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Original Article

Performing a multi-unit level-3 PSA with MACCS

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ABSTRACT

MACCS (MELCOR Accident Consequence Code System), WinMACCS, and MelMACCS now facilitate a multi-unit consequence analysis. MACCS evaluates the consequences of an atmospheric release of radioactive gases and aerosols into the atmosphere and is most commonly used to perform probabilistic safety assessments (PSAs) and related consequence analyses for nuclear power plants (NPPs). WinMACCS is a user-friendly preprocessor for MACCS. MelMACCS extracts source-term information from a MELCOR plot file.

The current development can combine an arbitrary number of source terms, representing simultaneous releases from a multi-unit facility, into a single consequence analysis. The development supports different release signatures, fission product inventories, and accident initiation times for each unit. The treatment is completely general except that the model is currently limited to collocated units.

A major practical consideration for performing a multi-unit PSA is that a comprehensive treatment for more than two units may involve an intractable number of combinations of source terms. This paper proposes and evaluates an approach for reducing the number of calculations to be tractable, even for sites with eight or ten units. The approximation error introduced by the approach is acceptable and is considerably less than other errors and uncertainties inherent in a Level 3 PSA.

1. Introduction

Evaluating the risks associated with a multi-unit site of nuclear power plants has been a topic of research dating back to at least 1983, when an early probabilistic safety assessment (PSA) was performed for the Seabrook Station in New Hampshire, USA [1]. However, very little work continued following that pioneering study until after 2011 when the Fukushima Daiichi accident occurred in Japan. Being the first multi-unit accident, Fukushima has spurred keen international interest in characterizing and quantifying risks for multi-unit sites.

Conducting a full multi-unit PSA is fraught with difficulties that are only recently being investigated. For existing reactors, most of the difficulties are associated with the Level 1 and Level 3 portions of the analysis.

In terms of Level 1, a significant difficulty is assessing the frequency of single-versus multi-unit accidents. The most obvious contributors to multi-unit frequency are from external events, like at Fukushima. However, other contributors are from shared resources between units, including both equipment and reactor operators and crew [2]. A variety of common cause failures can also lead to multi-unit accidents.

The Level 2 portion of a PSA can usually be performed independently for each unit, at least when shared resources between units contribute insignificantly to accident progression at a unit. Shared resources can result in coupling between the units, which complicates the analysis of accident progression. Some current generation commercial reactors, such as CANDU (Canada Deuterium Uranium) reactors, can have significant shared resources. CANDU reactors share a vacuum building that can lead to coupling effects when two or more units undergo an accident simultaneously. Potential future installations of small modular and other

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advanced reactors may have considerable shared resources and thus may need to be evaluated in a coupled manner. However, most current generation multi-unit sites are amenable to single unit source-term evaluations.

The primary difficulty with the Level 3 portion of a PSA is the untenable number of source-term combinations that may need to be evaluated to assess the overall risk to the public. The chief purpose for this paper is to explore several ideas for reducing the number of consequence calculations to a level that is tractable.

2. Current state of practice for multi-source evaluations

Integration of source terms from multiple sources is complex. The complexity arises from the following issues:

- In principle, reactor shutdown (the time when atomic fissioning and activation of nuclei essentially cease) may be different for each source. This shutdown time specifies the time corresponding to an initial inventory for each source. Prior to this time, the core inventory is usually changing very slowly; from this time forward, decay and ingrowth are assumed to occur and some fission products are rapidly depleted.
- Each source can have a different inventory. Differences can be based on differences in the units themselves or based on each unit being at a different point during its operating cycle.
- Different accident scenarios or variations in accident scenario can result in different release signatures from each unit or source.
- The locations of releases from the multiple sources can be different, i.e., there can be spatial offsets between units.
- Depending on the spatial offsets for the multiple sources, plumes can merge and form combined plumes or they can remain separate and transport independently. When plumes merge, the buoyancy and resulting rise height is different than when plumes rise independently.

