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Topical Issue Article

Multi-unit Level 3 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site

Sung-yeop Kim*, Yong Hun Jung, Sang Hoon Han, Seok-Jung Han, Ho-Gon Lim

Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea

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ABSTRACT

The importance of performing Level 3 probabilistic safety assessments (PSA) along with a general interest in assessing multi-unit risk has been sharply increasing after the Fukushima Daiichi nuclear power plant (NPP) accident. However, relatively few studies on multi-unit Level 3 PSA have been performed to date, reflecting limited scenarios of multi-unit accidents with higher priority. The major difficulty to carry out a multi-unit Level 3 PSA lies in the exponentially increasing number of multi-unit accident combinations, as different source terms can be released from each NPP unit; indeed, building consequence models for the astronomical number of accident scenarios is simply impractical. In this study, a new approach has been developed that employs the look-up table method to cover every multi-unit accident scenario. Consequence results for each scenario can be found on the table, established with a practical amount of effort, and can be matched to the frequency of the scenario. Preliminary application to a six-unit NPP site was carried out, where it was found that the difference between full-coverage and cut-off cases could be considerably high and therefore influence the total risk. Additional studies should be performed to fine tune the details and overcome the limitations of the approach.

1. Introduction

In the Level 3 probabilistic safety assessment (PSA), the risk of a nuclear power plant (NPP) accident is mathematically estimated by multiplying the release frequency of radioactive materials into the environment and the consequence, such as dose and public health effects by the release, as

$$\mathit{Risk} = \mathit{Frequency}\ (\mathit{Probability}) \times \mathit{Consequence}.$$

Compared to the risk assessment of an accident in a single unit, there exist additional considerations for assessment of a multi-unit accident. The number of combinations of multi-unit accident scenarios exponentially increases with the number of units on a site, because different types of source term categories (STC) can be released into the environment from each NPP unit by its accident progression. If n STCs and k units are concerned, a total of n^k multi-unit source term release scenarios should be regarded. If every accident is assumed to occur at the same place (one point) for simplicity, the number of multi-unit accident scenarios can be counted through combination with repetition as

$${}_nH_k = {}_{n+k-1}C_k, \tag{1}$$

where n is the number of STCs possibly released to the environment and k is the number of NPP units at the site. However, the above method combines only the cases where release occurs from every unit. Therefore, including zero release STC can be a way to count the combinations that include some units not releasing radioactive materials. Including zero release STC, the mathematical expression can be redefined as

$$(n+1)^k, \tag{2}$$

when spatial difference of release is regarded,

$${}_{n+1}H_k = {}_{n+k}C_k, \tag{3}$$

and when one point release is assumed.

To estimate the risk of a multi-unit NPP site, both frequency and consequence of possible multi-unit accident scenarios should be obtained. A detailed approach to find the frequency of multi-unit

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* Corresponding author.
E-mail address: sungyeop@kaeri.re.kr (S.-y. Kim).

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accident scenarios is described in the related papers on Level 1 multi-unit PSA (MUPSA) [1] and Level 2 MUPSA [2].

With typical approaches, individual consequence models are built up to obtain the consequence from each accident scenario. It is, however, impractical to perform such consequence analyses if the number of accident scenarios to be handled is beyond human capacity. For example, if a reference NPP site has 6 units and 21 STCs, the number of resulting scenarios is 296,010 ($={}_{22}H_6$) and thus, consequence analysis models for all 296,010 cases should be modeled to obtain the consequence from each accident scenario. Developing a method to solve this practical challenge is regarded as one of the major research tasks in the field of multi-unit risk assessment, and therefore, is the objective of this study.

Three different techniques to estimate the consequences of multi-unit accident scenarios could be considered:

(1) Building every model for each scenario by hand;
(2) Reducing the number of scenarios by using a cut-off method, such as risk-weighted cut-off, and then building a reasonable number of models by hand;
(3) Developing an innovative approach to cover every scenario with practical effort and estimate the consequences with the approach.

The first technique is impractical as aforementioned. Although only a few Level 3 MUPSA studies have been carried out to date, among them few limited numbers of STCs by importance and regarded only two units to solve the inherent difficulty of Level 3 MUPSA [3,4].

The present study has applied the third technique by developing a look-up table approach to provide a practical solution to this complicated matter. The concept behind this approach is to first establish a table of consequences composed of results calculated by trials requiring reasonable effort. The consequence of every scenario can then be searched in the prepared table, and the consequence in the gap between two points can be obtained by interpolation. In plain terms, it is a similar concept to the steam table approach in thermodynamics.

Considering that the frequency of a multi-unit accident scenario can be provided from the results of Levels 1 and 2 MUPSA, if the consequence of each scenario can be searched and obtained from an established table, then the risk of each scenario can be calculated by mapping the resulting consequence and frequency. Ultimately, the total risk of a multi-unit site can be estimated by combining all the risk from the multi-unit accident scenarios. A flow chart expressing the procedure of the look-up table approach is described in Fig. 1.

The strengths of the look-up table approach can be summarized as:

- Producing a tool that enables site risk assessment with a practical number of consequence analyses, or in other words, with practical effort;
- Allowing for an adequate number of units and STCs to be handled;
- Providing insight from results covering all multi-unit accident scenarios comprehensively.

