Plume Segmentation by Time Phase and Its Application to All Source Term Categories of OPR1000

Seunghwan Kim*, Sung-yeop Kim
Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Repulbic of Koreae
**Corresponding author: kimsh@kaeri.re.kr*

1. Introduction

The speed of analysis is very important because a huge amount of calculations is required to deal with all the scenarios of Level 2 PSA for a single-unit or multi-unit Level 3 PSA. Therefore, the speed of analysis is highly emphasized. Among the various input factors that influence the performance speed of the offsite consequence analysis, items that can be flexibly changed by the analyst, such as multiple plumes, spacial grid, and particle size distribution, can be input as detailed as possible to improve accuracy, but requires accepting the resulting increase in analysis time. Therefore, it is necessary to develop a method that satisfies both the accuracy of the offsite consequence analysis results in a massive analysis and the reduction of analysis time. In this study, we aimed to develop a method for effective time savings in massive analysis and presented an effective plume segmentation method that maintains accuracy and reduces the analysis time of the offsite consequence analysis.

2. Necessity of Massive Offsite Consequence Analysis

The improvement of accuracy in offsite consequence analysis has been much more emphasized than the fast analysis considering the analysis time, but the need for offsite consequence analysis for all scenarios of Level 2 PSA for a single-unit and a large number of multi-unit accident scenarios has begun to emerge. Especially in the case of multi-unit offsite consequence analysis, as the number of nuclear power plants and source term categories (STCs) considered increases, the number of accident scenarios increases exponentially as shown in Table 1, and it is realistically impossible to analyze them all.

Table 1. Number of combinations assuming same STCs for all units: $(N+1)^M-1$

Number of STC(N)	Number of Units Undergoing Accident(M)							
	1	2	3	4	5	6	7	8
5	5	35	215	1,295	7,775	46,655	279,935	1,679,615
10	10	120	1,330	14,640	161,050	1,771,560	19,487,170	214,358,880
15	15	255	4,095	65,535	1,048,575	16,777,215	268,435,455	4,294,967,295
20	20	440	9,260	194,480	4,084,100	85,766,120	1,801,088,540	36,822,859,360

3. Plume Segmentation for Offsite Consequence Analysis

Plume segmentation means performing an offsite consequence analysis by changing the release period of the plume. In this study, we investigated the effect of plume segmentation on offsite consequence analysis by observing the change in analysis time when changing the release by plume segmentation. To verify the significance of various scenario analyses (saving analysis time and consistency of results), we set the plume release to 1 hour (3,600 seconds) and performed an offsite consequence analysis, and designated the result as a base case and compared it with various plume segmentation experimental cases.

In order to have a minimum acceptable result error with the base case analysis result for plume segmentation, a strategic plume segmentation method should be prepared. For this purpose, we performed a sensitivity analysis by dividing the 72-hour plume release of the base case into initial/middle/later stages as shown in Fig. 1. and setting that only plumes are released in each section.

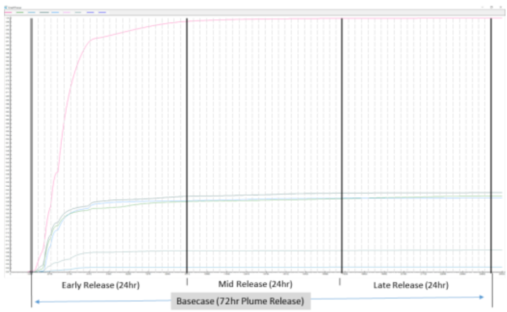

Fig. 1. The concept of plume segmentation (Early/Middle/Late)

