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# Numerical Study of Severe Accidents on Containment Venting Conditions

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## 1. Introduction

Under severe accident, the containment integrity can be challenged due to over-pressurization by steam and non-condensable gas generation. According to Seismic Probabilistic Safety Assessment (PSA) result, the late containment failure by over-pressurization has been identified as the most probable containment failure mode. In addition, the analyses of Fukushima nuclear power plant accident reveal the necessity of the proper containment depressurization to prevent the large release of the radionuclide to environment.

Containment venting has been considered as an effective approach to maintain the containment integrity from over-pressurization. Basic idea of containment venting is to relieve the pressure inside of the containment by establishing a flow path to the external environment. To ensure the containment integrity under over-pressure conditions, it is crucial to conduct the containment vent in a timely manner with a sufficient discharge flow rate. It is also important to optimize the vent line size to prevent additional risk of leakage and to install at the site with limited space availability.

The purpose of this study is to identify the effective venting conditions for preventing the containment over-pressurization and investigate the vent flow characteristics to minimize the consequence of the containment ventilation. In order that, thermodynamic behavior of the containment and the discharged flow depending on different vent strategies are analyzed and compared. The representative accident scenarios are identified by reviewing the Level 2 PSA result and the sensitivity analyses with varying conditions (i.e. vent line size and vent initiation pressure) are conducted. MAAP5 model for the OPR1000 Korea nuclear power plant has been used for severe accident simulations.

## 2. Major Severe Accident Scenarios

The containment pressurization mechanisms are categorized as follows:

**Gradual Pressurization**

- Coolant release of primary system to the containment atmosphere through the small break of primary system
- Release of emergency safety injection water to the containment atmosphere through the rupture of primary system
- Release of coolant to the containment atmosphere through pressurizer safety valves
- Steam generation by heat transfer between the safety injection and molten core in reactor cavity after reactor vessel failure
- Gas generation by molten core-concrete interaction (MCCI)

**Rapid Pressurization**

- Coolant release of primary system to the containment atmosphere through the large rupture of primary system or reactor vessel
- Steam generation by ejected molten core material into the cavity at the reactor vessel rupture

Followings are not considered because the explosive phenomena cannot be dealt with containment venting:

- Steam Explosion
- Hydrogen Explosion
- Direct Containment Heating

Conservatively, it is assumed that all safety injection systems except safety injection tank and external water injection by fire truck are not available. In order to consider the RCS pressure release rate, initiating events are chosen as Large/Small Break Loss of Coolant Accident (L/SLOCA) and Station Black-Out (SBO). It is expected that if the RCS pressure is decreased rapidly, the containment pressure would increase rapidly at the early stage of the accident and the containment atmosphere composition would be dependent on the MCCI. On the other hands, if the RCS stays intact filled with superheated steam, the clad would be oxidized extensively and a large amount of fission product would be retained in pipes and tube walls in RCS, which would differentiate the iodine chemistry and distribution. SLOCA is assumed to be initiated by $0.02\text{ft}^2$ break at cold leg. In case of SLOCA-RVI, the RCS is depressurized by manual-opening 2 pressure relief valves at 2 hours after the severe accident condition entrance. Accident sequences are composed to cover all phenomena described above as listed in **Table I.** Note that to emulate the Fukushima-type accident, the emergency external water injection is considered.

**Table I:** Severe Accident Sequences

| RCS Pressure Release 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** | - | SBO-RVF | SBO-NE |

[*] RVI: Reactor Vessel Intact (after entering severe accident condition, i.e. core exit temperature > 1200F, safety injection available)

[*] RVF: Reactor Vessel Failed (after reactor vessel breached, safety injection available)

## 3. Numerical Results

### *3.1 Plant Modeling for MAAP5 Simulation*

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 $2.727\times10^6$ $ft^3$ free volume, 393 kPa(g) design pressure[1]. Vent line is simply modeled as a flow path connecting the annular compartment of the containment and the environment. As a nominal case, the vent line size is assumed as 7 inch and the vent initiation pressure is 5 bar(a) at the containment.

The shutoff head of the external emergency water injection is assumed as 8 bar(a) in RCS. For RVI cases, it is assumed that the emergency water injection would be available 1 hour after the severe accident condition (core exit temperature >1200F). Then, the injection would be initiated and paused to maintain the reactor vessel water level between 6.4~6.6m. For RVF cases, the emergency water injection would be available 1 hour after reactor vessel fails. Then, the injection would be initiated and paused to maintain the water mass in the cavity between 100,000~110,000kg.