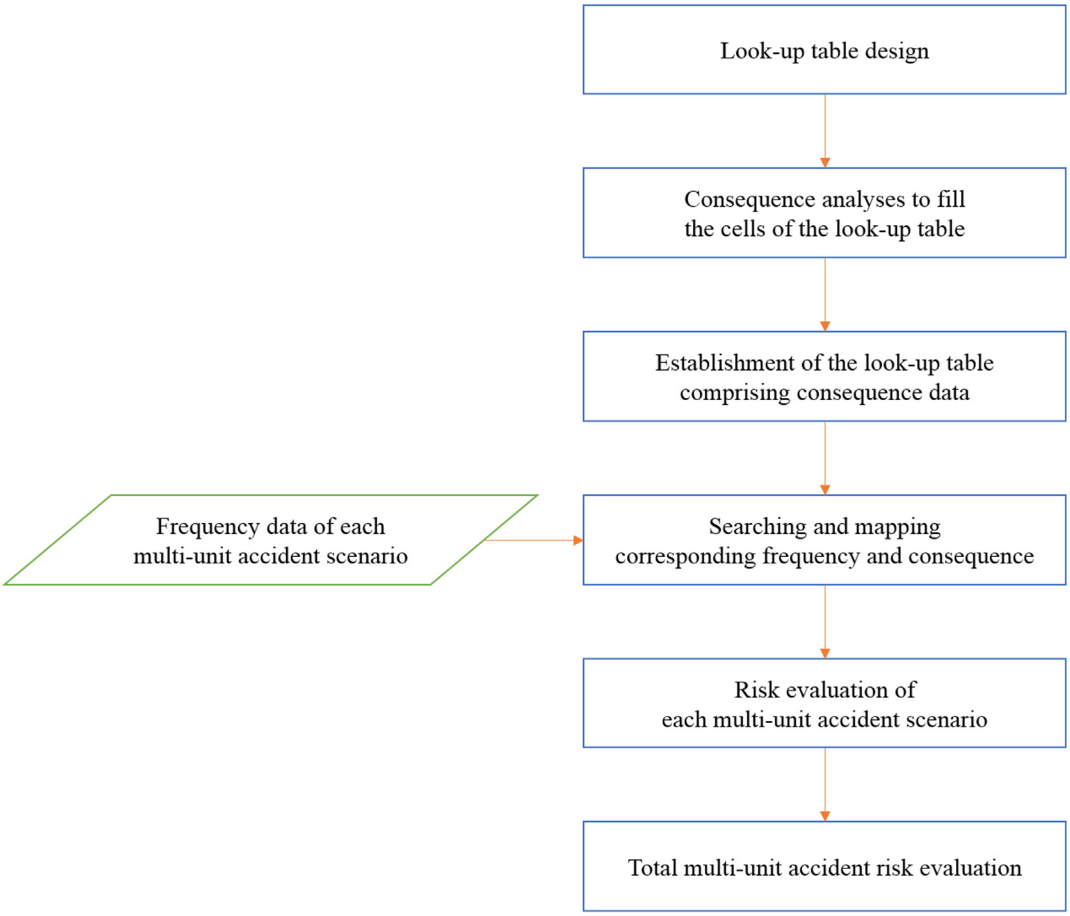


Fig. 1. Procedure of look-up table approach.

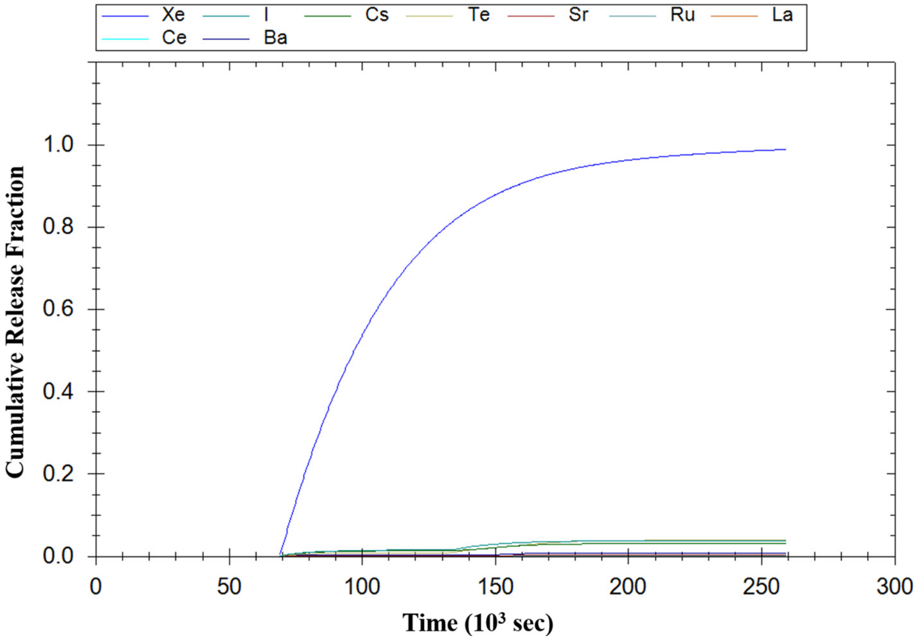


Fig. 2. An example of time-based STC release characteristics.

2. Look-up table approach for Level 3 MUPSA

Selecting the key parameters comprising the look-up table is one major task to apply the approach to Level 3 MUPSA. It is also necessary to find a means of equivalent conversion in order to compare the relative influence of different STCs, and further, it is fundamental to include important assumptions in order to constitute the look-up table with practically possible numbers of consequence analyses. After constructing the look-up table, the approximate consequence of each multi-unit accident scenario can be found from the table.

