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Practical Aspects of Performing a Multi-Unit Level 3 PSA with MACCS

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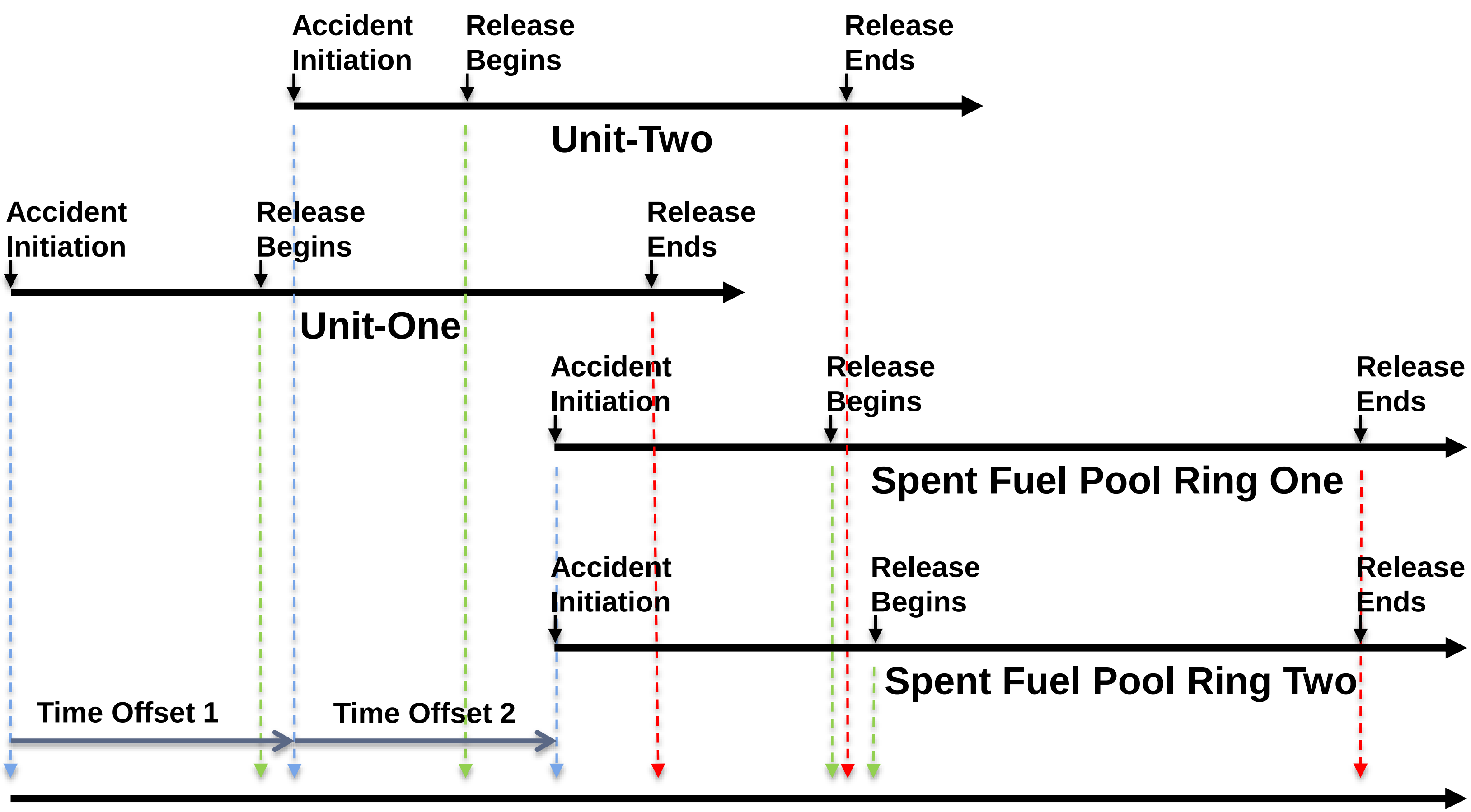
MACCS Best Estimate Framework for Multi-Unit Consequence Analyses

- Ability to treat multiple, overlapping source terms
  - Different accident initiation times
  - Different release signatures
  - Different isotopic inventories
- Spent fuel pools present a special case
  - Multiple fuel cooling times (different inventories)
  - Release signature may be a function of cooling time
- Overall release may continue for more than a week

