Current Status of Modeling Optimization Studies on Radiological Consequence Analyses at KAERI

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KAERI Korea Atomic Energy Research Institute

Table of Contents

Introduction

Introduction

- Increasing necessity of a large number of consequence calculations
  - A new trend of single-unit consequence analysis
    - Full spectrum of Level 3 PSA considering all source terms rather than categorized representative source terms
  - Multi-unit consequence analysis
    - Rapidly increasing number of multi-unit accident scenarios by the number of units and the number of STCs

Number of combinations assuming same STCs for all units: $(n+1)^k-1$

Number of STCs (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

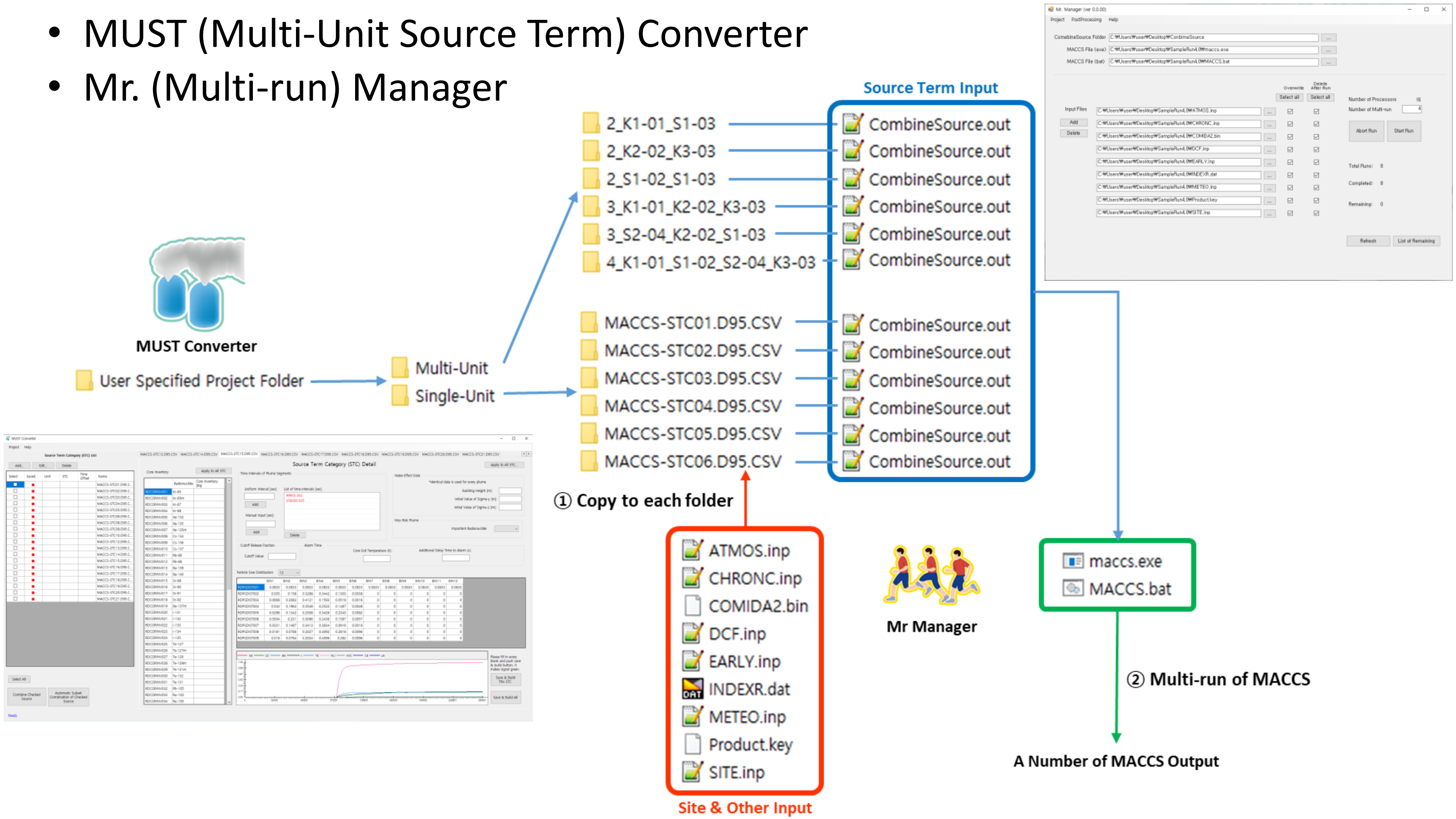
Number of combinations assuming same STCs for all units that are collocated: ${}_{n+1}H_k - 1$