2.1. Key parameters comprising the look-up table

When performing a Level 3 PSA, the most influential factor on accident consequence is the environmental release characteristics of related radionuclides, or in other words, the magnitude and temporal progress of the release. Parameters for the dispersion and deposition of radioactive materials and public health effects from exposure are possibly regarded to be identical for every STC when considering the same NPP site.

Typically, the first few days of accident progression are assessed by Level 2 PSA, for example at 72 h. The release of source terms begins and decrements in this period. Fig. 2 shows an example of release progression.

The total amount of release until the end point of an analysis is occasionally assumed to be released during a fixed duration, such as a few hours, for conservatism and facilitation of some aspects of analysis. This assumption also owes to the limitation of typical Gaussian plume models. Fixing the release duration is one of the key assumptions enabling the development of a look-up table, because it considers release duration not as a variable but a constant. With this assumption, the starting point of release and the total release amount can be selected as the primary parameters defining the rows and columns of the look-up table, because these two parameters are different for each STC. It is also important to note that the starting time of release has the same meaning as the delay time of release. The number of accidents, the amount of radionuclide release from each accident, and the timing of release in a multi-unit accident scenario are the major considerations of the look-up table approach.

2.1.1. Starting time of source release

Since the starting point of release varies for each STC, it is desirable to simplify them by categorization for the purpose of building the look-up table. The number of categories of release start times determines the dimensions of the look-up table; for example, if it is divided into two categories such as early and late release, the look-up table will have two dimensions. If three categories (e.g., early, intermediate, and late release) are categorized, then a 3-dimensional look-up table is established and a much larger number of consequence analysis trials are needed to fill in the table cells. Further categorization for more than three categories is also feasible.

2.1.2. Magnitude of source release

While the starting time of source release determines the dimensions of the look-up table, the magnitude of source release decides the range and values of each axis. For example, if the look-up table is 2D with early and late release categorizations, the axes of the look-up table describe the amount of radioactive material released as early and late releases. Fig. 3 depicts an example 2D look-up table showing such components as axes, values, and contents. The concept for higher dimensional look-up tables is the same except for the number of axes, or in other words, the number of time categories the starting point of release belongs to. Making look-up tables with higher dimensions enables more detailed consequence analyses.

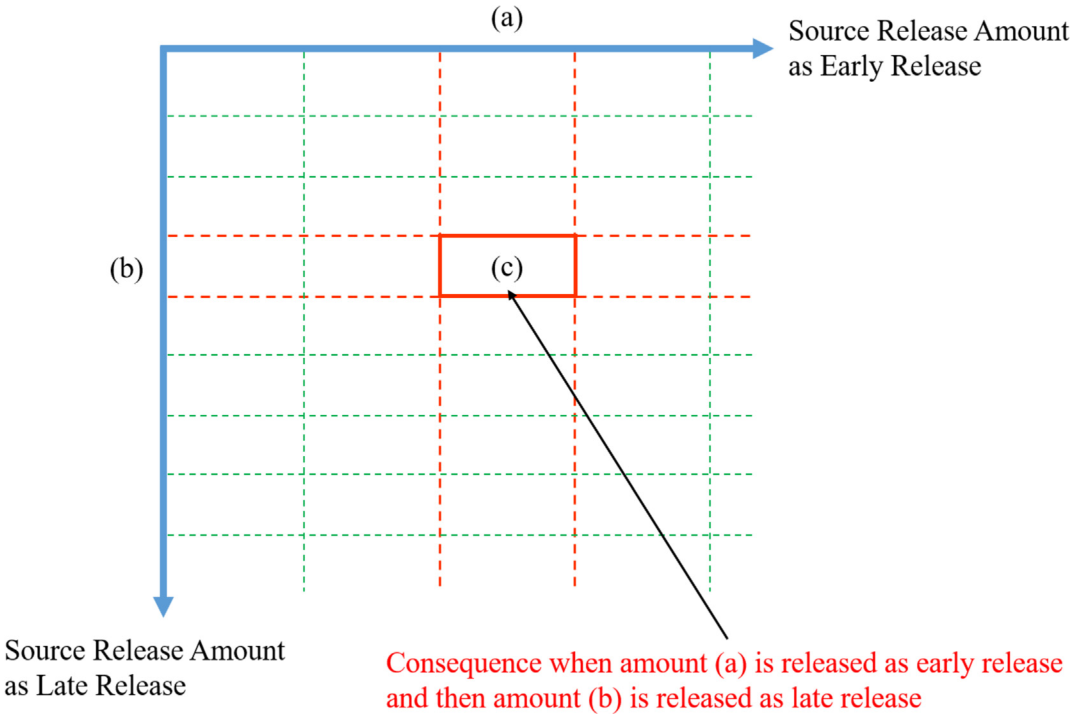


Fig. 3. Example 2D look-up table with components.

2.2. *Equivalent conversion of source terms*

Considering the most critical factors for off-site consequences, with several important assumptions, the starting time and magnitude of source release have been selected as the key parameters comprising the look-up table. As aforementioned, these two parameters determine the dimension and range of the table.

However, it is difficult to assign each STC directly on the axes as magnitudes of release because each STC is usually composed of the release of various radionuclides. Typically, in Level 3 PSA, radionuclides are sorted into several radionuclide groups by the similarity of both chemical and physical properties. The amount of individual radionuclide release is expressed as the release fraction of each radionuclide group representatively. To calculate individual radionuclide release, the release fraction of the radionuclide group is multiplied by the core inventory of the radionuclide. An example of such radionuclide groups applied in a MACCS2 analysis [5] is presented in Table 1.