Multi-Unit Consequence Analysis
Integrating Multiple Source Terms

- Time offsets account for delays between initiating events
- Radioactive decay is relative to each initiating event



Source Term Properties Treated with MACCS

- Source term for each unit can have unique properties
  - Inventory
  - SCRAM time (beginning of decay and ingrowth)
  - Release timing and signature
  - Initial release height and buoyancy
  - Aerosol size distribution
  - Building dimensions
- All source-term properties have an effect on consequence results

Strengths and Weaknesses of Current Best-Estimate WinMACCS Framework

- Strength
  - Uses rigorous superposition of source-term combinations to accurately estimate consequences

- Weaknesses
  - Does not currently facilitate automation of a large set of source term combinations
    - Weakness is being addressed by extension of cyclical file option
  - Currently limited to a single release location
    - Adequate for results averaged over a 10-km or larger radius
    - Typically conservative for peak doses near site boundary and early health effects (but not always)
    - Weakness can be overcome by further ATD development

Requirements for Best-Estimate MUPSA with M Unique Source Term Categories

Number of Consequence Variations for M Unique Units with N Source Term Categories								
Number of Source Term Categories (N)	Number of Units Undergoing Accident (M)							
	1	2	3	4	5	6	7	8
5	5	25	125	625	3,125	15,625	78,125	390,625
10	10	100	1,000	10,000	100,000	1,000,000	10,000,000	100,000,000
15	15	225	3,375	50,625	759,375	11,390,625	170,859,375	2,562,890,625
20	20	400	8,000	160,000	3,200,000	64,000,000	1,280,000,000	25,600,000,000

- Number of required consequence analyses is N^M for an accident at all M units and $(N+1)^M-1$ for accidents at any subset of the units
- Not practicable for MUPSA with more than about 2 units

Requirements for Best-Estimate MUPSA with M Identical Source Term Categories

Number of Consequence Variations for M Identical Units with N Source Term Categories								
Number of Source Term Categories (N)	Number of Units Undergoing Accident (M)							
	1	2	3	4	5	6	7	8
5	5	15	35	70	126	210	330	495
10	10	55	220	715	2,002	5,005	11,440	24,310
15	15	120	680	3,060	11,628	38,760	116,280	319,770
20	20	210	1,540	8,855	42,504	177,100	657,800	2,220,075

- Number of required consequence analyses is

  $$(N+M-1)!/[(N-1)!M!]$$

- Not practicable for MUPSA with
  - More than 2 to 4 units, depending on number of source term categories

Fundamental Issue for Level 3 Best-Estimate Framework for MUPSA

- A simplified approach is needed to reduce the number of source-term combinations to be evaluated.
- The simplified approach should be tested to ensure that approximation error is acceptably small.
  - A two-unit problem is constructed to demonstrate acceptable accuracy.
  - Extrapolation to more than two units is assumed for now, but should be tested in the future.

Simplified Approach for Reducing Number of Source Term Combinations

- Organize source term categories so that integrated release fractions of important chemical groups are factors of X, e.g., X = 10 and source term categories are
  - STC 1 – Cs release fraction between 10^0 and 10^{-1}
  - STC 2 – Cs release fraction less than 10^{-1} and 10^{-2}
  - STC3 – Cs release fraction less than 10^{-2} and 10^{-3}
  - …
- Only evaluate results for combinations of source term categories that differ by up to 1 (L = 1)
- Conservatively replace categories with differences greater than L-1 by categories with L-1
- Alternative assumptions not evaluated here
  - Ignore source term categories that are more than one category lower
  - Use a weighted average of the two results

Example of Simplified Approach

Comparison of Number of Consequence Variations for 2 Identical Units with 5 Source Term Categories - Best Estimate Vs. Simplified Approach															
	Source Term Combinations for 2 Units and 5 Source Terms														
Source Term Combination Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Best Estimate	1 x 1	1 x 2	1 x 3	1 x 4	1 x 5	2 x 2	2 x 3	2 x 4	2 x 5	3 x 3	3 x 4	3 x 5	4 x 4	4 x 5	5 x 5
Simplified Approach	1 x 1	1 x 2	1 x 2	1 x 2	1 x 2	2 x 2	2 x 3	2 x 3	2 x 3	3 x 3	3 x 4	3 x 4	4 x 4	4 x 5	5 x 5

- Two units
- Five source terms
- Required number of consequence analyses is reduced from 15 to 9