Of these issues, the first three have been addressed in the current version of the MELCOR Accident Consequence Code System (MACCS) for estimating the consequences of a release of radioactive materials into the atmosphere [3]. Issues of spatial offset of multiple source terms are currently being evaluated [4], but no model with a full suite of consequence metrics, such as MACCS, is known by the authors to be capable of implementing a general treatment of spatial offsets between multiple sources. In any case, approximating multiple sources as being collocated rather than spatially separated has little influence on consequence results beyond several kilometers for typical multi-unit reactor sites [4]. The conditions under which plumes merge or transport separately remains an issue for future research.

The current multi-source capability in MACCS has one major strength: it can evaluate a very general combination of release signatures representing different accident scenarios; unique plant characteristics, including core inventory; and different accident initiation times leading to distinct SCRAM (Safety Control Rod Axe Man, used to designate shutting down a reactor) times at the multiple units. The disadvantage is that it does not currently account for spatial offsets between units, and so it does not fully account for consequences like early health effect risks near the site boundary.

In a typical Level 3 PSA, potential accident progressions and source terms at each unit of a multi-unit site are evaluated independently, as discussed above. The normal process is often to create a unique set of source-term categories (STCs or release categories) for each unit that characterizes the releases from the full range of potential accidents. However, a unified set of STCs that can be applied to all units of a multi-unit site significantly reduces the number of source-term combinations that need to be evaluated in a Level 3 PSA, all else being equal, as discussed in the following section. In some cases, it may be advantageous to have distinct STCs that apply to a subset of the units at the site.

3. Need for a simplified approach

The need for a simplified approach becomes painfully obvious when the potential number of source-term combinations is considered. For example, when M unique units are evaluated, each having its own set of N STCs, Table 1 shows the number of source-term combinations required to perform a complete Level 3 consequence analysis.

Depending on computing resources available, the number of consequence calculations expressed in the table may not be tractable for a Level 3 analyst to perform. For example, the yellow shaded portion of the table requires 100 or more consequence calculations to be performed; the red portion requires 1,000 or more calculations to be performed. Even the most sophisticated computing system at the time of this writing could not perform millions or billions of consequence analyses in a reasonable time, each of which may take an hour or more to perform. (There are 8,760 h in a year. Even a computer that could perform 1,000 calculations simultaneously would require more than a year to evaluate many of the source-term combinations shown in the table if each calculation takes 1 h. In the following discussion, each consequence analysis is assumed to require 1 h of CPU time.)

In practice, the numbers of source-term combinations could be reduced from those shown in Table 1 (and similarly in Table 2) because of Level 1 and 2 considerations that evaluate some source-term combinations to have such low frequencies that they contribute insignificantly to risk. Thus, the numbers of accident combinations presented here should be viewed as upper bounds. Nonetheless, the number of source-term combinations in multi-unit accidents with more than a few units and more than a minimal set of STCs are likely to be too many to evaluate in a reasonable timeframe with typical computing resources without a simplified approach.

The equation for the number of combinations of source terms for all units simultaneously undergoing an accident is N^M. However, the consequence analyst would need to evaluate all subset combinations as well, i.e., calculations involving a single unit, two units, three units, etc., up to the total number of units at the site. Thus, the number of consequence analyses needed to perform a complete, rigorous, Level 3 analysis is $(N+1)^M-1$. This equation is derived by adding an additional STC to express the null source term and subtracting the case when all the source terms are null [5]. For example, the total number of consequence analyses for two units with 10 STCs is 120; the total number of consequence analyses for three units is 1,330. The latter number accounts for three sets of single unit accidents ($3 \times 10 = 30$), three combinations of two-unit accidents ($3 \times 100 = 300$), plus 1,000 combinations of three-unit accidents.

For the cases shown in Table 1, a user would be limited to about 2 units if the requirement were to perform all the analyses on a single processor in a week or less, to about 3 units if the requirement were to perform all the analyses on ten processors in a single week or less, and to about 4 units if the requirement were to perform all the analyses on 100 processors in a single week or less. Performing analyses for more than 4 units is untenable for most users unless the number of STCs is restricted to be very small.