### *3.2 Reference Calculation*

The scenarios in **Table I** are simulated by MAAP 5 code[2]. The containment pressure increases due to continuous generation of steam and gases mainly due to evaporation of water by decay heat and molten core-concrete interaction. Main event occurrence timing is listed in **Table II**. Major observations can be summarized as follows:

- The containment pressure would decrease instantly when the containment venting system initiated (**Figure 1**).
- If the emergency water is injected into the RCS before the reactor vessel fails, the containment pressurization rate would be increased.
- Containment ventilation would decrease the containment pressure, which enhance the vaporization of water in the cavity.
- In RVF cases, the assumed containment pressure to initiate the ventilation would be reached in advance of the external emergency injection started.
- If MCCI occurs while the venting is on, a large amount of fission products would be released along the vented flow. One can see the step-wise increase of decay heat of released fission products in **Figure 2**.
- Maximum discharge flow rate is not varied according to the accident sequences as can be seen in **Figure 3**. That is because the flow would be established by the pressure difference between the containment and the environment.

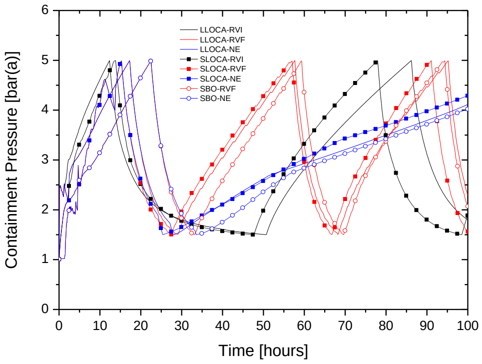

**Figure 1.** Containment Pressure

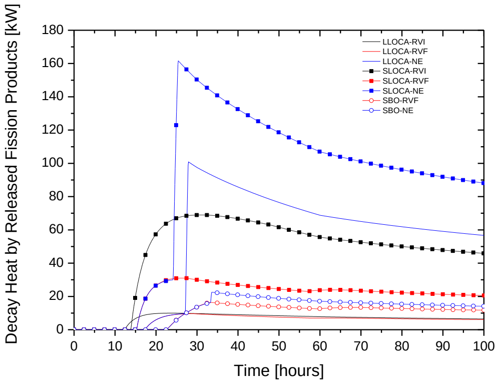

**Figure 2.** Decay Heat by Released Fission Products

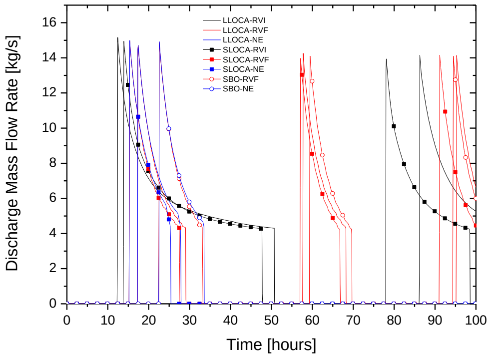

**Figure 3.** Discharge Mass Flow Rate

**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** | 0.512 | 0.512 | 0.512 | 171.497 | 171.497 | 171.497 | 0 | 0 |
| **Accumulator Water Depleted** | 88.366 | 88.366 | 88.366 | 18655.335 | 34034.784 | 34034.784 | 16826.943 | 16826.943 |
| **Core Uncovery** | 2.601 | 2.601 | 2.601 | 3117.614 | 3117.614 | 3117.614 | 7678.909 | 7678.909 |
| **CET > 1200F** | 1262.922 | 1262.922 | 1262.922 | 3991.175 | 3991.175 | 3991.175 | 9040.577 | 9040.577 |
| **CET > 2499K** | 1842.727 | 1842.727 | 1842.727 | 4995.234 | 4995.234 | 4995.234 | 11091.086 | 11091.086 |
| **Relocation of Core Materials to Lower Head** | 4005.265 | 4005.265 | 4005.265 | - | 19289.65 | 19289.65 | 14316.475 | 14316.475 |
| **Safety Injection Start (actual)** | 4895.2936 | 72340.423 | - | 19665.03 | 62816.002 | - | 91630.149 | - |
| **Reactor Vessel Failed** | - | 8536.271 | 8536.271 | - | 49390.589 | 49390.589 | 16408.453 | 16408.453 |
| **Design Pressure Reached (4 bar(g))** | 44371.507 | 62116.087 | 62116.087 | 49750.605 | 54799.681 | 54799.681 | 80899.21 | 80954.21 |