Required Analyses for Simplified Approach for MUPSA

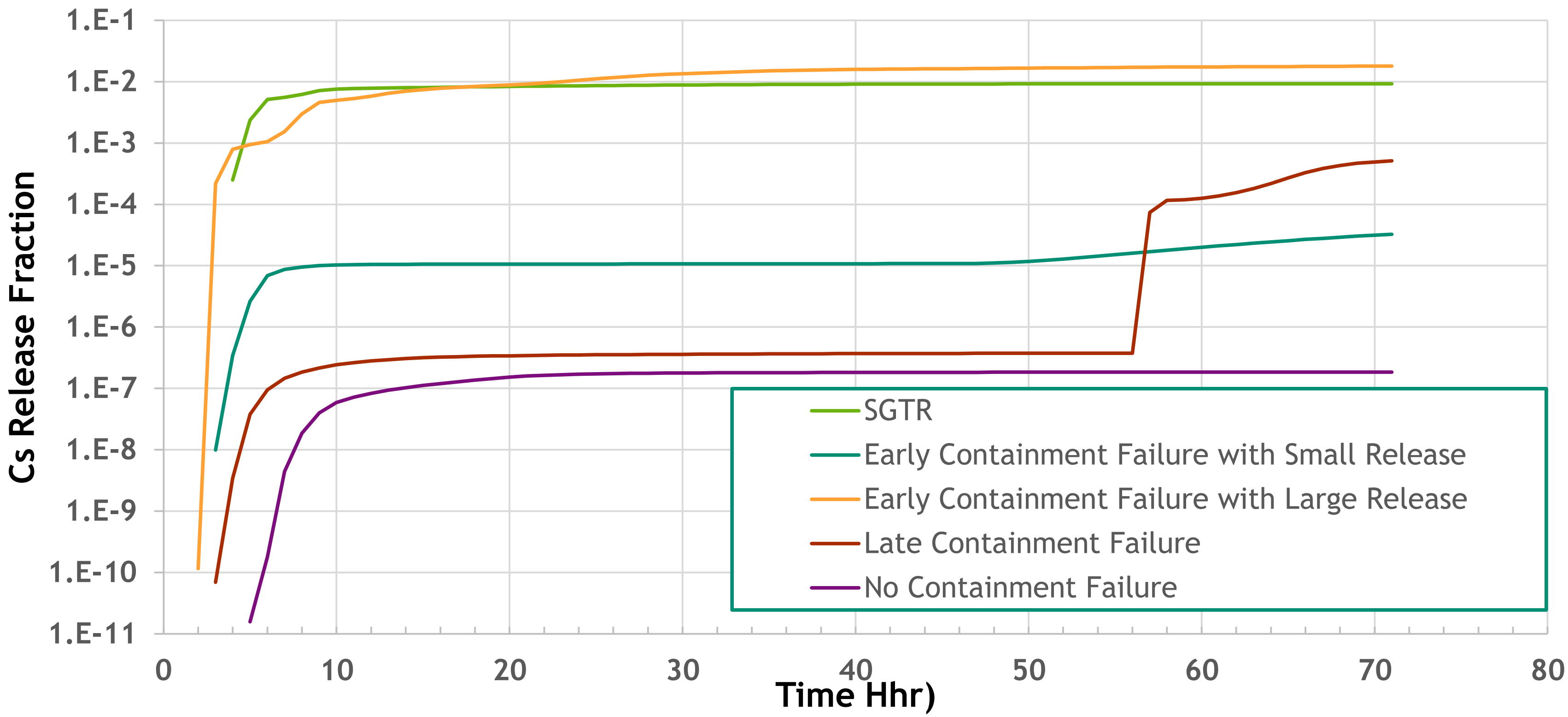
Number of Consequence Variations for M Identical Units with N Source Term Categories Using Simplified Approach								
Number of Source Term Categories (N)	Number of Units Undergoing Accident (M)							
	1	2	3	4	5	6	7	8
5	5	9	13	17	21	25	29	33
10	10	19	28	37	46	55	64	73
15	15	29	43	57	71	85	99	113
20	20	39	58	77	96	115	134	153

- Number of required consequence analyses is
  M*(N-1)+1
- Practicable for almost any reasonable number of units and source term categories!
- Requirements are higher but still reasonable (less than a factor-of-2 larger) when units have different source term categories.
- How much conservatism is introduced by approach?