Table 2 shows the analogous case where the same STCs are used for all the units. This table also assumes that all units are collocated; if they are not, the consequences for two units can be different even

Table 1
Number of analyses required to assess all combinations of M units, including subsets, with each unit represented by N unique STCs.

Number of Source-Term Categories (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	37,822,859,360

Table 2
Number of analyses required to assess all combinations of M units, including subsets, with each unit represented by the same N STCs.

Number of Source-Term Categories (N)	Number of Units Undergoing Accident (M)							
	1	2	3	4	5	6	7	8
5	5	20	55	125	251	461	791	1,286
10	10	65	285	1,000	3,002	8,007	19,447	43,757
15	15	135	815	3,875	15,503	54,263	170,543	490,313
20	20	230	1,770	10,625	53,129	230,229	888,029	3,108,104

when the source terms are the same. The numbers of source-term combinations are significantly less in this table than in Table 1, which creates some motivation to use the same STCs for most, if not all, of the units at a multi-unit site. This approach, using the same STCs for all units, allows about one or two additional units to be evaluated as compared with the previous approach, using different STCs for each unit, all else being equal.

The number of source-term combinations for M units simultaneously undergoing an accident is expressed by $(N + M - 1)!/[(N-1)! \times M!]$. Considering combinations involving subsets of units undergoing simultaneous accidents, the expression becomes $(N + M)!/[N! \times M!]$-1, where N in the previous equation is replaced by N+1 to account for the null source term and the combination with all null source terms is subtracted. Table 2 shows the number of evaluations needed to perform a complete Level 3 PSA, including all subset combinations.

The information in this section makes clear that it is not tractable to perform Level 3 consequence analyses for more than 6 units when 10 or more STCs are used in the analysis, even when about 100 processors are available for a week of dedicated computations. When only 10 processors are available for the analysis, the number diminishes to three or four units. Without a simplified approach, a user may in practice be limited to performing multi-unit consequence analyses on a relatively small number of units. As mentioned above, the combinations could be reduced if Level 1 and 2 considerations show some source-term combinations contribute insignificantly to risk. The following discussion assumes that no source-term combinations are eliminated from consideration.

4. Simplified approach

The focus of this paper is to identify a simplified approach that allows a user to perform a Level 3 consequence analysis on a relatively large number of units (eight or more) with a reasonable computational effort on common computer systems, i.e., ones that built around a large cluster or a supercomputer. Additionally, the simplified approach should introduce relatively small approximation errors so that the consequence results are not significantly distorted, since distorted results could lead to incorrect conclusions at the end of the Level 3 process.

The idea proposed in this paper is to first group source terms by order of magnitude in terms of the most important of the figures of merit. Several figures of merit could be considered, such as integral cesium release magnitude, integral iodine release magnitude, delay to the start of release, or duration of release. Release duration is important because longer durations tend to lead to larger contamination areas with lower contamination levels due to wind shifts. The footprints of areas contaminated at various levels have direct impacts on consequence metrics such as population dose and economic losses.

A conclusion of the recent SOARCA [6–10] studies is that most realistic source terms begin after several hours have elapsed (typically 3 h or more) and create essentially no potential for early health effects. For such source terms, the integral cesium release is generally the most important figure of merit. Thus, for the purposes of this study, integral cesium release fraction is chosen as the figure of merit used to bin the source terms and the STCs are defined as shown in Table 3.

The choice of cesium release magnitude as the sole criterion to define STCs is questionable when many units are involved in an accident because the effects of short-term dose on early health effects is highly nonlinear. When the contribution of all units undergoing an accident with the worst combination of source terms is enough to create early health effects, then a secondary criterion to distinguish the potential for early health effects should be considered. One possibility is to split the Level 3 consequence analysis into two parts, one part to evaluate the risk of early health effects and one to evaluate all other risk metrics. In principle, different source terms might be selected to represent the STCs for the two analyses. If this were done, it is very likely that the analysis to evaluate risk of early health effects would involve a small subset of the overall analyses because most source-term combinations would not create large enough short-term doses to produce a potential for early health effects. A defensible strategy to analyze early fatality risk for multi-unit accidents is a topic for future investigation.