Number of STCs (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

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*, 50 (2018) 1246–1254
N. E. Bixler & S.Y. Kim, **Performing a multi-unit Level-3 PSA with MACCS**, *Nuclear Engineering and Technology,* 53 (2021) 386–392

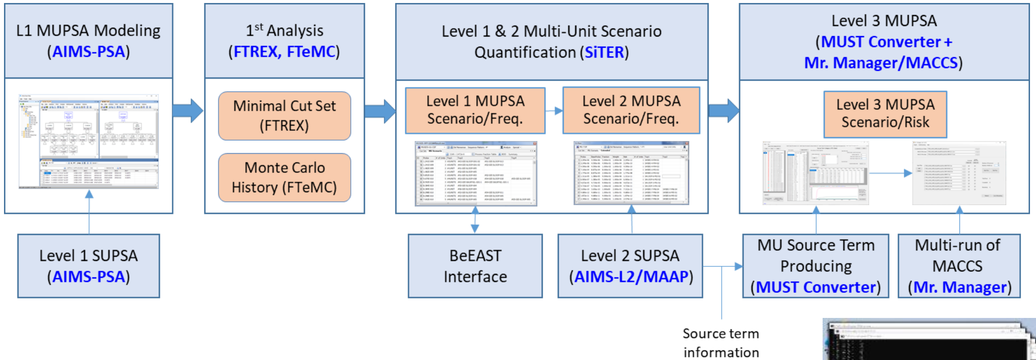
Introduction

- Automation tools for bulk calculations
  - MUST (Multi-Unit Source Term) Converter
  - Mr. (Multi-run) Manager

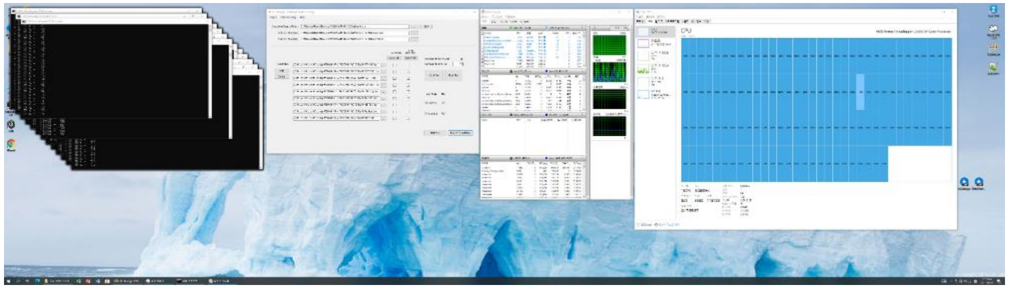


Introduction

- Limitation of current studies
  - Most of studies focused on best-estimate modeling
  - Increased importance of optimized modeling to reduce calculation time
- Requirements and strategy
  - Optimizations that can speed up calculations with little impact on the results



< Software to Perform MUPSA >



< Bulk Calculation by CPU with 128 Threads >

Introduction

MACCS Consequence Analyses Code Development Plan 2024-2028

2023 Asian MELCOR/MACCS User's Group Meeting

Salman Haq, Ph.D., P.E.

PM MACCS Code Development and Applications
Accident Analysis Branch
Division of Systems Analysis
NRC Office of Nuclear Regulatory Research

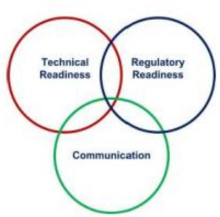
1

Applications Driven MACCS Development

- Prior to 2020
  - State of the Art Consequence Analyses
  - MACCS-HYSPLIT ATD model
- 2020 – 2024
  - NRC Non-Light Water Reactor Vision and Strategy
  - MACCS Documentation (Theory manual, Technical Bases for Consequence Analyses ..., Verification Report)
  - MACCS-UI (Code Modernization by Replacing VB and Database)
- 2024-2028
  - Continue/Complete Non-LWR Vision and Strategy
  - Focus on Knowledge Management and Knowledge Sharing
  - Update Fortran and Issue MACCS V5.0 (Modernization)
    - Execution efficiency
    - Pre and Post processors
    - Enhanced Graphics

U.S.NRC
Revision 1
January 31, 2020

NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy, Volume 3 – *Computer Code Development Plans for Severe Accident Progression, Source Term, and Consequence Analysis*



4

MACCS Fortran Execution Efficiency 2025-2028

- MACCS Execution
  - Cloud Computing
    - Linux version – Cloud and cluster processing
    - High Performance and cluster computing in progress
  - Challenges
    - Effective use of multiprocessor hardware (parallel computing)
    - Weather trials de-coupling
    - Source Term and Number of Plume Segment Optimization
    - Number of Cohorts, number of regions/radials Optimization
      - Social Economic and Population Regions modeling
    - Improve graphic reporting
- Pre & Post Processors
  - Standard tables and graphs used in licensing reactors

