Severe Accident Analysis for Containment Filtered Venting System Design

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1. Introduction

Containment venting has been considered as an effective approach to maintain the containment integrity from over-pressurization as a result of long-term steam/gas generations and to mitigate the consequences of radionuclide releases to environment. Basic idea of containment venting is to relieve the pressure inside of the containment by establishing a flow path to the external environment. After TMI accident, many countries (Sweden, Germany, France) requires containment venting system like FCVS (filtered containment venting system), which can allow for the release of the over-pressure through a scrubber normally containing water and chemicals to reduce the radioactive material releases to the environment. After Fukushima accident, Korea also starts to consider the containment venting to deal with Fukushima-like severe accidents [1].

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. This study examines the thermodynamic behavior due to different vent strategies for a large PWR during severe accidents for the OPR1000 Korea nuclear power plant. The representative accident scenario is identified and the sensitivity analysis with varying conditions (i.e. vent line size and vent initiation pressure) is conducted by using numerical simulation.

2. Accident Scenario Determination

2.1 Accident Scenario Candidate

Prior to the main sensitivity analysis, the representative accident sequence should be determined to reduce the number of calculations. First, the eleven accident sequences are derived by considering steam/gas generation mechanisms (e.g. in/ex-vessel steam generation, molten core-concrete interaction, Zr oxidation) as listed in **Table I**. Note that to derive the conservative results [1] in view of containment pressurization, the alternative safety injection by fire engine is assumed to be available (pump shutoff head: 8 bar(a)). Note that the phenomena which result in drastic pressurization (e.g. steam explosion and containment direct heating) and direct connection to environment (e.g. concrete melt-through) are not considered, because those would not be affected by venting operation.

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-RVF-NE
Continuous Release	SLOCA-DP-RVI	SLOCA-RVF	SLOCA-RVF-NE
Transitional Release	SBO-HCR-RVI	SBO-HCR-RVF	SBO-HCR-RVF-NE
Dynamic Release	N/A	SBO-noHCR-RVF	SBO-noHCR-RVF-NE

* LLOCA: Large break Loss of Coolant Accident
* SLOCA: Small break Loss of Coolant Accident
* SBO: Station Black-Out Accident
* HCR: Hot-leg Creep Rupture
* 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)

2.2 Numerical Simulation for Screening

The scenarios in **Table I** are simulated by MAAP 4.04 code [2]. 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 2.727×10^{6} ft^{3} free volume, 331 kPa(g) ILRT [2] pressure and 393 kPa(g) design pressure [3]. The simulation results are summarized in **Table II**. In all scenarios, the containment pressure increases due to continuous generation of steam and gases mainly due to evaporation by decay heat and molten core-concrete interaction.

Among the accident scenarios, LLOCA-RVF sequence and SBO-HCR-RVF scenario (initiated by SBO + hot leg creep rupture + safety injection after 1 hr

[1] 'Conservative sequence' means the sequence with a large amount of gas and decay heat generations. This would result in rapid containment pressurization and high loads to filtration system.
[2] Integrated Leakage Rate Test

from reactor vessel failure) show the high containment pressure increase rate and the large decay heat generation; thus, those are chosen to be the accident sequences for the sensitivity analysis on venting size and timing.