To reduce the number of source-term combinations required for

Table 3
Definition of STCs.

Name	Range of Integral Cesium Release Fractions
STC 1	10^{-1} to 10^{0}
STC 2	10^{-2} to 10^{-1}
STC 3	10^{-3} to 10^{-2}
STC 4	10^{-4} to 10^{-3}
STC 5	10^{-5} to 10^{-4}
STC 6	10^{-6} to 10^{-5}
STC 7	10^{-7} to 10^{-6}

the Level 3 consequence analysis, we suggest calculating combinations only where the smaller Cs release fraction contributes at least on the order of 10% to the overall release fraction. In other words, combinations of STC N with STC N-1 are considered, but not with STC N-2, STC N-3, etc. More generally, we define the maximum difference, L, between STC-number combinations to be calculated, and for the following discussion it is suggested that L = 1.

The methods proposed here to reduce the number of analyses to be performed are all based on substitution of consequences for source term combinations that fall below a prescribed relative difference in some release quantity. We refer to this general category of simplified approaches as Consequence Substitution Approaches (CSAs), where the relative magnitude of cesium release is chosen here as the quantity to define the levels below which consequences are substituted using one of the options described below.

Several options can be chosen to represent source-term combinations for which the difference in STCs is greater than L. The following list is written for a two-unit case.

1. Calculate consequences by substituting the smaller STC when the STCs differ by an integer I, where I > L, by the STC that differs by L. This option is intended to produce conservative results since consequences are always calculated for the same or greater release magnitude than the exact consequence analysis.
2. Calculate consequences by substituting the smaller STC when the STCs differ by an integer I, where I > L, by a null release, i.e., calculate consequences using a single-unit source term. This option is likely to produce nonconservative results since smaller source terms are used than the exact ones.
3. Calculate consequences by substituting the result when the smaller STC differs by an integer I, where I > L, by the average of the result for the STCs with a difference of L and the result for the smaller STC being replaced by a null release. This can be generalized for the consequence analyses with more than two units as described below. This option is likely to produce conservative results but may produce nonconservative results.
4. Calculate consequences by substituting the result when the smaller STC differs by an integer I, where I > L, by the weighted sum of the result for the case with the STCs having a difference of L and the result when the smaller STC is replaced by a null release, i.e., a single-unit source term, using the following equation:

$$C(N,\ N-I) = C(N, N-L) \times \frac{RF(N-I)}{RF(N-L)} + C(N)\frac{RF(N-L) - RF(N-I)}{RF(N-L)} \quad (1)$$

where.

$\boldsymbol{C}(\boldsymbol{N}, \boldsymbol{J})$ = consequence result for the combination of STC N and STC J

$\boldsymbol{C}(\boldsymbol{N})$ = consequence result for STC N alone, i.e., a single-unit consequence

$\boldsymbol{RF}(\boldsymbol{J})$ = integral Cs release fraction of STC J

CSA Option 4 could produce conservative or nonconservative results. There are other options for substituting consequences for STCs that contribute very little to the overall release, but the above set is proposed for evaluation. These options are explored in the following section.