Therefore, it is indispensable that the release magnitudes of STCs be compared equivalently. There are two representative ways to compare STC release magnitudes by an identical standard:

(1) Release amount of representative radioactive material;
(2) Equivalent conversion (scaling) of release amount.

While the former may seem relatively straightforward, it is difficult to comprehend the association between exposure and its effects considering the number of different radionuclides released into the environment following an accident and their diverse influence on human health. The latter provides a way to figure out the influence from radioactive materials, but has a complicated procedure of estimation which can hinder immediacy. A representative example of the former is the safety goal regarding Cs-137 release criteria [7], and a typical instance of the latter is the international nuclear and radiological event scale (INES) from the IAEA [8]. Equivalent conversion of source release magnitude will be explained in detail with a proper example in Section 3.1.

2.3. *Utilization of the look-up table*

Two look-up tables are constructed separately for each early and late health effect. The value in each cell of the look-up table, calculated from the consequence analysis for the scenario, represents the conditional consequence (i.e., early health effects or late health effects) given the occurrence of a specific accident scenario.

Table 1
Example radionuclide groups used in MACCS2 code [5].

Group Number	Group Name	Representative	Member Elements
1	Noble Gas	Xe	Xe, Kr
2	Halogens	I	I
3	Alkali Metals	Cs	Cs, Rb
4	Tellurium	Te	Te, Sb
5	Strontium	Sr	Sr
6	Noble Metals	Ru	Ru, Rh, Co, Mo, Tc
7	Lanthanum	La	La, Pr, Y, Nd, Am, Cm, Zr, Nb
8	Cerium	Ce	Ce, Np, Pu
9	Barium (part of group 5 in Reactor Safety Study [6])	Ba	Ba

To estimate the total risk of a multi-unit site, the frequency of each multi-unit accident scenario derived from Levels 1 and 2 MUPSA can be connected with the relevant conditional consequence found in the look-up table. Section 3 details this method with an example application of the approach.

3. Preliminary risk assessment of a six-unit NPP site with the look-up table approach

3.1. Source term

Source term information refers to the results of a severe accident analysis for the representative accident progression of each STC, which is singled out by frequency criteria. Source term information is produced from a Level 2 PSA and necessary data is chosen and converted into an appropriate format in the initial phase of a Level 3 PSA. This study utilized MAAP5 [9] and MACCS2 [5] as analyzing tools for source term and consequence analyses, respectively.

Following the Level 2 PSA [10], the starting point of release and release fraction of each radionuclide group were analyzed after the categorization of the source terms into 21 STCs. Owing to the difference between the definitions of radionuclide groups in MAAP5 and MACCS2, source term information produced by MAPP5 was converted into the appropriate input of MACCS2 using KOSCA-SOURCE [11], which is a source term conversion tool in the Korea Off-Site Consequence Analysis (KOSCA) software package developed by KAERI. Table 2 characterizes the 21 STCs.

Health effects from radiation exposure differ by radionuclide, exposure pathway, and target organ. Therefore, based on relative health effectiveness, a scaling method should be applied to quantify the relative release magnitude of each STC as composed of various radionuclides. Previous research by KAERI [10] has developed a scaling method for the health-effect-based conversion of the release of each radionuclide group into a representative isotope (Cs-137). By using the conversion factors presented in Table 3, Cs-137 equivalent scales of radionuclide groups for the reference plant can be estimated. This applied scaling method is but an example of equivalent conversion; other approaches can be flexibly applied for equivalent conversion.

Among equivalent conversion factors introduced in Table 3, DOSFAC2 and ICRP-60ED related conversion factors were adopted to construct the look-up table for early and cancer fatality, respectively, which were used in the MACCS2 [5] analysis. As STC-16 was evaluated as the most influential STC on health effects, its release magnitude acted as the basis for the scaling method to calculate the relative release magnitude of the other STCs. Results are listed in Table 4.

Table 3
Health effect-based equivalent conversion factors for the reference site [10].

Group Name	Cs-137 Equivalent Conversion Factors			
	Early Fatality		Latent Cancer Fatality	
	DOSFAC2	FGR13	ICRP-60ED	INES
Noble Gas	4.69	8.67	0.00	0.00
I	25.15	105.12	0.15	0.18
Cs	5.20	5.69	1.53	1.13
Te	6.36	7.99	0.02	8.95
Sr	22.63	32.38	0.04	0.28
Ru	8.02	11.07	0.72	0.86
Ba	87.57	78.68	2.59	0.32
La	26.55	22.05	2.68	0.59
Ce	10.05	19.27	0.02	0.00

The relative release magnitude by equivalent conversion based on health effect determines the range of the look-up table. If the equivalent release magnitude of STC-16 is assumed to be the unit magnitude, the maximum magnitude of both early and late release is six when a six-unit NPP site is considered. Thus, both axes (row and column) of the look-up table range from zero to six. This approach is acceptable due to the assumption that multi-unit accidents occur at the same location. The interval between rows and columns of the look-up table was set as 0.2 in this study with the results of the consequence analyses constituting the table cells. The consequence between established cells of the table can be estimated by interpolation.

3.2. Consequence analysis of multi-unit NPP accident

The MACCS2 code [5] developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission was employed as the consequence analysis tool in this study. Raw meteorological data of the reference site was converted into the appropriate form for MACCS2 input using KOSCA-METEO [11,12]. Population data for the

Table 2
Source term categories of the reference plant [10].