10

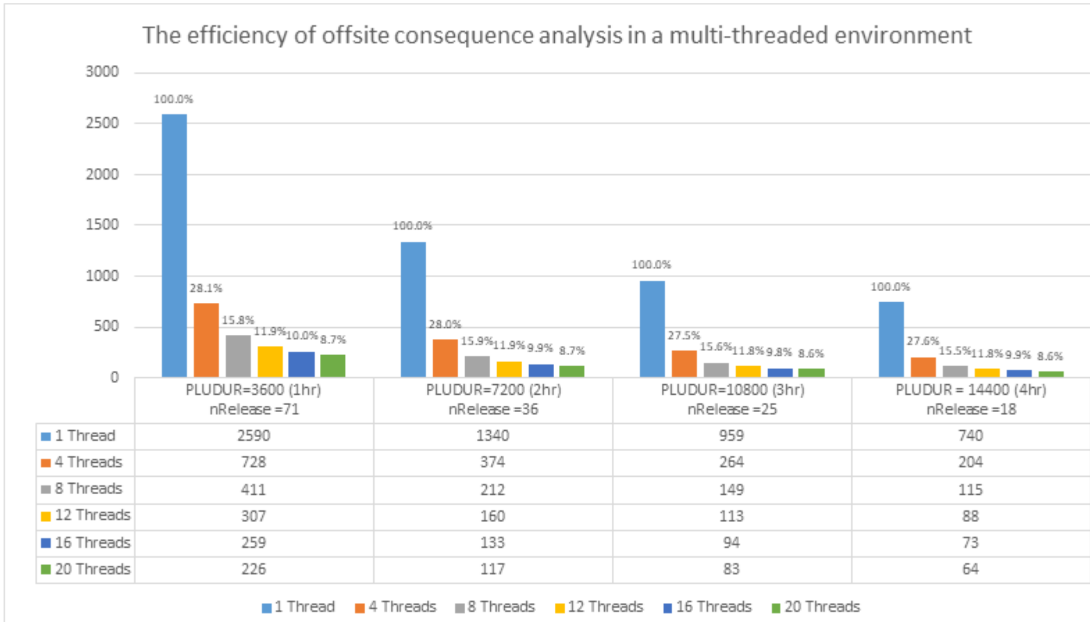
Plume Segmentation

Plume Segmentation

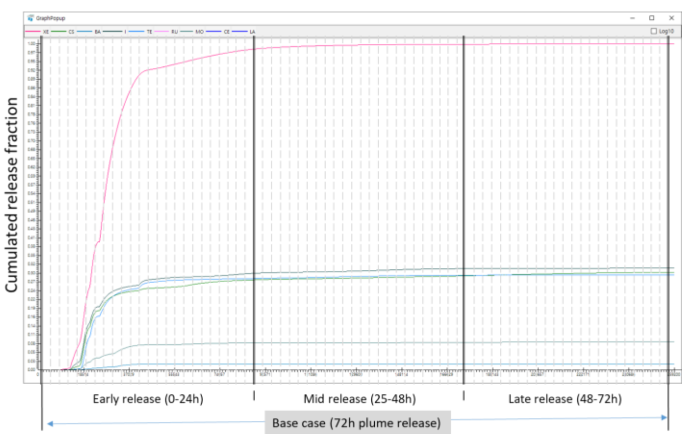
- Effect of various segmentation approaches and multi-threading

Plume Segmentation (second)	No of Plume Release	Early Fatality (0 Km~80 Km)			Cancer Fatality (0 Km~80 Km)		
		Base Case	Test Case	Error Rate	Base Case	Test Case	Error Rate
PLUDUR =3,600	71	100%	100.0%	0.0%	100%	100.0%	0.0%
PLUDUR =7,200	36	100%	115.3%	15.3%	100%	93.8%	6.3%
PLUDUR =10,800	25	100%	106.1%	6.1%	100%	93.3%	6.7%
PLUDUR =14,400	19	100%	114.3%	14.3%	100%	89.4%	10.6%