Eqn 1 is written for a two-unit analysis but it can be extended to a larger number of units. For example, for three units when I > L and J > L, it becomes

$$C(N,\ N-I,\ N-J) = C(N, N-L,\ N-L) \times \frac{RF(N-I) + RF(N-J)}{2 \times RF(N-L)} + C(N)\frac{2 \times RF(N-L) - RF(N-I) - RF(N-J)}{2 \times RF(N-L)} \quad (2)$$

For the case when I = L but J > L, Eqn 2 becomes a modified version of Eqn 1 as shown in Eqn 3.

$$C(N,\ N-L,\ N-J) = C(N, N-L,\ N-L) \times \frac{RF(N-J)}{RF(N-L)} + C(N, N-L)\frac{RF(N-L) - RRF(N-J)}{RF(N-L)} \quad (3)$$

To evaluate the CSA Options, consider an example in which there are two identical units and the same set of five STCs are used to characterize the potential releases from both units. Table 2 shows that a total of 20 consequence analyses are required, which are 15 combinations of two-unit source terms plus 5 single unit accidents for this case. The required two-unit STC combinations are shown in Table 4 below in the row labeled Best Estimate. Only 9 two-unit simulations are needed to perform the consequence analyses using any of the CSA Options described above, as seen by counting the number of unique entries in the row labeled CSA. That means that 14 calculations are required, 9 two-unit combinations plus 5 single-unit calculations. This does not seem like an impressive reduction from 20, but the reduction is greater when more units and STCs are considered.

The general equation for the number of required M-unit consequence analyses is M × (N-1)+1 when L = 1. Considering subsets of units undergoing an accident, the general equation is M × (M+1) × (N-1)/2 + M when L = 1. Table 5 shows the required number of consequence analyses using this approach for the same combinations of M and N as in Table 2. At the extreme corner of the table, an eight-unit analysis with 20 STCs requires a total of 692 consequence analyses. Thus, in the worst case, 4 processors might be needed to conduct the full set of consequence analyses in about one week using any of the CSA Options. Clearly, the number of required analyses using any of the options listed above are significantly less than the numbers shown in Table 2.

5. Evaluation of consequence substitution approach

To evaluate the CSA Options proposed in the previous section, a simple benchmark problem is defined. Then each of the options described above, the best-estimate and the four CSA Options, are evaluated for the benchmark problem to determine the approximation error introduced by each of the options. A set of consequence metrics, some of which are highly nonlinear, are evaluated to assess the approximation error for a range of outcomes of general interest.

5.1. Benchmark problem definition

The problem is defined to be relatively simple to reduce the effort needed to perform a best-estimate analysis. The following characteristics are adopted:

- Severe accidents are initiated simultaneously at two identical, collocated units.
- The same five STCs are used to characterize accidents at each of the units.
- The source terms representing the five STCs are taken from recent SOARCA work, as described below.

Table 4
Comparison of the two-unit STC combinations needed for two identical units with 5 STCs for the best-estimate and the CSA options described above.

Number	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Best	1	STC 1	STC 1	STC 1	STC 1	STC 1	STC 2	STC 2	STC 2	STC 2	STC 3	STC 3	STC 3	STC 4	STC 4	STC 5
Estimate	2	STC 1	STC 2	STC 3	STC 4	STC 5	STC 2	STC 3	STC 4	STC 5	STC 3	STC 4	STC 5	STC 4	STC 5	STC 5
CSA	1	STC 1	STC 1	STC 1	STC 1	STC 1	STC 2	STC 2	STC 2	STC 2	STC 3	STC 3	STC 3	STC 4	STC 4	STC 5
	2	STC 1	STC 2	STC 2	STC 2	STC 2	STC 2	STC 3	STC 3	STC 3	STC 3	STC 4	STC 4	STC 4	STC 5	STC 5

Table 5
Number of analyses required to assess all combinations of M units, including subsets, with each unit represented by the same N STCs for any of the CSA options.