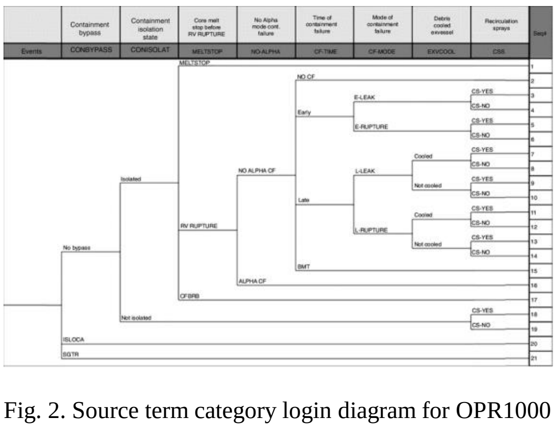

Fig. 2. Source term category login diagram for OPR1000

Twenty-one source term categories (STCs) were examined to verify the effect of plume segmentation. Fig. 2. depicts the source term category logic diagram for OPR1000 used in this study. The STCs were characterized by eight significant variables with consideration of dependencies between the variables.

Table 2 shows the initial/middle/later stage plume segmentation analysis results for all source term categories. Table 2 includes early fatality and cancer fatality risk results compared with base case for each source term category and information on analysis time required. First, looking at Table 2 which analyzes the effect of plume segmentation for all source term categories, it shows that it takes at least 37.8% to a maximum of 65.3% of base case execution time for all source term categories, which shows that execution time is linearly proportional to number of plumes compared with base case for each category. For example, in case of STC01 where base case plume release is 69 times, when dividing into initial/middle/later stages it shows 25~26 times release and shows that execution time decreased by 38% level.

Table 2. Impact of plume segmentation for all STCs (Early/Middle/Late)