< 1/2/3/4 Hour-Plume-Segmentation >



< Calculation Time by Plume Segmentation and Multi-Threading >



< Early / Middle / Late Phase of Release >

Plume Segmentation	No of Plume Release	Time Estimated		Early Fatality (0 Km~80 Km)			Cancer Fatality (0 Km~80 Km)		
		Time (sec)	%	Base Case	Test Case	Error Rate	Base Case	Test Case	Error Rate
Base-case	71	2,590	100%	100%	100.0%	0.0%	100%	100.0%	0.0%
Early 24hr Plume Segmentation	25	950	36.7%	100%	99.8%	0.2%	100%	98.4%	1.6%
Mid 24hr Plume Segmentation	26	977	37.7%	100%	128.7%	28.7%	100%	75.3%	24.7%
Late 24hr Plume Segmentation	26	970	37.5%	100%	128.7%	28.7%	100%	74.7%	25.3%

< Comparison of Dense Plume Segmentation for Early / Middle / Late Phase >

S.H. Kim, 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*, 37(6), pp. 166-173, December 2022.

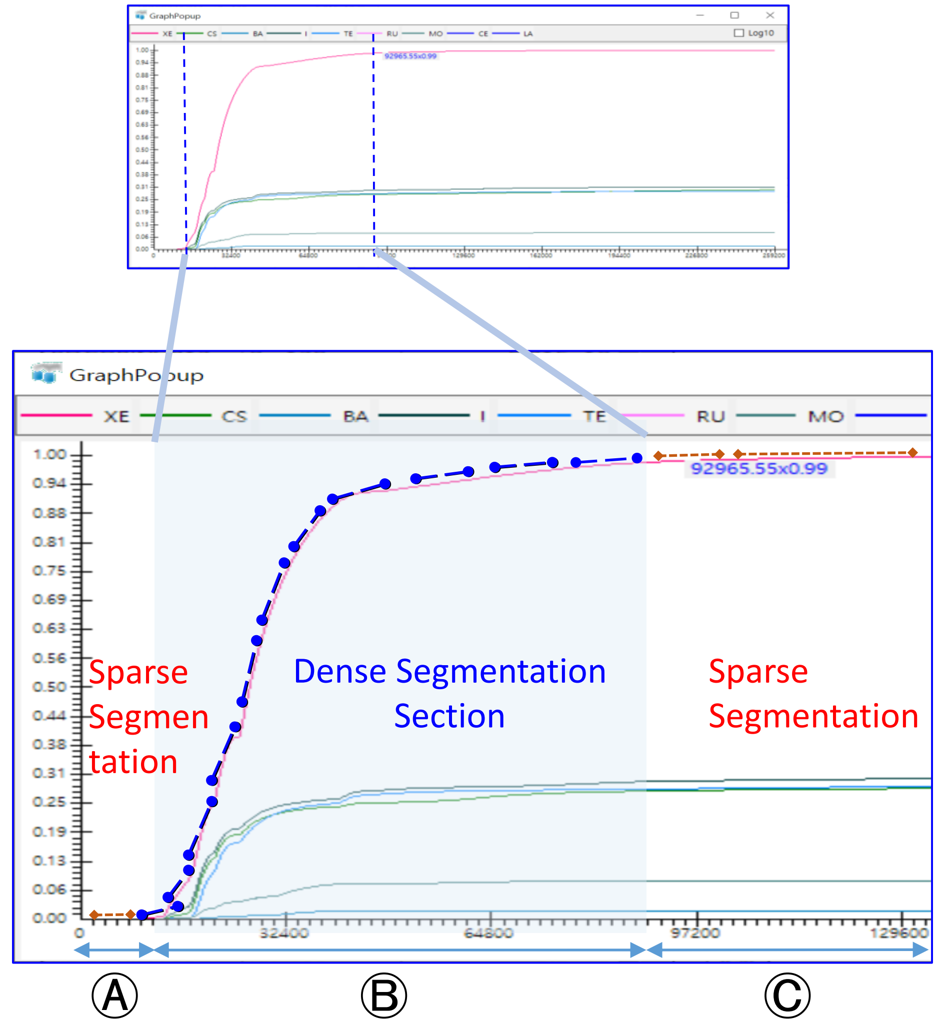
Plume Segmentation Optimization Method

- Concept of optimization

  Ⓐ Sparse segmentation
  Plume release is initially slow
  (or no release)

