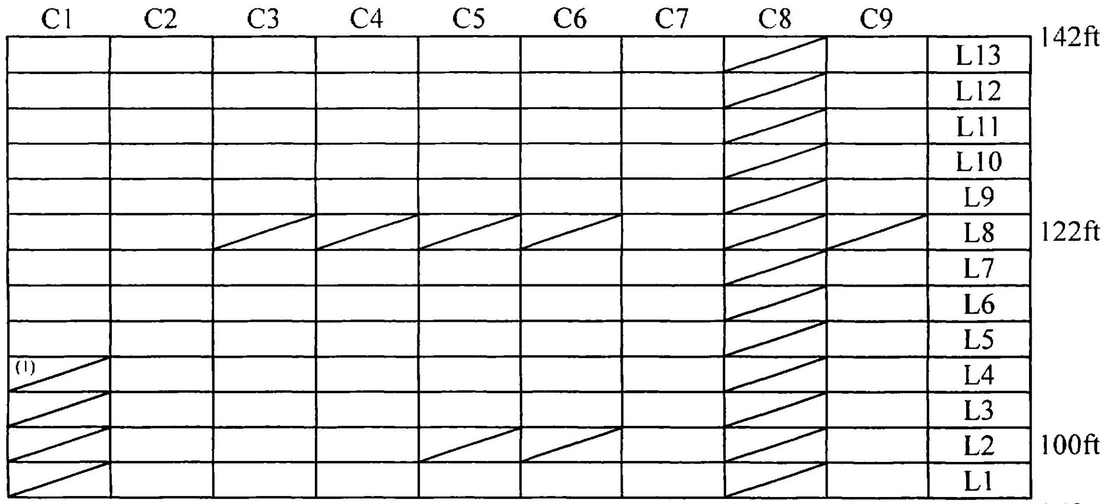


Figure 1. Containment Node Model for KSNPP

90° 108° 127° 147° 162° 180° 199° 223° 235° 255°

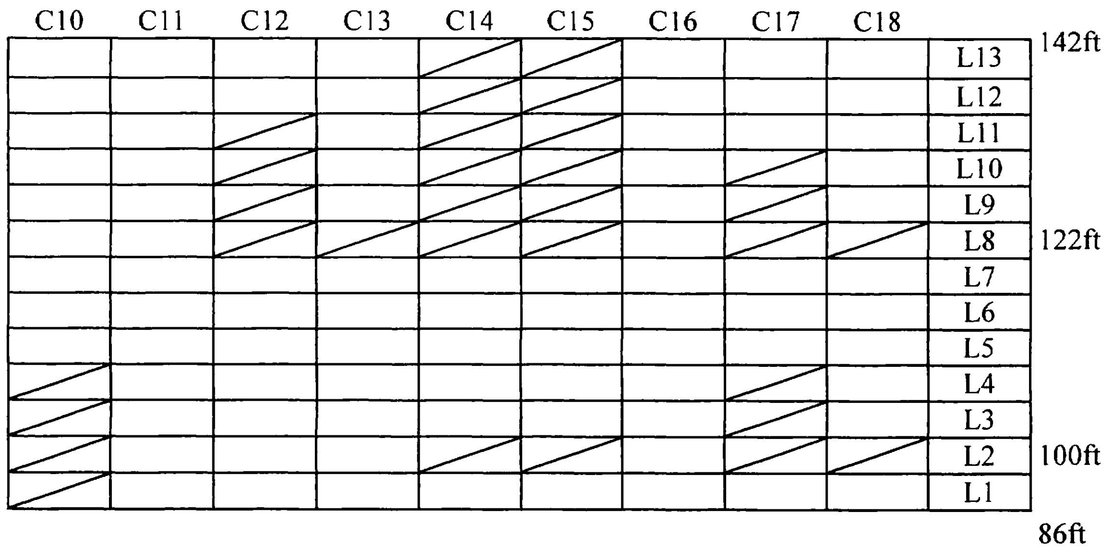
C1	C2	C3	C4	C5	C6	C7	C8	C9	Outside Annulus
C10	C11	C12	C13	C14	C15	C16	C17	C18	Inside Annulus

Top View of Containment Annulus Region



note : 1. Diagonal means null cell

Elevation View of Containment Annulus Region-Outside (C1 – C9)



Elevation View of Containment Annulus Region-Inside (C10 – C18)