Source Term Catagory	Plume Segmentation	No of Plume Release	Time Estimated for Basecase (sec)	Time Estimated		Early Fatality (0Km~80Km)			Cancer Fatality (0Km~80Km)		
				Time (sec)	%	Base Case	Test Case	Error Rate	Base Case	Test Case	Error Rate
STC01	Base case	69	2221.97	2221.97	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	25		858.11	38.6%	100.0%	100.0%	0.0%	100.0%	98.8%	1.2%
	Mid	26		854.39	38.5%	100.0%	100.0%	0.0%	100.0%	79.7%	20.3%
	Late	26		844.34	38.0%	100.0%	100.0%	0.0%	100.0%	79.4%	20.6%
STC02	Base case	61	2170.16	2170.16	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	22		822.98	37.9%	100.0%	100.0%	0.0%	100.0%	92.1%	7.9%
	Mid	23		853.48	39.3%	100.0%	100.0%	0.0%	100.0%	89.3%	10.7%
	Late	24		849.84	39.2%	100.0%	100.0%	0.0%	100.0%	84.8%	15.2%
STC03	Base case	52	1220.91	1220.91	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	19		559.03	45.8%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Mid	20		495.58	40.6%	100.0%	100.0%	0.0%	100.0%	79.9%	20.1%
	Late	21		500.81	41.0%	100.0%	100.0%	0.0%	100.0%	79.9%	20.1%
STC04	Base case	66	2430.61	2430.61	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	24		918.17	37.8%	100.0%	100.0%	0.0%	100.0%	89.1%	10.9%
	Mid	25		943.23	38.8%	100.0%	100.0%	0.0%	100.0%	70.1%	29.9%
	Late	25		939.00	38.6%	100.0%	100.0%	0.0%	100.0%	69.4%	30.6%
STC05	Base case	52	1740.22	1740.22	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	19		662.78	38.1%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Mid	20		688.05	39.5%	100.0%	100.0%	0.0%	100.0%	90.2%	9.8%
	Late	21		768.95	44.2%	100.0%	100.0%	0.0%	100.0%	90.2%	9.8%
STC06	Base case	66	2410.55	2410.55	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	24		918.63	38.1%	100.0%	100.0%	0.0%	100.0%	97.3%	2.7%
	Mid	25		945.11	39.2%	100.0%	1204.0%	1104.0%	100.0%	65.3%	34.7%
	Late	25		932.20	38.7%	100.0%	1209.0%	1109.0%	100.0%	65.5%	34.5%
STC08	Base case	25	941.44	941.44	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	10		403.28	42.8%	100.0%	100.0%	0.0%	100.0%	92.1%	7.9%
	Mid	11		441.03	46.8%	100.0%	100.0%	0.0%	100.0%	91.4%	8.6%
	Late	12		477.88	50.8%	100.0%	100.0%	0.0%	100.0%	90.0%	10.0%
STC09	Base case	12	430.69	430.69	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	6		238.52	55.4%	100.0%	100.0%	0.0%	100.0%	96.7%	3.3%
	Mid	7		272.17	63.2%	100.0%	100.0%	0.0%	100.0%	96.9%	3.1%
	Late	7		256.47	59.5%	100.0%	100.0%	0.0%	100.0%	95.3%	4.7%
STC10	Base case	25	945.48	945.48	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	10		403.77	42.7%	100.0%	100.0%	0.0%	100.0%	93.2%	6.8%
	Mid	11		442.14	46.8%	100.0%	100.0%	0.0%	100.0%	90.2%	9.8%
	Late	12		475.48	50.3%	100.0%	100.0%	0.0%	100.0%	87.5%	12.5%
STC12	Base case	25	918.27	918.27	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	10		402.95	43.9%	100.0%	100.0%	0.0%	100.0%	94.6%	5.4%
	Mid	11		431.95	47.0%	100.0%	100.0%	0.0%	100.0%	90.1%	9.9%
	Late	12		456.88	49.8%	100.0%	100.0%	0.0%	100.0%	92.1%	7.9%
STC13	Base case	12	371.45	371.45	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	6		224.34	60.4%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Mid	7		242.56	65.3%	100.0%	100.0%	0.0%	100.0%	97.0%	3.0%
	Late	7		225.56	60.7%	100.0%	100.0%	0.0%	100.0%	97.0%	3.0%
STC14	Base case	25	920.84	920.84	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	11		436.67	47.4%	100.0%	100.0%	0.0%	100.0%	98.6%	1.4%
	Mid	11		433.97	47.1%	100.0%	100.0%	0.0%	100.0%	89.8%	10.2%
	Late	12		459.91	49.9%	100.0%	100.0%	0.0%	100.0%	90.0%	10.0%
STC17	Base case	37	1332.36	1332.36	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	14		543.98	40.8%	100.0%	100.0%	0.0%	100.0%	83.8%	16.2%
	Mid	15		568.55	42.7%	100.0%	100.0%	0.0%	100.0%	84.6%	15.4%
	Late	16		602.73	45.2%	100.0%	100.0%	0.0%	100.0%	92.6%	7.4%
STC18	Base case	71	1559.55	1559.55	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	27		680.77	43.7%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Mid	27		626.81	40.2%	100.0%	100.0%	0.0%	100.0%	73.2%	26.8%
	Late	27		631.02	40.5%	100.0%	100.0%	0.0%	100.0%	73.2%	26.8%
STC19	Base case	71	2591.14	2591.14	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	27		1019.05	39.3%	100.0%	99.8%	0.2%	100.0%	96.6%	3.4%
	Mid	27		1012.06	39.1%	100.0%	128.7%	28.7%	100.0%	58.2%	41.8%
	Late	26		969.23	37.4%	100.0%	128.7%	28.7%	100.0%	57.9%	42.1%
STC20	Base case	69	2497.50	2497.50	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	25		944.39	37.8%	100.0%	99.8%	0.2%	100.0%	95.3%	4.7%
	Mid	26		970.73	38.9%	100.0%	71.2%	28.8%	100.0%	71.3%	28.7%
	Late	27		985.75	39.5%	100.0%	71.4%	28.6%	100.0%	71.3%	28.7%
STC21	Base case	34	813.69	813.69	100.0%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Early	12		386.42	47.5%	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%
	Mid	13		324.36	39.9%	100.0%	6423.8%	6323.8%	100.0%	73.0%	27.0%
	Late	14		342.39	42.1%	100.0%	6423.8%	6323.8%	100.0%	73.0%	27.0%

When considering plume segmentation at 1hour intervals for the initial 24 hours of rapid release, the results of early/cancer death evaluation were compared with base case and the time required was reduced by about 1/3, and the evaluation results of early phase of each STCs also showed a slight difference from base case. As can be seen in the graph of Fig. 1, it is judged that the initial 24-hour plume release with a rapid increase in cumulative release rate has a great influence on early/cancer death results, and it is judged that plume release in middle and later stages where the slope of the graph is relatively stabilized does not have a great influence on early/cancer death evaluation results. It should be noted that applied consequence analysis model is simplified model for the sensitivity analysis. The consequence analysis model is not reflecting actual environment or practical emergency responses.

