# Severe Accident Analysis for Combustible Gas Risk Evaluation inside CFVS

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## 1. Introduction

Under severe accidents, the containment integrity can be challenged due to over-pressurization by steam and combustible gas generation. Containment filtered venting system (CFVS) has been considered as an effective approach to maintain the containment integrity from over-pressurization. Basic idea is to relieve the pressure inside of the containment by establishing a flow path to the external environment through filtration system. In order to ensure the safety of the public and environment, the ventilation system should be designed properly by considering discharged gas flow rate, aerosol loads, radiation level, etc.

One of considerations to be resolved is the risk due to combustible gas, especially hydrogen. Hydrogen can be generated largely by oxidation of cladding and decomposition of concrete. If the hydrogen concentration is high enough and other conditions like oxygen and steam concentration is met, the hydrogen can burn, deflagrate or detonate, which result in the damage the structural components. In particularly, after Fukushima accident, the hydrogen risk has been emphasized as an important contributor threatening the integrity of nuclear power plant during the severe accident.

The purpose of this study is to identify the composition of gases discharged into the containment filtered venting system by analyzing severe accidents. The accident scenarios which could be significant with respect to containment pressurization and hydrogen generation are derived and composition of containment atmosphere and possible discharged gas mixtures are estimated. These results will be used to analyze the risk of hydrogen combustion inside the CFVS as boundary conditions. Severe accident simulation results are presented and discussed qualitatively with respect to hydrogen combustion.

## 2. Plant Modeling and Severe Accident Simulation

### *2.1 Plant Modeling*

OPR1000, which is a 1000MWe PWR nuclear reactor designed by KHNP and KEPCO in Korea is selected to be modeled. It has a containment with $2\times10^6$ $ft^3$ free volume, 393 kPa(g) design pressure [1]. MAAP5 is used to numerically model the plant [2]. CFVS is simply modeled as a flow path connecting the annular compartment of the containment and the environment and Passive Autocatalytic Recombiner (PAR) is included.

### *2.2 Major Severe Accident Scenarios*

In order to consider the differences due to different initiating events and accident progression, several initiating events and operation of safety system are considered as shown in **Table I** [3]. Three initiating events are considered as LLOCA (Large break Loss of Coolant Accident), SLOCA (Small break Loss of Coolant Accident) and SBO (Station Black-Out Accident) to reflect the variations due to pressure in reactor coolant system while the core degraded. Basically, it is assumed that the engineered safety features except the safety injection tank are not available to emulate the Fukushima-type accidents. However, in order to consider the possibility of safety injection, the emergency external water injection by using fire engine is considered. According to safety injection available timing, the scenarios are divided into RVI, RVF and NE. RVI represents reactor vessel is intact due to timely safety injection. It is assumed that the safety injection would be available since 1 hour after entering the severe accident condition. The injection would be initiated and paused to maintain the reactor vessel water level. RVF represents safety injection is available since 1 hour after reactor vessel fails. The injection would be initiated and paused to maintain the cavity water level. NE represents no injection conducted. Note that the shutoff head of fire engine pump for external injection is assumed as 8 bar(a) in RCS. The analysis of vent flow characteristics has been conducted with varying the vent initiating pressure [bar(a)]: 5, 7 and 9.

**Table I:** Severe Accident Candidate Sequences

| RCS Pressure Type | Safety Injection Timing | | |
|---|---|---|---|
| | **Timely Injection** | **Delayed Injection** | **No Injection** |
| **Early Release** | LLOCA-RVI | LLOCA-RVF | LLOCA-NE |
| **Continuous Release** | SLOCA- RVI | SLOCA-RVF | SLOCA--NE |
| **Late Release** | N/A | SBO- RVF | SBO-NE |

[*] LLOCA: Large break Loss of Coolant Accident
[*] SLOCA: Small break Loss of Coolant Accident
[*] SBO: Station Black-Out Accident

* RVI: Reactor Vessel Intact (after entering severe accident condition (core exit temperature > 1200F), safety injection initiated)
* RVF: Reactor Vessel Failed (after reactor vessel breached, safety injection initiated)
* NE: No Injection

### 3. Numerical Results

The containment pressure increases due to continuous generation of steam and gases mainly by decay heat and molten core-concrete interaction. Main event timing is summarized in **Table II**. The containment pressure is shown in **Figure 1~Figure 3**.