Figure 2. Containment Annulus Node Model for GOTHIC Analysis

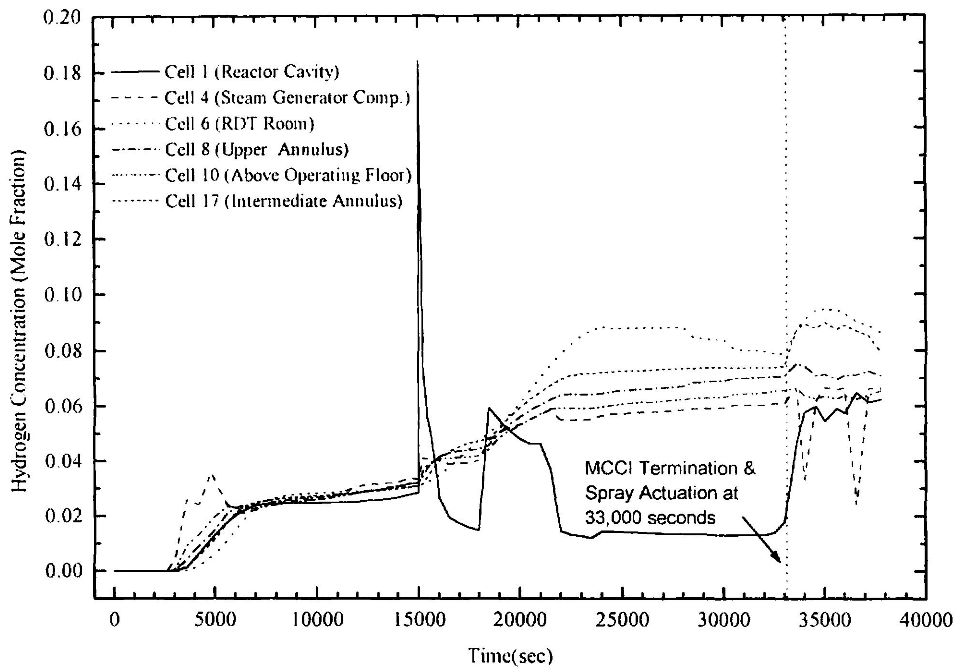


Figure 3. CONTAIN Calculation for KSNPP Large Break LOCA Hydrogen Burn (1,4,5,6 Cells), 100% MWR, Late Spray Operation

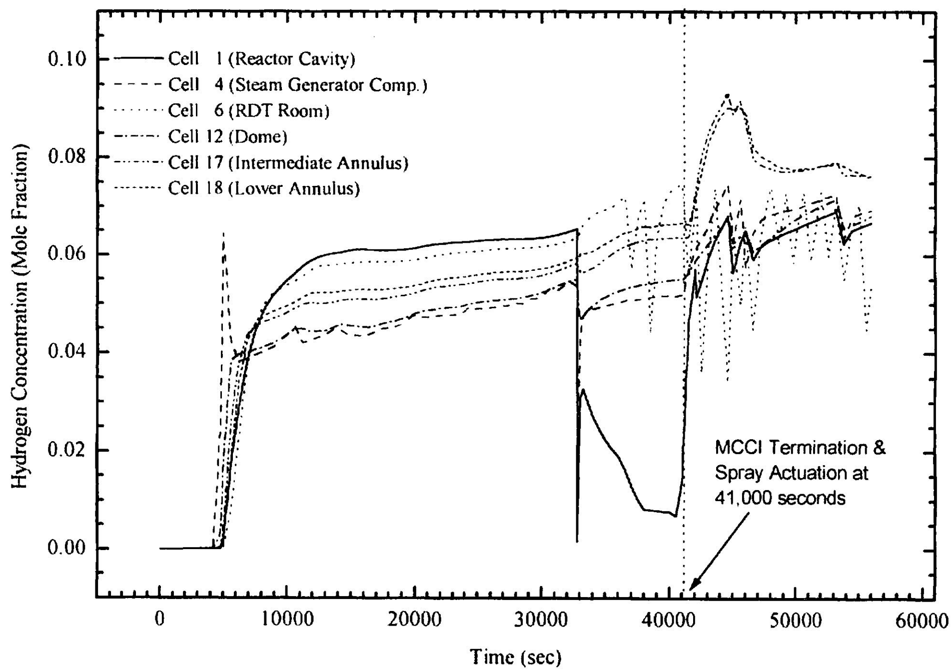


Figure 4. CONTAIN Calculation For KSNPP Small Break LOCA Hydrogen Burn (1,4,5,6 Cells), 100%MWR, Late Spray Operation