STC	Containment Failure Mode	Late Containment Spray	Ex-vessel Cooling
1	No Containment Failure	–	–
2	No Containment Failure	–	–
3	Early Containment Failure (Leak)	Success	–
4	Early Containment Failure (Leak)	Failure	–
5	Early Containment Failure (Rupture)	Success	–
6	Early Containment Failure (Rupture)	Failure	–
7	Late Containment Failure (Leak)	Success	Cooled
8	Late Containment Failure (Leak)	Failure	Cooled
9	Late Containment Failure (Leak)	Success	Not cooled
10	Late Containment Failure (Leak)	Failure	Not cooled
11	Late Containment Failure (Rupture)	Success	Cooled
12	Late Containment Failure (Rupture)	Failure	Cooled
13	Late Containment Failure (Rupture)	Success	Not cooled
14	Late Containment Failure (Rupture)	Failure	Not cooled
15	Basement Melt-through	–	–
16	Alpha mode failure	–	–
17	Containment Failure before Reactor Vessel Rupture	–	–
18	Isolation Failure	Success	–
19	Isolation Failure	Failure	–
20	Interfacing System LOCA	–	–
21	Steam Generator Tube Rupture	–	–

Table 4
Relative release magnitude of each STC based on early fatality and latent cancer fatality.

STC No	Relative Release Magnitude of each STC		Beginning of Release (hr)	
	Early Fatality	Latent Cancer Fatality	ER: Early Release LR: Late Release	
01	0.00103	0.00001	6.25	ER
02	0.00161	0.00067	17.01	ER
03	0.10163	0.00045	17.01	ER
04	0.83804	0.40742	8.00	ER
05	0.16405	0.00215	17.01	ER
06	0.95609	0.52182	8.00	ER
07	–	–	–	–
08	0.26172	0.00310	48.06	LR
09	0.17366	0.00005	61.55	LR
10	0.26407	0.00776	48.00	LR
11	–	–	–	–
12	0.29081	0.00800	48.06	LR
13	0.25664	0.00032	61.55	LR
14	0.30033	0.01387	48.00	LR
15	0.40916	0.13384	34.02	ER
16	**1.00000**	**1.00000**	11.67	ER
17	0.30237	0.01303	82.00	LR
18	0.06586	0.00195	1.92	ER
19	0.83512	0.84514	17.17	ER
20	0.91802	0.85277	4.05	ER
21	0.21859	0.05985	45.25	LR

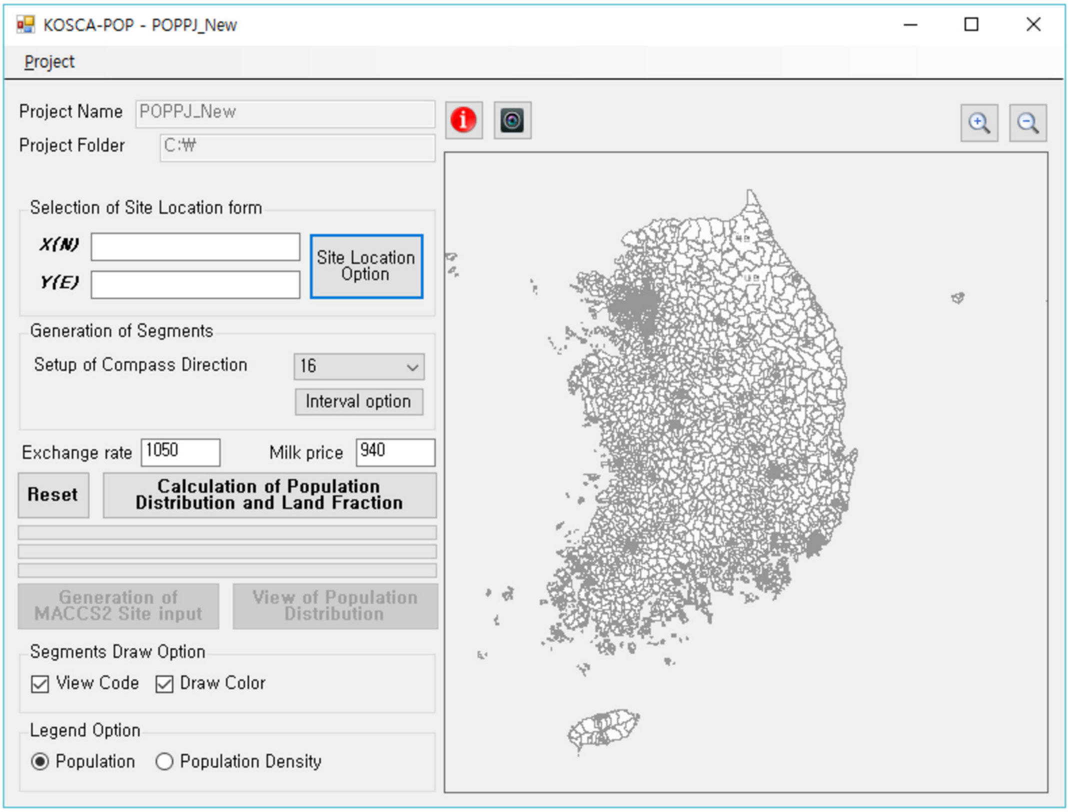
reference site was produced using KOSCA-POP [11,12], which integrated 2010 census data with a recent digital geographic map of the administrative district. KOSCA-POP is a preprocessor to create Korean site-specific population data, and it is similar to SECPOP [13] which is used in the U.S. Fig. 4 shows the main program window of KOSCA-POP. Several input data were updated to reflect Korea site-specific data as well as recent studies on MACCS best practices [14] and non-site-specific parameters [15].