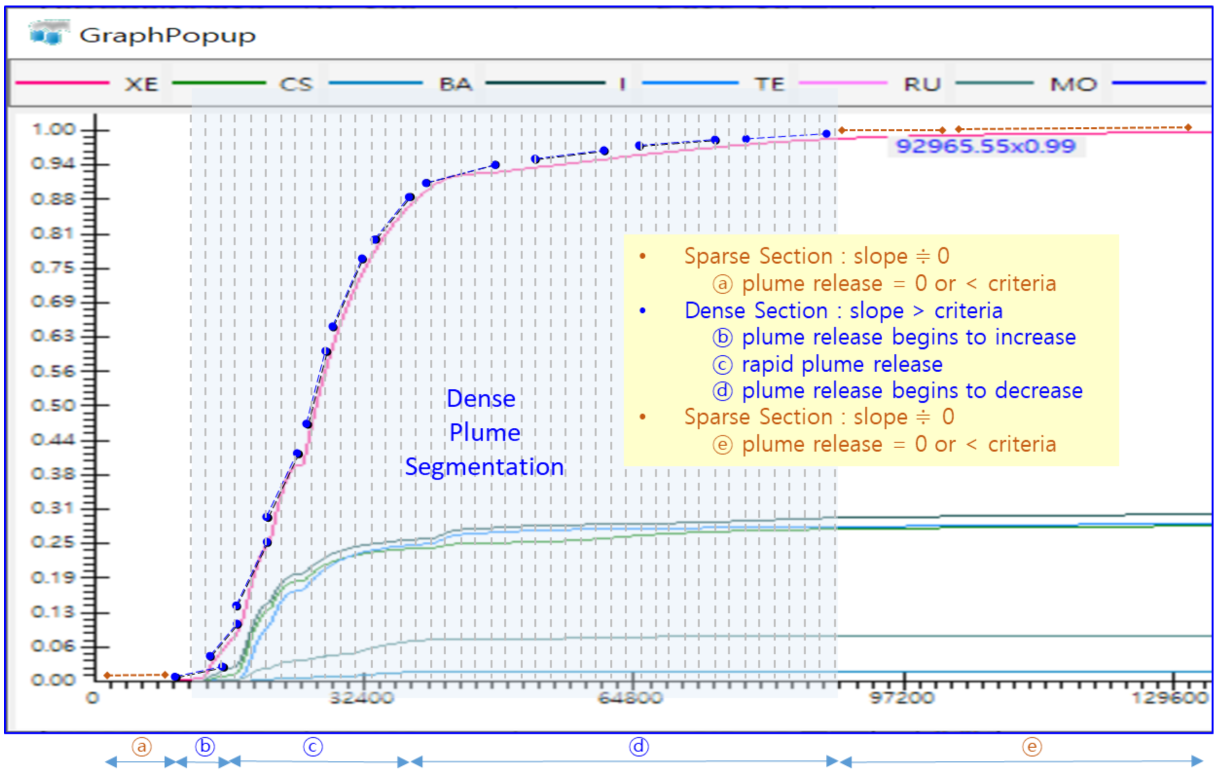
  Ⓑ Dense segmentation
  Plume release is rapidly
  increasing

  Ⓒ Sparse segmentation
  Plume release is no longer
  rapidly increasing, no longer
  releasing, or stabilizing