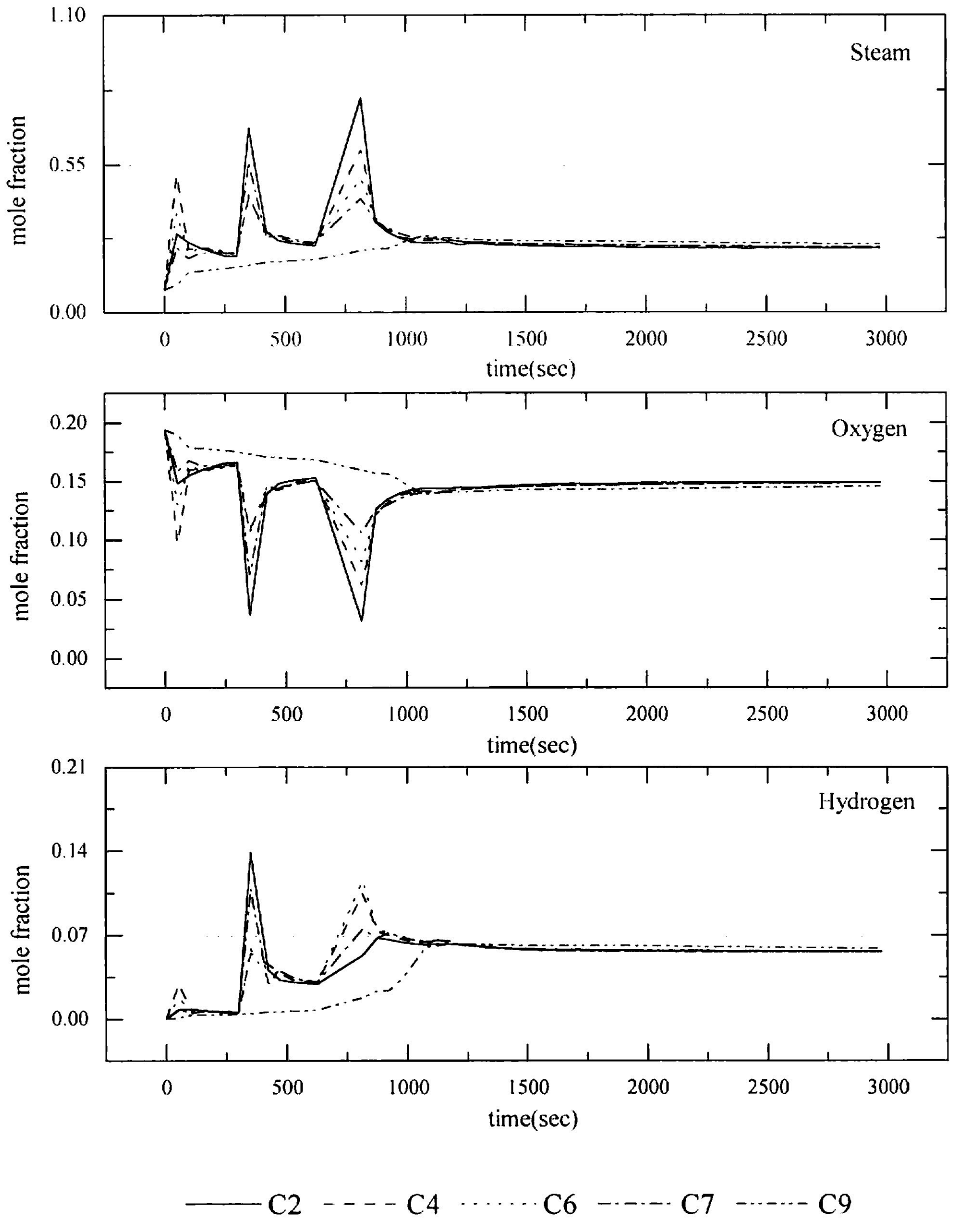
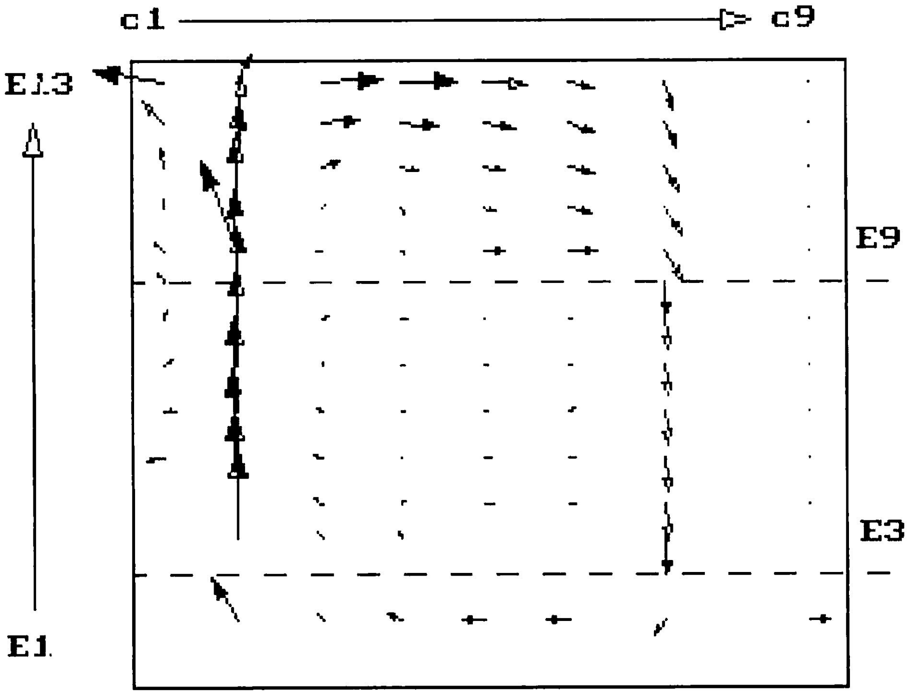