Table II: Main Event Occurrence Timing

(hours)	LLOCA-RVI	LLOCA-RVF	LLOCA-RVF-NE	SLOCA-DP-RVI	SLOCA-RVF	SLOCA-RVF-NE	SBO-HCR-RVI	SBO-HCR-RVF	SBO-HCR-RVF-NE	SBO-noHCR-RVF	SBO-noHCR-RVF-NE
Reactor Scram	0.00	0.00	0.00	0.13	0.13	0.13	0.00	0.00	0.00	0.00	0.00
SIT Injection	0.00	0.00	0.00	3.26	4.67	4.67	3.22	3.22	3.22	4.40	4.40
Core Uncov	0.38	0.38	0.38	1.75	1.75	1.75	1.99	1.99	1.99	1.99	1.99
CET > 1200F	0.56	0.56	0.56	2.07	2.07	2.07	2.34	2.34	2.34	2.34	2.34
CET > 2200F	0.69	0.69	0.69	2.96	2.96	2.96	2.84	2.84	2.84	2.84	2.84
CET > 2499 K	0.75	0.75	0.75	3.08	3.08	3.08	2.95	2.95	2.95	2.95	2.95
Relocation of Core Materials to Lower Head	1.43	1.43	1.43	33.62	4.20	4.20	30.92	6.36	6.36	4.10	4.10
Creep Rupture	0.00	0.00	0.00	0.00	0.00	0.00	3.21	3.21	3.21	-	-
Safety Injection Start	1.56	3.71	-	4.50	5.67	-	3.34	8.79	-	5.40	-
Reactor Vessel Failed	-	2.71	2.71	-	4.67	4.67	-	7.79	7.79	4.40	4.40
ILRT Pressure (331kPa(g))	5.10	4.19	4.19	7.03	10.40	10.40	7.12	7.95	7.95	9.57	9.57
Design Pressure (393kPa(g))	7.28	6.03	6.03	9.45	12.74	12.74	9.70	9.14	9.14	11.40	11.40
150% Design Pressure (590 kPa(g))	14.82	12.13	11.86	18.62	19.66	19.66	19.12	15.07	14.73	17.90	17.90

3. Sensitivity Analysis on Venting Size and Timing

The sensitivity analysis of containment venting on containment behavior under the severe accident is conducted with varying the vent line size[3] and the vent initiating pressure:

- vent line size: 5 in, 10 in, 12 in, 15 in
- vent initiating pressure: ILRT pressure (431 kPa(a)), 150% design pressure (689.5 kPa(a)), 200% design pressure (886 kPa(a))

In **Table III**, the simulation results are summarized. The first column describes the simulation condition, i.e., the number after the first hyphen means the diameter of the vent line (5, 10, 12 and 15 in) and the number after the second hyphen the vent initiation pressure (e.g. ILRT is the ILRT pressure, 150 is 150% of design pressure, 200 is 200% of design pressure). The second column indicates the maximum containment pressure during 72 hours of the accident. The third column and the fourth column show the maximum values of discharged flow rate through the vent line and the decay heat generation rate in the discharged flow during the 72 hours, respectively. The fifth and the sixth columns show the total discharged flow and total discharged decay heat during 72 hours, respectively.

[3] Vent line size has not an explicit physical meaning because there is no consideration on pressure drop in CFVS. Therefore, it should be noted that the vent line size in this study is not corresponding to the actual pipe size. However, for ease explanation, the vent line size is used as a control variable to vary the discharge flow rate.

Based on the results in **Table III**, the followings can be concluded:

1) when the venting initiated at low containment pressure (i.e., early stage of accident), the containment pressure can be increased further due to high gas generation rate.

2) the maximum discharge flow rate would be higher (i.e. the amount of discharged flow in unit time is larger) when the venting initiated at the higher containment pressure than the one of the low.

3) as the venting initiation is delayed, the total discharged decay heat and the decay heat generation rate in the discharged flow would be lowered because the decay heat itself is decreased and radioactive aerosol is reduced due to deposition and settling.

4) the total discharged flow is not sensitive on the venting size and vent timing.

5) SBO-HCR-RVF shows the higher vent flow rate and decay heat generation because of enhanced Zr oxidation in the high pressure/temperature RCS condition before hotleg creep rupture.