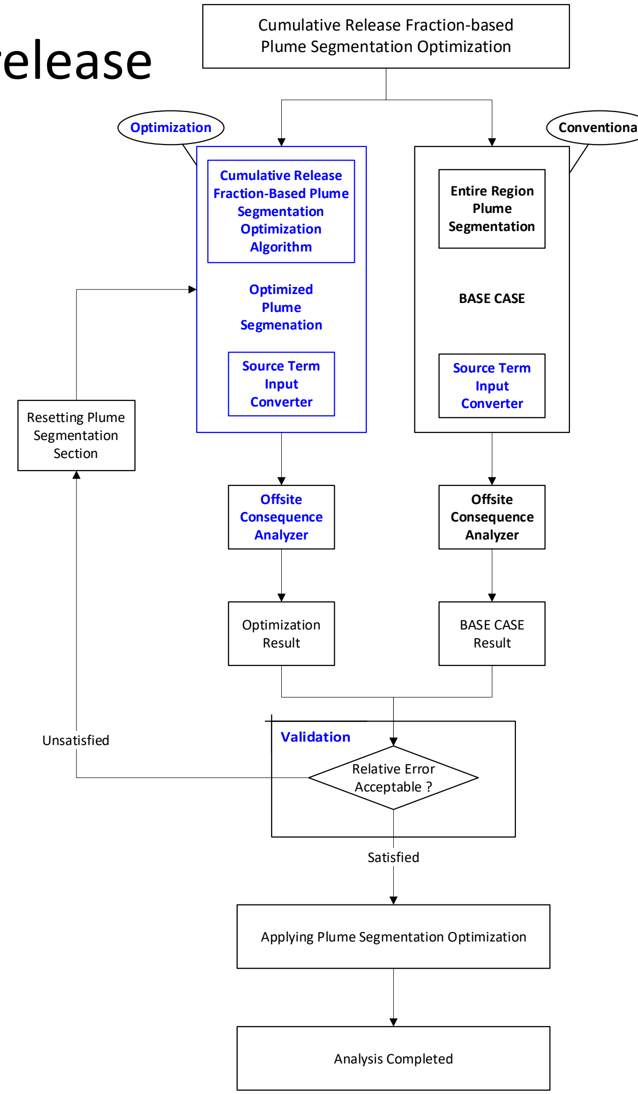


Plume Segmentation Optimization Method

- Optimization based on the slope of cumulative release



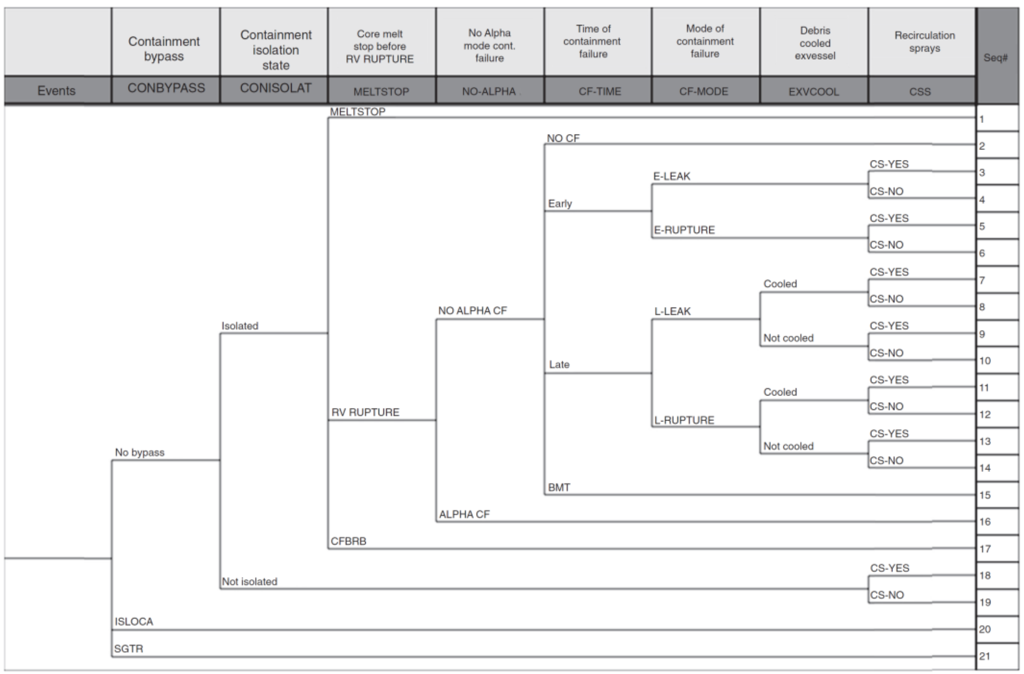
< Criteria for Distinguishing between the Dense and Sparse Plume Segmentation Regions >



< Flowchart of Optimization and Validation >

Results and Validation of Optimization

- Results (Base case vs. Optimization case)



< Source Term Category Logic Diagram for OPR1000 >

Source Term Category	Time Estimated (%)	Health Effect (Early Fatality)	Health Effect (Cancer Fatality)
STC01	99.3%	0.0%	0.0%
STC02	100.0%	0.0%	0.0%
STC03	31.5%	0.0%	0.0%
STC04	62.7%	0.0%	6.0%
STC05	16.9%	0.0%	0.0%
STC06	38.0%	0.0%	2.7%
STC08	100.2%	0.0%	0.0%
STC09	100.3%	0.0%	0.0%
STC10	99.6%	0.0%	0.0%
STC12	77.5%	0.0%	0.8%
STC13	67.3%	0.0%	0.0%
STC14	44.0%	0.0%	2.4%
STC17	87.2%	0.0%	0.7%
STC18	19.6%	0.0%	0.0%
STC19	38.0%	0.2%	3.4%
STC20	23.4%	0.2%	5.2%
STC21	40.2%	0.0%	0.0%
Average	**61.5%**	**0.02%**	**1.25%**

Before Excluding

Source Term Category	Time Estimated (%)	Health Effect (Early Fatality)	Health Effect (Cancer Fatality)
STC01			
STC02			
STC03	31.5%	0.0%	0.0%
STC04	62.7%	0.0%	6.0%
STC05	16.9%	0.0%	0.0%
STC06	38.0%	0.0%	2.7%
STC08			
STC09			
STC10			
STC12	77.5%	0.0%	0.8%
STC13	67.3%	0.0%	0.0%
STC14	44.0%	0.0%	2.4%
STC17	87.2%	0.0%	0.7%
STC18	19.6%	0.0%	0.0%
STC19	38.0%	0.2%	3.4%
STC20	23.4%	0.2%	5.2%
STC21	40.2%	0.0%	0.0%
Average	**45.5%**	**0.03%**	**1.77%**