The containment pressure would decrease instantly right after the vent initiation. If the vent is paused when the containment pressure reaches 1.5 bar(a), the containment pressure would increase again. The vent would be re-initiated if the vent initiation pressure is set at low pressure or the containment is pressurized slowly during the simulation time (100 hours after accident initiation). In this study, the eight cases out of twenty four cases show the second venting.

It can be seen that the vent initiation pressure is set to higher, the vent initiation timing would be delayed. This is important because as the venting is delayed, the aerosol in containment atmosphere would be reduced by natural removal mechanisms and the oxygen would be depleted due to operation of PAR. Especially, the oxygen concentration is important because the hydrogen combustion would require sufficient oxygen.

The characteristics of discharge flow at the timing of the first vent initiation and the second vent initiation are summarized in **Table III** and **Table IV**, respectively. Compared to the first venting, the flow for the second venting would contain higher portion of steam. This implies that the evaporation of water would be the major contributor of containment pressurization. Note that the nitrogen initially in containment atmosphere would be released during the first venting and little generated. Therefore, the nitrogen portion would be decreased in the second venting. Thus, in the second venting, the composition of steam and hydrogen would be increased. This could be adverse in hydrogen risk management. When the venting is firstly initiated, the condition in CFVS would be atmospheric. Therefore, most of the steam would be condensed in the CFVS tank. If the concentrations of hydrogen and oxygen are high enough, the combustion would occur. It is important to note that the risk of the hydrogen combustion would be the highest at the moment of the first venting.

It is expected that the hydrogen concentration in the containment atmosphere would decrease due to PAR operation. This would also reduce the oxygen concentration. Until the oxygen in the containment is depleted, PAR would not be operated and the hydrogen concentration would be increased. Compared to the first venting, the oxygen concentration in the discharged flow for the second venting is significantly decreased while the hydrogen concentration would be increased. This implies that the oxygen is depleted in the containment and hydrogen generated by molten core concrete interaction is accumulated. Though the hydrogen concentration is high, the risk of hydrogen combustion would be low due to lack of oxygen. This condition can be expected to occur inside of the CFVS. Therefore, it can be expected that, if there is no supply of the oxygen outside of the CFVS, the hydrogen in the CFVS would be difficult to be combusted.