Table III: Summary of Simulation Results

	MAX. CNMT PRESS (kPa(a))	MAX. FLOW RATE (kg/s)	MAX. DECAY HEAT (kW)	INT. FLOW (kg)	INT. DECAY HEAT (kJ)

LLOCA-5-ILRT	431.10	6.79	91.22	1.07262E+06	1.77436E+07
LLOCA-5-150	689.89	10.41	16.65	1.05707E+06	3.07560E+06
LLOCA-5-200	886.26	13.08	6.57	1.03236E+06	1.09422E+06
LLOCA-10-ILRT	431.44	25.64	283.11	1.00841E+06	4.80068E+07
LLOCA-10-150	690.22	39.91	30.87	9.85480E+05	5.15132E+06
LLOCA-10-200	887.20	49.63	6.47	8.26490E+05	1.00937E+06
LLOCA-12-ILRT	431.61	35.08	327.20	1.03945E+06	5.30008E+07
LLOCA-12-150	690.63	54.98	27.65	8.89487E+05	4.50587E+06
LLOCA-12-200	886.76	68.11	5.00	7.60150E+05	7.70273E+05
LLOCA-15-ILRT	431.48	53.17	336.71	9.36964E+05	5.29048E+07
LLOCA-15-150	690.10	83.31	21.78	8.16605E+05	3.49405E+06
LLOCA-15-200	886.72	104.88	4.23	7.04863E+05	6.45859E+05
SBO-5-ILRT	479.74	7.43	96.98	1.36607E+06	2.53413E+07
SBO-5-150	689.52	10.34	19.73	1.35783E+06	5.04741E+06
SBO-5-200	886.21	13.04	7.56	1.33850E+06	1.82386E+06
SBO-10-ILRT	468.28	28.60	242.81	1.31812E+06	5.69181E+07
SBO-10-150	690.41	39.29	37.40	1.14857E+06	8.50827E+06
SBO-10-200	887.18	49.75	7.11	1.13321E+06	1.56373E+06
SBO-12-ILRT	461.67	39.53	267.94	1.19838E+06	6.11191E+07
SBO-12-150	690.23	54.10	35.46	1.14727E+06	7.89749E+06
SBO-12-200	887.16	69.23	5.67	1.09794E+06	1.22957E+06
SBO-15-ILRT	449.39	60.52	289.87	1.21477E+06	6.44526E+07
SBO-15-150	690.18	81.40	28.01	1.06312E+06	6.16094E+06
SBO-15-200	886.56	103.94	5.23	1.03110E+06	1.12317E+06

* MAX.: maximum value during 72 hours of the accident
* INT.: integrated value during 72 hours of the accident

4. Further Sensitivity Studies

Because the SBO-HCR-RVF scenario shows the more conservative behavior, further sensitivity analyses are conducted on the SBO-HCR-RVF sequence with conditions.

In **Figure 1** and **Figure 2**, the containment pressures in cases that the vent line size is 6 inch and 7 inch are presented, respectively. To prevent the containment failure due to negative pressure, it was assumed that the venting would be terminated when the containment pressure reaches 1.5 bar(a). However, the venting can be re-initiated when the preset containment pressure is reached again. It can be seen that the containment pressure would converge to a certain value where the gas generation rate is balanced with venting rate. Considering the simplification of the vent line modeling in this simulation, it is concluded that, to depressurize the containment in the postulated SBO accident scenario, the vent line size should be larger than 7 inch.

In **Table IV**, the compositions in the discharged flow are compared during 100 hours simulation[4]. It can be seen that the gas generation in containment is dominated by steam generation. As the CFVS opening delayed, the steam content increases. In **Table V**, the total mass of discharged aerosol during 100 hour simulation is compared. As the CFVS opening pressure increases, the first opening timing would be delayed. Meantime, the aerosols would be reduced due to deposition and settling. Eventually, the aerosol released with the discharged containment air would be decreased.