After Excluding

Particle Size Distribution Setting

Particle Size Distribution Setting

- Particle size bins of MACCS (MELCOR) and MAAP5

$$RDPSDIST_{MB,MG} = \int \left(\sum_{SB,IV,IG,IS,JJ,II,IE,t} \left(\frac{FMXRB_{SG,IV,t} \times WFPJ_{IG,IS,JJ,t} \times MFPIN_{II} \times FAFP0_{IE} \times MTFP0_{IG}}{NFPIN_{II} \times MFP0_{IG}} \right) \right) dt$$

t : Calculation Time [s]
MB : Number of Particle Size Bin in MACCS (1~12)
MG : Fission Product Group Number in MACCS (1~10)
RDPSDIST : Fraction of Aerosol in Each Particle Size Array in Group MG
SB : Number of Particle Size Bin in MAAP5 (1~30)
IV : Donor Compartment Index of Release Junction
IG : Fission Product Group Number in MAAP5 (1~18)
IS : Species Type (1 = Vapor, 2 = Aerosol)
JJ : Release Junction Number
II : Number of Element (1~25)
IE : Number of Element for Mole Fraction (1~31)
FMXRB : Fraction of Aerosol in Each Particle Size Array in Compartment IV
WFPJ : Fission Product Flows through Junction JJ [kg/s]
MFPIN : Initial Mass of Element II [kg]
FAFP0 : Element Mole Fraction in Fission Product Group
MTFP0 : Initial Number of Fission Product Atoms in Group IG
NFPIN : Initial Number of Fission Product Atoms by Element II
MFP0 : Initial Mass of Group IG [kg]

< Equation to Interface MAAP Output to MACCS Particle Size Bin >

MELCOR Particle Size Bin			
Bin No.	Diameter range [μm]		MAAP5 Bin
	Min	Max	
1	6.53E-02	1.21E-01	Bin 1~3
2	1.21E-01	2.23E-01	Bin 4~5
3	2.23E-01	4.12E-01	Bin 6~7
4	4.12E-01	7.61E-01	Bin 8~9
5	7.61E-01	1.41E+00	Bin 10~11
6	1.41E+00	2.60E+00	Bin 12~13
7	2.60E+00	4.80E+00	Bin 14~15
8	4.80E+00	8.88E+00	Bin 16~17
9	8.88E+00	1.64E+01	Bin 18~19
10	1.64E+01	3.30E+01	Bin 20~21
11	3.30E+01	5.60E+01	Bin 22~23
12	5.60E+01	1.04E+02	Bin 24~30

< Mapping of 30 MAAP Bins to 12 MACCS Bins >

Particle Size Distribution Setting

- Base case: 6 bins
  - Bins 7~12 are rarely used due to big size

Particle Size Distribution: 6

	BIN1	BIN2	BIN3	BIN4	BIN5	BIN6	BIN7	BIN8	BIN9	BIN10	BIN11	BIN12
RDPSDIST001	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667						
RDPSDIST002	0.0055	0.0239	0.0705	0.1936	0.2604	0.4462						
RDPSDIST003	0.0043	0.0193	0.064	0.2024	0.2775	0.4324						
RDPSDIST004	0.0053	0.023	0.0687	0.1917	0.2597	0.4516						
RDPSDIST005	0.0053	0.023	0.0698	0.2092	0.2962	0.3965						
RDPSDIST006	0.0047	0.0206	0.0664	0.2041	0.2802	0.424						
RDPSDIST007	0.0041	0.0182	0.0606	0.1913	0.2714	0.4545						
RDPSDIST008	0.005	0.0222	0.0699	0.2073	0.2768	0.4188						
RDPSDIST009	0.0048	0.0213	0.0685	0.2092	0.2808	0.4154						

< Example of 6 Bins (MUST Converter) >

- 6 Bins → 3 / 2 / 1 Bins

6 Bins (Base case)			3 Bins			2 Bins			1 Bin		
Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)
1	6.53E-02	1.21E-01	1	6.53E-02	2.23E-01	1	6.53E-02	4.12E-01	1	6.53E-02	2.60E+00
2	1.21E-01	2.23E-01									
3	2.23E-01	4.12E-01	2	2.23E-01	7.61E-01						
4	4.12E-01	7.61E-01				2	4.12E-01	2.60E+00			
5	7.61E-01	1.41E+00	3	7.61E-01	2.60E+00						
6	1.41E+00	2.60E+00									