### *3.3 Sensitivity Analysis*

The sensitivity analysis of vent flow characteristics has been conducted with varying the vent line size and the vent initiating pressure:

- vent line size: 5 inch, 6 inch, 7 inch, 8 inch
- vent initiating pressure: 5 bar(a), 6 bar(a), 7 bar(a), 8 bar(a), 9 bar(a)

In **Table III ~ V**, the results with varying the vent line size and the vent initiating pressure are presented. Major observations can be summarized as follows:

- The maximum discharge mass flow rate would be increased as the vent initiating pressure and the vent line size increase.
- The maximum decay heat generation rate by vented flow and the vented aerosol mass would be increased as the vent line size increases.
- The maximum decay heat generation rate by vented flow and the vented aerosol mass would be decreased as the vent initiation pressure increases. This is because the aerosol in containment would be settled down as the time elapsed. Therefore, as the ventilation is delayed, the more aerosol would be deposited and the less would be discharged along the vented flow.
- Very large decay heat and vented aerosol mass would be expected if the MCCI occurs during the ventilation (i.e. NE cases).

**Table III.** Sensitivity Analysis of LLOCA

| Accident Sequence | Vent Initiating Pressure (Bar(a)) | Vent Line Size (inch) | Maximum Mass Flow Rate (kg/s) | Maximum Decay Heat (kW) | Vented Aerosol Mass (kg) |
|---|---|---|---|---|---|
| **LLOCA-RVI** | 5 | 7 | 15.157 | 9.969 | 3.128 |
| | 6 | | 17.901 | 3.457 | 1.128 |
| | 7 | | 20.452 | 0.883 | 0.255 |
| | 8 | | 23.036 | 0.295 | 0.058 |
| | 5 | 5 | 7.785 | 6.654 | 2.215 |
| | | 6 | 11.174 | 8.372 | 2.700 |
| | | 7 | 15.157 | 9.969 | 3.128 |
| | | 8 | 19.710 | 11.443 | 3.472 |
| **LLOCA-RVF** | 5 | 7 | 14.713 | 9.638 | 5.700 |
| | 6 | | 17.589 | 4.401 | 3.576 |
| | 7 | | 20.342 | 1.974 | 1.652 |
| | 8 | | 23.118 | 0.995 | 0.742 |
| | 9 | | 25.493 | 0.386 | 0.228 |
| | 5 | 5 | 7.618 | 7.022 | 5.083 |
| | | 6 | 10.895 | 8.513 | 5.799 |
| | | 7 | 14.713 | 9.638 | 5.700 |
| | | 8 | 19.040 | 10.230 | 5.466 |
| **LLOCA-NE** | 5 | 7 | 14.713 | 100.875 | 13.558 |
| | 6 | | 17.658 | 205.704 | 22.985 |
| | 7 | | 20.161 | 256.326 | 31.631 |
| | 8 | | 22.763 | 269.375 | 39.003 |
| | 9 | | 25.489 | 61.706 | 24.504 |
| | 5 | 5 | 7.618 | 180.960 | 29.030 |
| | | 6 | 10.895 | 183.554 | 23.342 |
| | | 7 | 14.713 | 100.875 | 13.558 |
| | | 8 | 19.040 | 10.522 | 5.653 |

**Table IV.** Sensitivity Analysis of SLOCA

| Accident Sequence | Vent Initiating Pressure (Bar(a)) | Vent Line Size (inch) | Maximum Mass Flow Rate (kg/s) | Maximum Decay Heat (kW) | Vented Aerosol Mass (kg) |
|---|---|---|---|---|---|
| **SLOCA-RVI** | 5 | 7 | 14.946 | 68.983 | 11.410 |
| | 6 | | 17.694 | 33.373 | 6.018 |
| | 7 | | 20.214 | 10.317 | 2.067 |
| | 8 | | 23.178 | 4.154 | 1.443 |
| | 9 | | 25.549 | 3.459 | 1.191 |
| | 5 | 5 | 7.684 | 46.700 | 6.964 |
| | | 6 | 11.025 | 58.703 | 10.206 |
| | | 7 | 14.946 | 68.983 | 11.410 |
| | | 8 | 19.428 | 77.819 | 11.197 |
| **SLOCA-RVF** | 5 | 7 | 14.995 | 31.017 | 92.519 |
| | 6 | | 17.524 | 9.801 | 34.783 |
| | 7 | | 20.320 | 3.858 | 9.336 |
| | 8 | | 22.731 | 1.758 | 4.443 |
| | 9 | | 25.467 | 0.957 | 2.544 |
| | 5 | 5 | 7.722 | 22.915 | 64.721 |