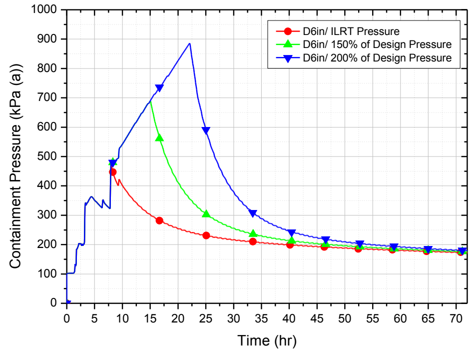

Figure 1. The containment pressure with venting (vent line diameter: 6 inch, closing pressure: 1.5 bar)

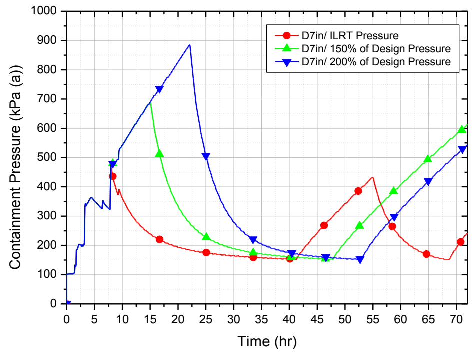

Figure 2. The containment pressure with venting (vent line diameter: 7 inch, closing pressure: 1.5 bar)

Table IV: Discharged Flow Composition

CFVS operation	Set pressure	Mass Fraction [%]					
		Steam	H2	O2	N2	CO2	CO
1st opening	4 bar	57.67	0.28	8.37	32.69	0.00	0.98
	5 bar	64.05	0.22	6.19	26.82	0.00	2.72
	6 bar	68.09	0.19	4.78	22.80	0.02	4.13
	7 bar	70.87	0.14	3.68	19.72	1.06	4.52
1st closing	4 bar	86.19	0.20	1.17	6.64	0.05	5.75
	5 bar	87.96	0.06	0.68	4.20	5.02	2.07
	6 bar	88.51	0.02	0.65	3.76	6.13	0.93
	7 bar	89.45	0.01	0.56	3.42	5.82	0.74
2nd opening	4 bar	83.63	0.05	0.00	2.49	10.45	3.37
	5 bar	85.06	0.01	0.19	1.28	12.82	0.63
	6 bar	86.43	0.00	0.21	0.99	12.13	0.24
	7 bar	88.03	0.00	0.17	0.77	10.86	0.17
2nd closing	4 bar	90.70	0.01	0.01	0.69	7.66	0.93
	5 bar	91.66	0.00	0.08	0.33	7.77	0.16
	6 bar	92.86	0.00	0.07	0.24	6.76	0.06
	7 bar	94.01	0.00	0.06	0.20	5.68	0.04
3rd opening	4 bar	87.77	0.00	0.04	0.26	11.56	0.36
	5 bar	89.24	0.00	0.08	0.10	10.53	0.05
3rd closing	4 bar	91.82	0.00	0.04	0.08	7.94	0.11
	5 bar	93.56	0.00	0.04	0.03	6.35	0.02

4 During 100 hours, CFVS would repeat opening/closing according to the containment pressure. Therefore, 100 hours is the time elapsed since the accident initiation.

* In case of 6 bar and 7 bar, the CFVS is not opened three times during 100 hours of simulation.

Table V: Total Discharged Aerosol Mass

CFVS Opening Pressure	Cumulative Discharged Aerosol Mass during 100 hours
4 bar(a)	72.4 kg
5 bar(a)	35.4 kg
6 bar(a)	19.1 kg
7 bar(a)	7.14 kg

5. Conclusions

The effects of venting during the severe accident with containment pressurization are examined. The accident scenarios are selected by using both of the qualitative judgement and the preliminary calculations and the sensitivity analysis on vent line size and vent initiation timing is conducted. As a result, the general trend of containment behavior due to venting can be found.

Summarizing the findings, two conflict trends are found:

- The maximum discharged flow rate would be higher as the vent line size and vent opening pressure increases.
- The decay heat and the aerosol mass delivered to CFVS would be higher as the vent line size and vent opening pressure decreases.

Regarding the flow rate, decay heat and aerosol mass are important factor for CFVS design, it would be necessary to find the optimum design specification with economical and regulatory considerations.

Acknowledgements

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