Emergency responses such as sheltering, evacuation, dose-dependent relocation, and distribution of potassium iodide (KI) were assumed to not be performed for conservatism. The emergency phase (one week) is the only period considered in the analysis, due to the prevailing high uncertainty of current long-term exposure models such as food chain and water ingestion models.

The consequences composing the look-up table were calculated by MACCS2 for both early and late release magnitude as relative to the release magnitude of STC-16. Each axis has 31 cells which range from zero to six at 0.2 intervals. Hence, the total number of cells (combination of early and late release) is 31^2, which indicates the number of required consequence analysis models. However, as the maximum release magnitude is six and the sum of early and late release magnitudes cannot exceed six, almost half of the 31^2 models do not have to be created, as exhibited in Fig. 5.

Each consequence model includes two Gaussian plumes representing early and late release, and the magnitude of both releases is relative to the unit magnitude (STC-16). As the starting point of release varies for each STC, a representative starting point was established for early and late release by a risk-weighted average using data introduced in Table 4. This average was calculated for early and late health effects separately due to the differing early and late health effects of each STC. Representative starting points of early and late release for early and late health effects are presented in Table 5, which were used as ATMOS input information in MACCS2.

The duration of release should also be standardized to build consequence models for the look-up table. Release duration is assumed to be 1 h for every STC in this study, so the cumulative



Project Name POPPJ_New
Project Folder C:₩
Setup of Compass Direction 16
Exchange rate 1050
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Fig. 4. Preprocessor KOSCA-POP to produce population and land use data for MACCS2.

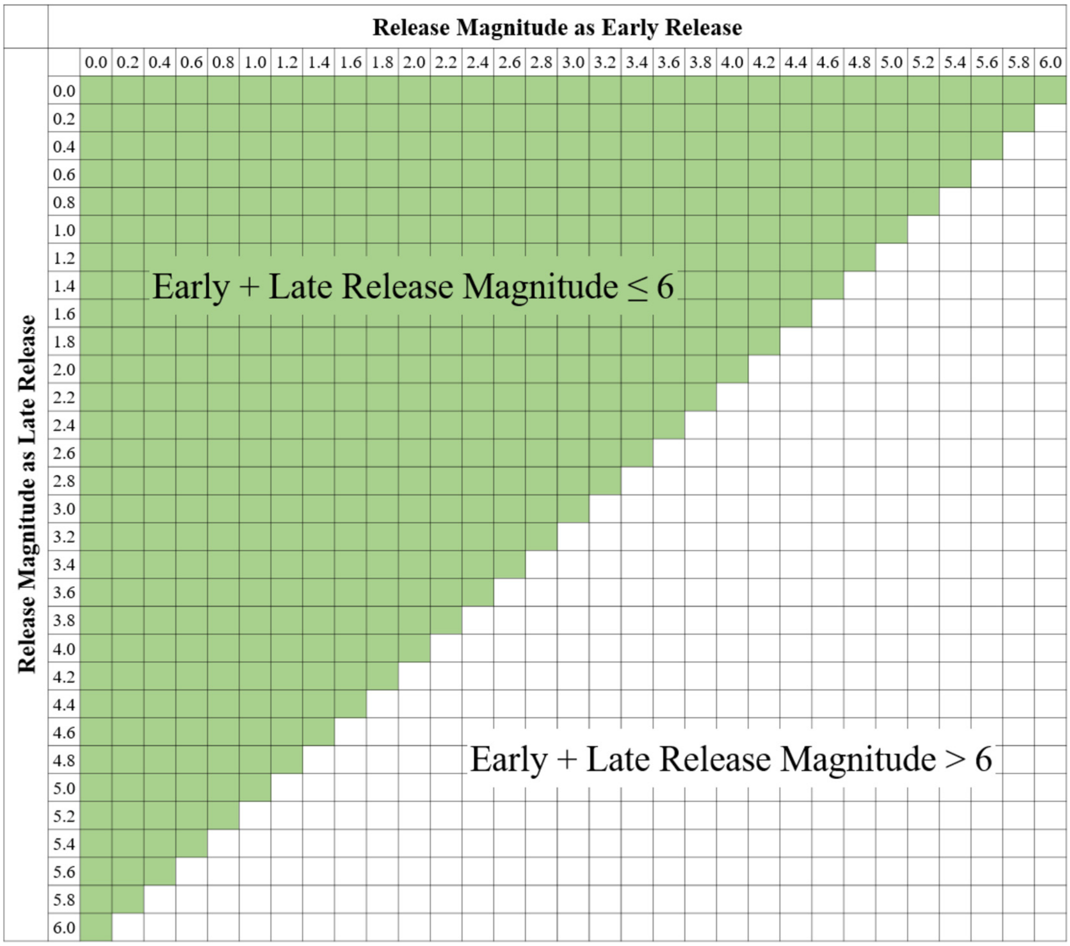

Fig. 5. Consequence models required to tabulate the look-up table (green).

Table 5
Representative starting point of early and late release for early and late health effects.

Early Health Effect (Early Fatality)		Late Health Effect (Late Cancer Fatality)	
Starting Point of Early Release	Starting Point of Late Release	Starting Point of Early Release	Starting Point of Late Release
45,680 s	219,765 s	36,719 s	194,800 s

amount of release during 72 h is regarded to be released in just 1 h. This assumption of a 1-h release duration is adopted for its conservatism in some aspects and because it facilitates the look-up table by treating release duration as a controlled variable. However, it should be noted that consequence models with a single plume segment can lead to under-estimation or over-estimation in practical consequence analyses for one STC. Time-discretization of release with adequate numbers of plume segments is recommended for more realistic modeling when the consequence of a specific STC is evaluated.