| | | | | | |
|---|---|---|---|---|---|
| | | 6 | 11.071 | 26.214 | 80.709 |
| | | 7 | 14.995 | 31.017 | 92.519 |
| | | 8 | 19.472 | 35.131 | 94.427 |
| **SLOCA-NE** | 5 | 7 | 14.995 | 161.647 | 100.589 |
| | 6 | | 17.446 | 227.587 | 51.032 |
| | 7 | | 20.128 | 273.536 | 30.804 |
| | 8 | | 23.035 | 290.517 | 28.619 |
| | 9 | | 25.286 | 52.497 | 9.539 |
| | 5 | 5 | 7.722 | 209.221 | 77.864 |
| | | 6 | 11.071 | 210.684 | 86.068 |
| | | 7 | 14.995 | 161.647 | 100.589 |
| | | 8 | 19.472 | 36.942 | 110.989 |

**Table V.** Sensitivity Analysis of SBO

| **Accident Sequence** | **Vent Initiating Pressure (Bar(a))** | **Vent Line Size (inch)** | **Maximum Mass Flow Rate (kg/s)** | **Maximum Decay Heat (kW)** | **Vented Aerosol Mass (kg)** |
|---|---|---|---|---|---|
| **SBO-RVF** | 5 | 7 | 14.874 | 16.419 | 3.890 |
| | 6 | | 17.490 | 6.233 | 1.489 |
| | 7 | | 20.183 | 2.141 | 0.639 |
| | 8 | | 23.109 | 0.812 | 0.338 |
| | 9 | | 25.961 | 0.431 | 0.237 |
| | 5 | 5 | 7.659 | 16.534 | 3.548 |
| | | 6 | 10.982 | 17.787 | 3.958 |
| | | 7 | 14.874 | 16.419 | 3.890 |
| | | 8 | 19.315 | 16.425 | 3.798 |
| **SBO-NE** | 5 | 7 | 14.926 | 22.563 | 4.468 |
| | 6 | | 17.703 | 44.343 | 4.904 |
| | 7 | | 20.434 | 64.416 | 7.095 |
| | 8 | | 22.927 | 73.834 | 9.196 |
| | 9 | | 25.699 | 30.622 | 8.433 |
| | 5 | 5 | 7.672 | 59.007 | 8.849 |
| | | 6 | 11.009 | 48.761 | 6.599 |
| | | 7 | 14.926 | 22.563 | 4.468 |
| | | 8 | 19.405 | 17.748 | 3.965 |

## 4. Conclusion

Containment venting can be an effective strategy to prevent the significant failure of the containment due to over-pressurization. However, it should be carefully conducted because the vented flow would contain the significant amount of radioactive materials, which have harmful effects on the public and the environment. In this study, the effects of venting during the severe accident with containment pressurization and the vent flow characteristics are examined by using MAAP5 simulations with accident scenarios carefully selected to cover the major containment pressurization phenomena. Based on the calculation results, the followings can be concluded:

- The vent initiation pressure should be sufficiently high to delay the vent. The suspended particles (i.e. aerosols) in containment would be settled and deposited; thus, the less amount of aerosol would be vented as the time elapsed.
- At the same time, the vent initiation pressure should not be too high. There could be leakages of radionuclide through airlocks and doors. Also, venting at high pressure would induce the flashing the water in the cavity, which worsen the containment pressure control and the cooling recovery.
- The decay heat and the aerosol mass delivered to CFVS would be higher as the vent line size and vent opening pressure decreases.
- The containment condition should be checked before the vent is decided to be initiated. MCCI should not occur during the venting. Also, once MCCI occurs, several hours should be waited to vent to avoid large release of radioactive materials.

## Acknowledgements

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