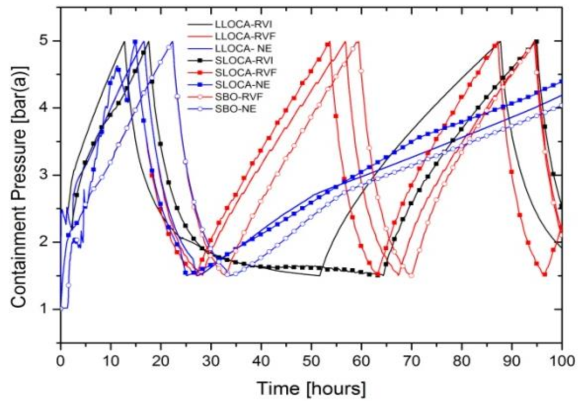


**Figure 1.** Containment pressure with Venting at 5 bar(a)

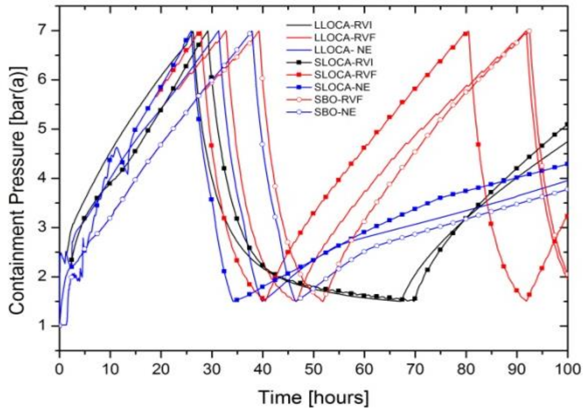


**Figure 2.** Containment pressure with Venting at 7 bar(a)

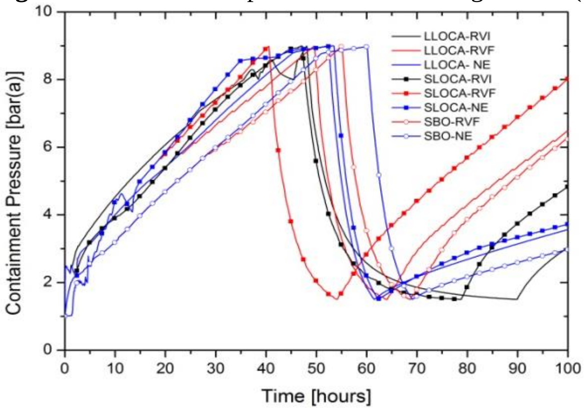


**Figure 3.** Containment pressure with Venting at 9 bar(a)

**Table II:** Main Event Occurrence Timing

| (seconds) | LLOCA-RVI | LLOCA-RVF | LLOCA-NE | SLOCA-RVI | SLOCA-RVF | SLOCA-NE | SBO-RVF | SBO-NE |
|---|---|---|---|---|---|---|---|---|
| **Reactor Scram** | 0.51 | 0.51 | 0.51 | 171.50 | 171.50 | 171.50 | 0.00 | 0.00 |
| **Accumulator Water Depleted** | 92.23 | 92.23 | 92.23 | 37801.14 | 37672.59 | 37672.59 | 16824.02 | 16824.02 |
| **Core Uncovery** | 2.60 | 2.60 | 2.60 | 3117.81 | 3117.81 | 3117.61 | 7678.91 | 7678.91 |
| **CET > 1200F** | 1272.56 | 1272.56 | 1272.56 | 3991.18 | 3991.18 | 3991.18 | 9040.58 | 9040.58 |
| **CET > 2499K** | 1853.71 | 1853.71 | 1853.71 | 4995.23 | 4995.23 | 4995.23 | 11091.09 | 11091.09 |
| **Relocation of Core Materials to Lower Head** | 3952.45 | 3952.45 | 3952.45 | - | 19277.71 | 19462.61 | 14316.38 | 14316.38 |
| **Safety Injection Start (Set Point)** | 4872.69 | 12262.30 | - | 39002.88 | 52075.65 | - | 20012.63 | - |
| **Safety Injection Start (Actual)** | 4907.11 | 69769.48 | - | 39133.64 | 61297.73 | - | 90730.83 | - |
| **Reactor Vessel Failed** | - | 8657.56 | 8657.56 | - | 48474.71 | 48474.71 | 16408.76 | 16408.76 |

**Table III:** Discharge Flow Characteristic at First Venting

| Accident Sequence | Vent Initiating Pressure [bar(a)] | Time [seconds] | Discharge Flow Rate [kg/s] | Concentration [%] | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $H_2$ | $O_2$ | Steam | CO | $CO_2$ | $N_2$ |
| **LLOCA-NE** | 5 | 60307.3 | 14.84 | 0.2146 | 3.9635 | 67.7553 | 0.9373 | 0.0029 | 27.1265 |
| | 7 | 113107.3 | 20.31 | 0.1961 | 1.6566 | 76.5851 | 1.0223 | 0.1208 | 20.4190 |
| | 9 | 189307.3 | 25.52 | 0.1041 | 1.6675 | 81.3422 | 0.6069 | 0.1685 | 16.1109 |
| **LLOCA-RVF** | 5 | 60307.3 | 14.84 | 0.2146 | 3.9635 | 67.7553 | 0.9373 | 0.0029 | 27.1265 |
| | 7 | 118519.4 | 20.07 | 0.1790 | 1.5510 | 76.7634 | 1.0159 | 0.1916 | 20.2991 |
| | 9 | 60307.3 | 25.55 | 0.0948 | 1.1182 | 81.1668 | 0.8022 | 0.7894 | 16.0287 |
| **LLOCA-RVI** | 5 | 46214.87 | 15.11 | 0.1327 | 7.2226 | 65.9702 | 0.0000 | 0.0000 | 26.6745 |
| | 7 | 95129.92 | 20.29 | 0.0937 | 5.3021 | 74.8749 | 0.0000 | 0.0000 | 19.7292 |
| | 9 | 173445 | 26.07 | 0.0777 | 4.2862 | 79.6871 | 0.0000 | 0.0000 | 15.9490 |
| **SLOCA-NE** | 5 | 54330.65 | 14.97 | 0.1291 | 6.1814 | 67.0794 | 0.0422 | 0.0000 | 26.5679 |
| | 7 | 93632.93 | 20.40 | 0.1287 | 3.7634 | 75.6066 | 0.3991 | 0.0001 | 20.1021 |
| | 9 | 192932.9 | 25.52 | 0.1041 | 1.6675 | 81.3422 | 0.6069 | 0.1685 | 16.1109 |
| **SLOCA-RVF** | 5 | 54330.65 | 14.97 | 0.1291 | 6.1814 | 67.0794 | 0.0422 | 0.0000 | 26.5679 |
| | 7 | 100553.4 | 20.31 | 0.1232 | 3.5712 | 75.9082 | 0.3992 | 0.0004 | 19.9979 |
| | 9 | 146461.1 | 25.58 | 0.1044 | 2.1637 | 81.2383 | 0.4638 | 0.0025 | 16.0272 |
| **SLOCA-RVI** | 5 | 63626.72 | 14.82 | 0.0726 | 6.1284 | 69.0843 | 0.0000 | 0.0000 | 24.7147 |
| | 7 | 105354.5 | 20.29 | 0.0551 | 4.6564 | 76.5088 | 0.0000 | 0.0000 | 18.7797 |
| | 9 | 170471.6 | 25.58 | 0.0522 | 3.7901 | 80.8718 | 0.0000 | 0.0000 | 15.2859 |
| **SBO-NE** | 5 | 80709.78 | 14.87 | 0.1986 | 3.3067 | 68.2179 | 0.9001 | 0.1141 | 27.2625 |
| | 7 | 136809.8 | 20.32 | 0.0874 | 2.1762 | 76.3694 | 0.6642 | 0.5857 | 20.1171 |
| | 9 | 216609.8 | 25.82 | 0.0705 | 2.0124 | 80.2990 | 0.5280 | 1.1559 | 15.9341 |
| **SBO-RVF** | 5 | 80709.78 | 14.81 | 0.1986 | 3.3043 | 68.2530 | 0.8992 | 0.1134 | 27.2314 |
| | 7 | 142000.00 | 20.16 | 0.0871 | 2.1684 | 76.5201 | 0.6606 | 0.6288 | 19.9351 |
| | 9 | 198632.2 | 25.94 | 0.0698 | 1.9340 | 80.6123 | 0.5261 | 1.0015 | 15.8563 |