4. Conclusions

In this study, we performed a study to optimize analysis time and enable effective mass analysis in recent situations where large-scale offsite consequence analysis is needed. As a result of understanding the effect of applying plume segmentation modeling technique, we confirmed that execution time when dividing plumes was shortened proportionally to number of plumes used for calculation compared to base case execution time, and therefore when effectively dividing plume release groups, we confirmed that analysis time can be shortened without causing large deviation in health impact evaluation (early death/cancer death) results.

ACKNOWLEDGEMENT

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science, ICT) (No. RS-2022-00144405).

REFERENCES

[1] N. Rasmussen, "Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants", WASH-1400 (NUREG-75/014), U.S. Nuclear Regulatory Commission, 1975.
[2] S. J. Lee, et al., "Probabilistic Safety Assessment of Nuclear Power Plants", Korea eBook Publishing Company, pp. 89-143, 2021.
[3] S. Y. Kim, et al., "Interfacing between MAAP and MACCS to perform radiological consequence analysis Development of MUST (Multi-Unit Source Term) Converter", Nuclear Engineering and Technology, Volume 54, Issue 4, pp. 1516-1525, 2022.
[4] K. H. Jin, J. H. Cho, S. Y. Kim, "Machine learning-based categorization of source terms for risk assessment of nuclear power plants", Nuclear Engineering and Technology, Volume 54, Issue 9, pp. 3336-3346, 2022.
[5] S. Y. Kim, et al., "Multi-unit Level 3 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site", Nuclear Engineering and Technology, Volume 50, Issue 8, pp. 1246-1254, 2018.
[6] N. E. Bixler and S. Y. Kim, "Performing a multi-unit level-3 PSA with MACCS", Nuclear Engineering and Technology, Volume 53, Issue 2, pp. 386-392, 2021.
[7] S. Y. Kim, et al., "Development of MUST (Multi-Unit Source Term) Converter Version 1.0", Transactions of the Korean Nuclear Society Autumn Meeting, October 21-22, 2021, Changwon, Korea.
[8] S. Y. Kim, "Development of Mr (Multi-run) Manager Version 1.0", Transactions of the Korean Nuclear Society Autumn Meeting, October 21-22, 2021, Changwon, Korea
[9] S. Y. Kim, "Current development status of MACCS-related pre- and post-processors at KAERI", 2022 Asian MACCS User group meeting, November 9-11, Singapore.
[10] S. H. Kim and S. Y. Kim, "Development of Interfacing Software to Support MACCS Sensitivity Analyses", 2022 Asian MACCS User group meeting, November 9-11, Singapore.
[11] S. H. Kim and S. Y. Kim, “A study on the Optimization of Offsite Consequence Analysis by Plume Segmentation and Multi-Threading”, Journal of the Korean Society of Safety, Volume 37, Issue 4, pp. 166-173, 2022.
[12] S. H. Kim and S. Y. Kim, "Influence of plume segmentation on the results and speed of offsite consequence analysis", Asian Symposium on Risk Assessment and Management 2022, November 30-December 2, Daejeon, Korea.
[13] ASME and ANS, "Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Applications", ASME/ANS RA-S-1.3-2017, American Nuclear Society, 2017.
[14] Jaehyun Cho, et. al., “Multi-Unit Level 2 Probabilistic Safety Assessment: Approaches and Their Application to a Six-Unit NPP Site”, Nuclear Engineering and Technology, Volume 40, Issue 8, pp. 1234-1245, 2018