By performing consequence analyses, the conditional consequences of an accident can be calculated and the cells of the look-up table can be filled with those results. The conditional consequence found in the look-up table can be connected with the frequency of relevant multi-unit accidents evaluated from the Levels 1 [1] and 2 [2] MUPSA.

3.3. Mapping between consequence and frequency

In this study, mapping refers to the connecting of frequency and related conditional consequence from the look-up table in order to calculate the risk of a multi-unit accident scenario. Multi-unit site risk can then be calculated by totaling up the risk of each multi-unit accident scenario.

Consider the following example of a multi-unit accident scenario, referring to Table 4. If a three-unit accident comprising the release of STC-3, STC-12, and STC-15 is regarded, STC-3 and STC-15 are categorized as early release and STC-12 is categorized as late release. The relative release magnitudes of STC-3, STC-12, and STC-15 for latent cancer fatality are 0.00045, 0.00800, and 0.13384, respectively, and thus, the total release magnitude of early release (STC-3 and STC-15) is 0.13429 (= 0.00045 + 0.13384) and the total release magnitude of late release (STC-12) is 0.00800. The consequence of this three-unit accident scenario can then be found at the point (x = 0.13429, y = 0.00800) in the look-up table. Likewise, the consequence of every multi-unit accident scenario for both early fatality and latent cancer fatality can be found in the look-up table following the same method.

Mapping the consequence data to the frequency data was conducted using Microsoft Excel with the aid of VBA. The mapping process file consists of the following four spreadsheets: STC, EF_LCF, CDF, and EFR_LCFR.

The STC sheet contains various reference tables that provide essential information for all 21 STCs. Consequence results such as fatality data calculated in the consequence analysis and relevant information are summarized in the EF_LCF sheet, while frequency results such as core damage and source term release data calculated in Levels 1 [1] and 2 [2] MUPSA along with relevant information are summarized in the CDF sheet. These are all merged together in the last EFR_LCFR sheet.

The EFR_LCFR sheet is the key element of the whole mapping process file in which every piece of information from all other sheets is compared, classified, and processed to extract integrated risk information and insights. The final products of the EFR_LCFR sheet are, as its title implies, EFR (population-weighted average individual risk of early fatality) and LCFR (population-weighted average individual risk of latent cancer fatality), which are the same risk metrics employed in the SOARCA project [16].

Even though the interval between each row and column in the look-up table is 0.2, values for intermediate cases can be found using a double interpolation considering both early and late release. Similarly, for a 3-D look-up table, triple interpolation should be employed with regard to early, intermediate, and late releases.

3.4. Results and discussion of preliminary multi-unit Level 3 PSA for six-unit NPP

This study conducted a preliminary multi-unit risk assessment based on the PSA framework using the proposed look-up process to connect frequency data and consequence data. It should be noted that the objective of the current work was not to perform a detailed multi-unit Level 3 PSA but rather to focus on developing a new approach that enables and facilitates Level 3 MUPSA. An assessment with preliminary levels has been carried out to verify the operability of the approach; appropriate aspects should be added and modified to the basis of this approach as necessary.

Four representative multi-unit initiating events were considered in the preliminary assessment, namely MU-LOOP (multi-unit loss of off-site power), MU-LOUHS (multi-unit loss of ultimate heat sink), MU-TSUNAMI (multi-unit tsunami-induced event), and MU-SEISMIC-0.3 g/0.5 g/0.7 g/0.9 g/1.1 g (multi-unit seismic-induced event by various magnitudes). Data assuming an inter-unit seismic correlation coefficient of 0.3 was employed in the Level 1 MUPSA [1].

Due to restrictions of the current tool—not to the fundamental limitations of the approach— frequency data numbering only 10,000 could be connected to consequence data. In the future, a capable program should be developed to manage over 10,000 scenarios with PC memory. All scenarios in MU-LOOP, MU-LOUHS, and MU-S-0.3 were covered here though as their scenarios numbered below 10,000. The percentage distributions of CDF (core damage frequency), EFR, and LCFR for the example multi-unit accident are described in Table 6. From the results, it was found that EFR and LCFR are distributed consistently with CDF. The single-unit accident takes the largest proportion in case of MU-LOOP, MU-LOUHS, and MU-S-0.3. Detailed discussion can be found in the Level 1 MUPSA [1].

For the other initiating events, CDF distributions of the full-coverage case and the cut-off case are compared in Table 7. From the results of the comparison, the full-coverage and cut-off cases showed quite different CDF distributions. This implies that including an adequate amount of multi-unit accident scenarios in the Level 3 MUPSA is not optional but rather mandatory to estimate more comprehensive risk of multi-unit accidents.

4. Limitations of the study and further work

In this study, the starting time of release was categorized into

Table 6
Percentage distribution of CDF, EFR, and LCFR for MU-LOOP, MU-LOUHS, and MU-SEISMIC-0.3 g from the results of Level 3 MUPSA.