**Table IV:** Discharge Flow Characteristic at Second Venting

| Accident Sequence | Vent Initiating Pressure [bar(a)] | Time [seconds] | Discharge Flow Rate [kg/s] | Concentration [%] | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $H_2$ | $O_2$ | Steam | CO | $CO_2$ | $N_2$ |
| **LLOCA-RVF** | 5 | 204985.10 | 14.84 | 0.0754 | 0.7162 | 94.8426 | 0.2531 | 2.2875 | 1.8253 |
| | 7 | 331030.00 | 20.07 | 0.0054 | 0.7921 | 96.6011 | 0.0372 | 1.7904 | 0.7738 |
| **LLOCA-RVI** | 5 | 316299.40 | 15.11 | 0.0000 | 0.0003 | 99.9962 | 0.0000 | 0.0000 | 0.0035 |
| **SLOCA-RVF** | 5 | 193650.90 | 14.97 | 0.3450 | 0.0000 | 96.9045 | 0.7322 | 0.2540 | 1.7643 |
| | 7 | 290288.30 | 20.31 | 0.0993 | 0.0344 | 98.0554 | 0.2714 | 0.4478 | 1.0916 |
| **SLOCA-RVI** | 5 | 342074.10 | 14.81 | 0.0000 | 0.0002 | 99.8691 | 0.0000 | 0.0000 | 0.1307 |
| **SBO-RVF** | 5 | 214640.10 | 14.81 | 0.0010 | 0.5152 | 98.0983 | 0.0058 | 1.1900 | 0.1896 |
| | 7 | 333000.00 | 20.16 | 0.0048 | 0.8038 | 96.4236 | 0.0333 | 1.6991 | 1.0355 |

## 4. Conclusions

The hydrogen combustion risk inside of the CFVS has been examined qualitatively by investigating the discharge flow characteristics. Because the composition of the discharge flow to CFVS would be determined by the containment atmosphere, the severe accident progression and containment atmosphere composition have been investigated. Due to PAR operation, the hydrogen concentration in the containment would be decreased until the oxygen is depleted. After the oxygen is depleted, the hydrogen concentration would be increased. As a result, depending on the vent initiation timing (i.e. vent initiation pressure), the important factor for hydrogen combustion (i.e. composition of steam, hydrogen and oxygen) could be varied but it seems that hydrogen combustion would be difficult to occur due to effectiveness of PAR which reduce the hydrogen and oxygen. However, in order to quantitatively assess the risk of hydrogen combustion, more work needs to be done. For example, analyzing the distribution of hydrogen inside of the containment and the CFVS and investigating the possibility of air inflow into CFVS (e.g. stack) should be conducted. Also, the other CFVS operation strategies (e.g. refilling the CFVS tank) have to be considered.

## Acknowledgements

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