Figure 5. Distribution of steam, oxygen and hydrogen of the annulus for SBO



Vmax = 4.47952 (m/s)
Scaling Power = 1
Time = 814.009
/ Volume : Channels : Levels /
/ 2 : 1-9 : 1-13 /

E1 : 86 - 100FT
E2 : 100FT FLOOR
E3 - E7 : 100 - 122FT
E8 : 122FT FLOOR
E9 - 13 : 122 - 142FT

Figure 6 . Flow Pattern, SBO, Annulus

Table 1 Results of CONTAIN Analysis (Average and Local Hydrogen Concentration)

unit : %

Representative Compartment			Base Case						H2 Burn Case		
									All Cell Burn		
No.	Location	Volume weight[1]	SBO	MBLOCA	LBLOCA	SBLOCA	TLOFW	Cell Average [2]	SBO	MBLOCA	TLOFW
12	Dome	0.280	<u>6.25</u>	7.23	6.19	6.40	7.67	6.90	5.54	4.07	3.53
10	Above Operating Floor	0.458	6.25	7.23	6.20	6.40	7.67	6.90	5.54	4.07	3.53
11	Upper Annulus	0.046	6.78	7.56	6.70	6.73	7.71	7.19	5.58	4.25	3.58
17	Intermediate Annulus	0.052	7.48	7.69	7.33	7.21	7.85	7.56	6.22	4.31	3.57
18	Lower Annulus	0.033	7.73	7.74	7.71	7.82	7.97	7.83	6.26	4.34	3.57
6	RDT Room	0.001	<u>8.71</u>	<u>7.84</u>	<u>9.33</u>	<u>9.94</u>	<u>8.09</u>	<u>8.71</u>	6.21	4.41	3.60
4	Steam Generator Comp.	0.086	6.57	<u>6.72</u>	<u>5.83</u>	<u>6.37</u>	<u>7.50</u>	<u>6.76</u>	5.45	3.93	3.53
1	Reactor Cavity	0.045	3.70	2.71	1.38	4.62	5.19	3.90	3.25	2.37	4.83
Average H2 Concentration			6.29	7.05	6.09	6.43	7.57	6.84	5.50	4.02	3.60
Max. Diff. H2 Concen. between Compartments.[3]			2.58	1.12	3.50	3.57	0.59	1.95	0.81	0.48	0.07
Max. Diff. H2 Concen. between upper and lower Comp.[4]			1.54	0.51	1.52	1.42	0.30	0.93	0.72	0.27	0.04
Scenario Frequency per Reactor Year			1.181×10^{-6}	8.473×10^{-7}	1.126×10^{-6}	1.245×10^{-6}	2.451×10^{-6}	-	-	-	-

<u>note</u>
1. Volume weighting value used for average H2 concentration
2. Accident frequency used for the average H2 concentration
3. Reactor cavity is excluded for the maximum differential concentrations
4. Maximum differential H2 concentration along the elevation

Table 2 Results of CONTAIN Analysis (Average and Local Hydrogen Concentration)

unit : %

Representative Compartment			H2 Burn Case	
			Local Cell Burn[1]	
No.	Location	Volume weight	SBO	LBLOCA
12	Dome	0.280	6.17	5.10
10	Above Operating Floor	0.458	6.17	5.11
11	Upper Annulus	0.046	6.68	5.18
17	Intermediate Annulus	0.052	7.25	5.37
18	Lower Annulus	0.033	7.51	5.62
6	RDT Room	0.001	5.28	6.47
4	Steam Generator Comp.	0.086	6.40	5.08
1	Reactor Cavity	0.045	3.73	6.47
Average H2 Concentration			6.20	5.20
Max. Diff. H2 Concen. Between Compartments			1.34	1.39
Max. Diff. H2 Concen. Between upper and lower Comp.			1.34	0.52

note 1. Local Cell Burn means that hydrogen burning modeled in the cell 1, 6, 20 for SBO and in the cell 1, 3, 4, 5, 6, 20 for LBLOCA