Number of Source-Term Categories (N)	Number of Units (M)							
	1	2	3	4	5	6	7	8
5	5	14	27	44	65	90	119	152
10	10	29	57	94	140	195	259	332
15	15	44	87	144	215	300	399	512
20	20	59	117	194	290	405	539	692

- Each STC is assigned a conditional probability that is loosely consistent with the likelihood of the source term from the SOARCA work.
- The STC at Unit 2 is independent of the STC at Unit 1.
- The risk for the two units simultaneously undergoing an accident is assessed from the following equation:

$$Risk = \sum_{i=1}^{N} \sum_{j=1}^{N} f(i,j) \times C(i,j) \quad (4)$$

where the symbols in Eqn 4 have the following definitions:

$Risk$ = Risk of a 2-unit accident
$f(i,j)$ = Joint frequency of STC i in Unit 1 and STC j in Unit 2
$C(i,j)$ = Consequence of simultaneous STC i in Unit 1 and STC j in Unit 2

The five STCs are defined in Table 3 and i.e., ordered by decades of cesium release fraction. Table 6 lists the representative source terms selected for each of the STCs, the corresponding integral cesium release fractions, and provides the conditional probabilities for each STC. Conditional probability here means the probability of a specific STC conditional on an accident occurring.

Fig. 1 shows the release timing for each of the source terms. Notice that STC 5 skips an order of magnitude, i.e., the release fraction is in the range of 10^{-7} to 10^{-6} and there is no STC in the range of 10^{-6} to 10^{-5}. The CSA Options are applied as though there were no gap in source-term magnitude.

For the purposes of this investigation, the joint frequency distribution in Equation (4) is replaced by the product of the conditional probabilities in Table 6. So, the consequences are presented as being conditional on a two-unit accident occurring rather than per year of reactor operation. Using the products of conditional probabilities is consistent with the above assumption that the STC in Unit 2 is independent of the one in Unit 1.

5.2. Benchmark results

The results of the best-estimate approach and the four CSA Options are evaluated for 9 consequence metrics:

- Population dose within 80 km of the site. Population dose is the sum of the individual doses to members of the population.
- Individual latent cancer fatality (LCF) risk for the population within 80 km of the site. LCF risk is averaged over the population and includes doses from inhalation, cloudshine, and groundshine.
- Early fatality risk within 1.6 km of the site. Early fatality risk has a highly nonlinear dose response. It represents the average risk to individuals within a 1.6 km radius of the site.
- Land area exceeding an activity of Cs-137 per square meter of land. Four threshold levels are considered: 1 μCi/m^2, 5 μCi/m^2, 15 μCi/m^2, and 40 μCi/m^2.
- Area requiring decontamination to restore land to EPA requirements for habitability
- Population displaced in order to perform decontamination

The results are shown in Table 7, first for the best-estimate approach, then comparisons are provided for the four CSA Options described in Section 4. Of the four options, Option 1 is the most conservative and Option 4 is the most accurate. Option 2 is simpler than Option 4 and produces almost the same results but is slightly less conservative. If some of the source terms, especially STC 2 and STC 3, had been more closely spaced, Option 2 could have shown larger errors, so Option 4 is recommended when accuracy is the primary consideration and conservatism is not critically important. For this benchmark, the maximum nonconservative error for CSA Option 4 is only −2%, which is quite acceptable. However, there is no guarantee that the error could not be larger for other cases.

To put a 2% error into perspective, the relative percentage difference between mean and median LCF risk (mean results are displayed in Table 7) ranges from 10% to 66% for the five single-unit source terms shown in Table 6 and Fig. 1. Thus, the approximation error introduced by the CSA Option 4 is significantly smaller than the variability created by uncertain weather.

6. Conclusions

One of the significant complications with performing a multi-unit Level 3 PSA has been dealing with the intractable number of source-term combinations that can result for sites with more than a few units. Several options are proposed and evaluated that significantly reduce the number of source-term combinations required to perform a Level 3 PSA. All the proposed simplification options appear to be viable in terms of accuracy while reducing the number of required calculations to a tolerable level, making consequence analyses to support eight or more units with 20 STCs viable. One of the proposed options is almost certain to be conservative while another is likely to provide the most accurate results. The best of

Table 6
STCs used in the benchmark problem.