Demonstration Problem to Evaluate Simplified Approach

- Assume simultaneous initiation of severe accidents at two identical, collocated units
- Five source terms chosen from SOARCA uncertainty analysis to represent range of accident progression variations (source term categories)
  - Induced SGTR (Conditional Probability, CP = 0.12)
  - Early containment failure with small release (CP = 0.315)
  - Early containment failure with large release (CP = 0.01)
  - Late containment failure (CP = 0.435)
  - No containment failure (CP = 0.12)
- Assess risk by calculating weighted sum of (conditional probability) x (consequence)
- Assess accuracy of simplified approach by comparing best estimate and simplified approaches

Integral Cs Release Fractions for Five Source Term Categories



- All source terms fall into different release categories
- SGTR and Early Containment Failure with Large Release are similar magnitude but different timing
- Other source terms separated by an order of magnitude in Cs release fraction

Relative Error in Risk Introduced by Simplified Approach

Result	Population Dose (Sv) (0 to 80 km)	LCF Risk (0 to 80 km)	Early Fatality Risk (0 to 1.6 km)	Land Area (ha) Exceeding 1 μCi Cs-137	Land Area (ha) Exceeding 5 μCi Cs-137
Best Estimate	3,983	4.97E-05	0.00E+00	90,600	13,125
Simp. Approach	4,356	5.47E-05	0.00E+00	96,590	14,448
Relative Error	9%	10%	0%	7%	10%

Result	Land Area (ha) Exceeding 15 μCi Cs-137	Land Area (ha) Exceeding 40 μCi Cs-137	Economic Losses ($M)	Area Decon. (ha)	Population Displaced by Decon.
Best Estimate	3,605	969	303,170	5,211	10,123
Simp. Approach	3,814	1,079	332,459	5,678	10,984
Relative Error	6%	11%	10%	9%	9%

- Results for simplified approach are biased to be conservative (too high), but only about 10%

Further Thoughts on Simplified Approach

- For typical applications, there are only 5 or 6 orders between smallest and largest releases
  - Smallest release fractions, r_s, (typically for containment leakage) are on the order of 10^{-6} or 10^{-7}
  - Largest release fractions, r_l, are on the order of 10^{-1} or 10^{0}
  - Thus, choosing 10 for the spacing between source term categories results in 5 to 7 source term groups
- The relationship between the number of source term groups (N) and the source term spacing (X) is

$$N \approx \log(r_l/r_s)/\log(X)$$

- Increase number of source term categories by decreasing X (e.g., $X = 10^{1/2}$)
- To maintain accuracy, evaluate results for combinations of source term categories that differ in release fraction by up to factor of Y
  - $L = \log(Y)/\log(X)$
- ($X = Y = 10$ and $L = 1$ in previous example)

Generalization of Simplified Approach

- Number of required consequence analyses for the general case is

$$(N-L)(M+L-1)!/[(M-1)!(L)!]+\sum_{I=1}^{L}\{(M+L-I-1)!/[(M-1)!(L-I)!\}$$

Number of Consequence Variations for M Identical Units with N Source Term Categories Using Simplified Approach Accounting for Relationship between N and L									
Number of Source Term Categories (N)	L	Number of Units Undergoing Accident (M)							
		1	2	3	4	5	6	7	8
5	1	5	9	13	17	21	25	29	33
10	2	10	27	52	85	126	175	232	297
15	3	15	54	130	255	441	700	1,044	1,485
20	4	20	90	260	595	1,176	2,100	3,480	5,445

- Many of the combinations of M and N are practicable
- Without further simplification, combinations of larger numbers of units (M) and source term categories (N) may not be practicable

Summary

- A simplified approach is proposed that significantly reduces the number of source term combinations for a MUPSA
- The approach is evaluated for a 2-unit site with 5 source term categories
  - Results are within about 10% of the best estimate results
- Evaluating risks for existing multi-unit sites appears to be practicable using this approach!

- Issues not yet resolved
  - Automation of large sets of source term combinations (requires extension of cyclical file option)
  - Accounting for physical offsets in source locations (shown to be important for near-field consequences)

List of Acronyms

ATD	Atmospheric Transport and Dispersion
MACCS	MELCOR Accident Consequence Code System
MUPSA	Multi-Unit Probabilistic Safety Assessment
PSA	Probabilistic Safety Assessment
SGTR	Steam Generator Tube Rupture
SOARCA	State-of-the-Art Reactor Consequence Analyses