Initiating Event	MU-LOOP			MU-LOUHS			MU-SEISMIC-0.3 g		
Core Damaged NPPs/Total Number of NPPs	CDF (%)	EFR (%)	LCFR (%)	CDF (%)	EFR (%)	LCFR (%)	CDF (%)	EFR (%)	LCFR (%)
1/6	92.1%	87.9%	87.9%	98.0%	94.7%	95.6%	96.8%	92.9%	93.9%
2/6	7.1%	10.7%	10.8%	98.0%	94.7%	95.6%	96.8%	92.9%	93.9%
3/6	0.8%	1.4%	1.3%	1.6%	3.9%	3.2%	3.1%	6.9%	5.9%
4/6	0.1%	0.1%	0.1%	0.3%	1.1%	0.9%	0.1%	0.2%	0.2%
5/6	0.0%	0.0%	0.0%	0.1%	0.3%	0.2%	0.0%	0.0%	0.0%
6/6	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

CDF: Core damage frequency.
EFR: Population-weighted average individual risk of early fatality.
LCFR: Population-weighted average individual risk of latent cancer fatality.

Table 7
Comparison of CDF distribution between full-coverage and cut-off cases.

IE	MU-TSUNAMI		MU-SEISMIC-0.5 g		MU-SEISMIC-0.7 g		MU-SEISMIC-0.9 g		MU-SEISMIC-1.1 g	
# of Scenario	Total > 1,048,562	Cut-off below 10,000th order	Total 290,379	Cut-off below 10,000th order	Total > 1,048,562	Cut-off below 10,000th order	Total 579,590	Cut-off below 10,000th order	Total 257,467	Cut-off below 10,000th order
Core Damaged NPPs/ Total Number of NPPs	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)	CDF (%)
1/6	41.6%	73.1%	47.1%	49.2%	0.7%	2.4%	0.0%	0.0%	0.0%	0.0%
2/6	0.6%	1.1%	34.8%	36.0%	4.2%	12.0%	0.2%	0.2%	0.2%	0.2%
3/6	0.1%	0.0%	14.0%	13.2%	13.8%	31.6%	1.1%	1.1%	1.0%	1.0%
4/6	1.6%	2.0%	3.4%	1.5%	27.7%	38.7%	4.5%	4.3%	4.0%	4.0%
5/6	0.2%	0.1%	0.6%	0.0%	33.2%	13.3%	17.1%	15.9%	10.0%	10.1%
6/6	55.8%	23.7%	0.1%	0.0%	20.3%	2.1%	77.1%	78.5%	84.8%	84.7%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

only two categories (early and late release) and therefore, the resulting look-up table was two-dimensional. In further studies, release may be divided into three categories (early, intermediate, and late release) or more. It is expected that look-up tables with higher dimensions will have diminished uncertainties and provide more reliable consequence results.

In order to treat release duration as a controlled variable, it should be identical for each STC. The duration of release was set to 1 h in this work and the release amount cumulated over 72 h of accident progression was assumed to be released in this duration; this assumption could lead to under-estimation or over-estimation of the consequences. Further, absolute release amounts of the actual STCs were not treated, but rather the relative release magnitude to the highest release amount (STC-16) was accounted for. This made it difficult to configure more realistic release durations and temporal progression. However, as mentioned in Section 2, a variety of equivalent converting methods can be employed and tested to scale the magnitude of releases—such trials could provide the solution to the present limitation regarding temporal progression of release.

Another assumption made in this work was that each release occurred from the same location (single point). If the units are constructed at various distances from each other in a site though, this assumption could be a source of uncertainty that influences the consequence results. A method to designate the appropriate point representing all constituting units can be suggested, or a new approach reflecting the location of each unit should be developed.

The reactor type was assumed here to be identical in all units, but if different reactor types are employed at a site, different STCs can be released from each one. However, they can still be treated relatively by the same criteria after applying the appropriate equivalent conversion method.

Based on health effect, the relative release magnitude of the most severe STC was set to be the unit magnitude. Another setting can be employed if it is helpful to enhance the reliability of the look-up table approach.

When performing the consequence analysis, long-term exposures such as ingestion were not considered in order to only focus on the exposure during the specified emergency phase (one week). Long-term exposure should be included in developing updated look-up tables in the future, after developing long-term exposure models such as food chain models with a high degree of completion.

For conservatism, emergency response was not considered in the consequence analysis. Another reason for its exclusion is that emergency response varies by STC. Release amount and timing can influence public emergency response at the emergency preparedness zone, especially at the UPZ (urgent protective action planning zone), which is considered a barrier to building the look-up table.

The number of multi-unit accident frequency data provided by the Levels 1 [1] and 2 [2] MUPSA ranges from about a thousand to more than a million depending on the initiating events and cut-off criteria. The method to map reference consequence data to each frequency data used in this study requires many calculation cells, and if the number of multi-unit accident frequency data exceeds a certain number, the number of required cells reaches beyond the limit that Microsoft Excel can practically handle. Considering this limitation, the number of multi-unit accident frequency data used in the mapping process here was limited to a maximum of 10,000. A more appropriate computer program using PC memory for full-coverage of all multi-unit accident scenarios can be developed to overcome this limitation.

As aforementioned, this study focused on the development of a new approach to enable and facilitate Level 3 MUPSA covering all multi-unit accident scenarios with practical modeling effort. Following-up studies are welcomed to resolve the limitations and reinforce the reliability of this approach.

5. Conclusions

To date, few studies on Level 3 multi-unit PSA have been conducted, which concentrated on selected multi-unit accident scenarios having relatively high priority. In order to fully cover the consequences of all multi-unit accident scenarios, a new method adopting a look-up table approach has been developed in this study. With this approach, each consequence result can be found on the established look-up table and connected with corresponding frequency in order to estimate risk.

It was ascertained that there could exist a large difference between cases whether all multi-unit accident scenarios were covered or not. This insight supports the importance of developing an approach that can provide comprehensive consequence results for each multi-unit accident scenario.

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