STC Number	Name	Integral Cesium Release Fraction	Conditional Probability of STC
STC 1	Early Containment Failure with Large Release	1.8×10^{-2}	0.01
STC 2	Induced Steam Generator Tube Rupture	9.2×10^{-3}	0.12
STC 3	Late Containment Failure	5.1×10^{-4}	0.435
STC 4	Early Containment Failure with Small Release	3.3×10^{-5}	0.315
STC 5	No Containment Failure	1.8×10^{-7}	0.12

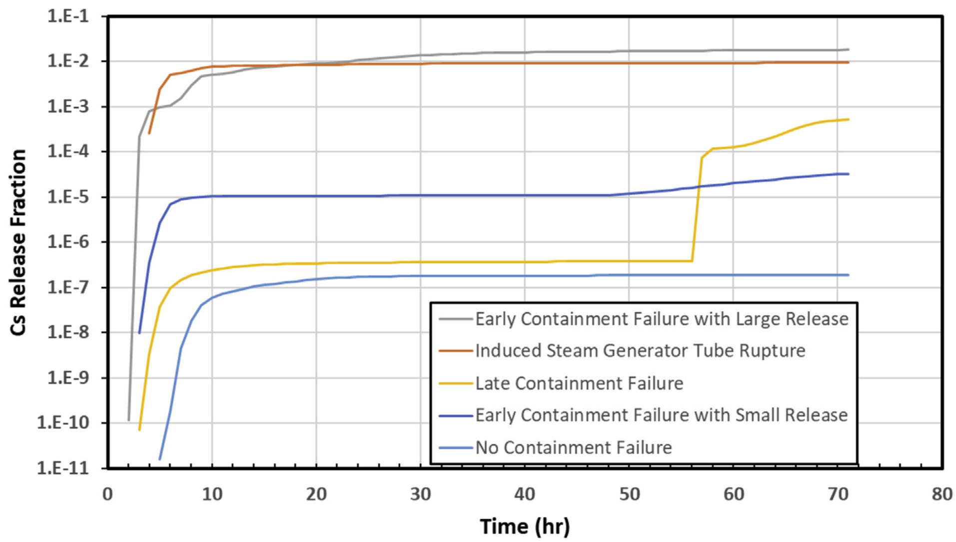

Fig. 1. Cesium release timing for five STCs.

Table 7
Mean (over weather) consequence results for the benchmark problem.

Result	Population Dose (Person-Sv) (0–80 km)	LCF Risk (0–80 km)	Early Fatality Risk (0–1.6 km)	Land Area (ha) Exceeding 1 μCi Cs-137/m^2	Land Area (ha) Exceeding 5 μCi Cs-137/m^2
Best Estimate	3,983	4.97E-05	0.00E+00	90,600	13,125
CSA Option 1	4,356	5.47E-05	0.00E+00	96,590	14,448
Relative Error 1	9%	10%	0%	7%	10%
CSA Option 2	3,903	4.95E-05	0.00E+00	91,105	13,136
Relative Error 2	−2%	0%	0%	1%	0%
CSA Option 3	4,130	5.21E-05	0.00E+00	93,847	13,792
Relative Error 3	4%	5%	0%	4%	5%
CSA Option 4	3,923	4.98E-05	0.00E+00	91,278	13,182
Relative Error 4	−2%	0%	0%	1%	0%

Result	Land Area (ha) Exceeding 15 μCi Cs-137/m^2	Land Area (ha) Exceeding 40 μCi Cs-137/m^2	Area Decon. (ha)	Population Displaced by Decon.
Best Estimate	3,605	969	5,211	10,123
CSA Option 1	3,814	1,079	5,678	10,984
Relative Error 1	6%	11%	9%	9%
CSA Option 2	3,568	965	5,211	10,097
Relative Error 2	−1%	0%	0%	0%
CSA Option 3	3,691	1,022	5,444	10,541
Relative Error 3	2%	5%	4%	4%
CSA Option 4	3,576	969	5,231	10,134
Relative Error 4	−1%	0%	0%	0%

the simplified approach options, referred to here as Consequence Substitution Approach Options, produces results that are within about 2% of the exact result in this benchmark comparison, but errors could be somewhat larger for other cases.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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