< Diameter range of 6 /3 / 2 / 1 Bins >

Particle Size Distribution Setting

- Example of 6 / 3 / 2 / 1 Bins
  - Dry deposition velocity

$$ln(v_d) = -2.964 + 0.992(lnd_p) + 0.190(lnd_p)^2 - 0.072(lnd_p)^3 + 1.061z_0 + 0.169V$$

  - Particle size distribution

$$RDPSDIST_{MB,MG} = \int \left(\sum_{SB,IV,IG,IS,JJ,II,IE,t} \left(\frac{FMXRB_{SG,IV,t} \times WFPJ_{IG,IS,JJ,t} \times MFPIN_{II} \times FAFP0_{IE} \times MTFP0_{IG}}{NFPIN_{II} \times MFP0_{IG}} \right) \right) dt$$

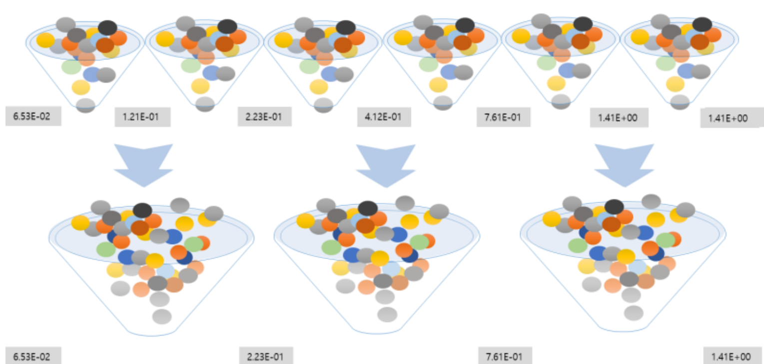
		Number of Particle Size Bin											
		6 Bins						3 Bins			2 Bins		1 Bin
		1	2	3	4	5	6	1	2	3	1	2	1
Dry deposition velocity (VDEPOS)		8.10E-04	9.01E-04	1.35E-03	2.46E-03	4.94E-03	9.87E-03	8.84E-04	2.18E-03	7.94E-03	1.22E-03	6.73E-03	6.21E-03
Fraction	RDPSDIST001	1.67E-01	1.67E-01	1.67E-01	1.67E-01	1.67E-01	1.67E-01	3.33E-01	3.33E-01	3.33E-01	5.00E-01	5.00E-01	1.00E+00
	RDPSDIST002	5.50E-03	2.39E-02	7.05E-02	1.94E-01	2.60E-01	4.46E-01	2.94E-02	2.64E-01	7.07E-01	9.99E-02	9.00E-01	1.00E+00
	RDPSDIST003	4.30E-03	1.93E-02	6.40E-02	2.02E-01	2.78E-01	4.32E-01	2.36E-02	2.66E-01	7.10E-01	8.76E-02	9.12E-01	1.00E+00
	RDPSDIST004	5.30E-03	2.30E-02	6.87E-02	1.92E-01	2.60E-01	4.52E-01	2.83E-02	2.60E-01	7.11E-01	9.70E-02	9.03E-01	1.00E+00
	RDPSDIST005	5.30E-03	2.30E-02	6.98E-02	2.09E-01	2.96E-01	3.97E-01	2.83E-02	2.79E-01	6.93E-01	9.81E-02	9.02E-01	1.00E+00
	RDPSDIST006	4.70E-03	2.06E-02	6.64E-02	2.04E-01	2.80E-01	4.24E-01	2.53E-02	2.71E-01	7.04E-01	9.17E-02	9.08E-01	1.00E+00
	RDPSDIST007	4.10E-03	1.82E-02	6.06E-02	1.91E-01	2.71E-01	4.55E-01	2.23E-02	2.52E-01	7.26E-01	8.29E-02	9.17E-01	1.00E+00
	RDPSDIST008	5.00E-03	2.22E-02	6.99E-02	2.07E-01	2.77E-01	4.19E-01	2.72E-02	2.77E-01	6.96E-01	9.71E-02	9.03E-01	1.00E+00
	RDPSDIST009	4.80E-03	2.13E-02	6.85E-02	2.09E-01	2.81E-01	4.15E-01	2.61E-02	2.78E-01	6.96E-01	9.46E-02	9.05E-01	1.00E+00

< Example of 6 /3 / 2 / 1 Bins >

Particle Size Distribution Setting

- Impact of setting: 6 bins → 3 bins

6 Bins (Base case)			3 Bins			2 Bins			1 Bin		
Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)
1	6.53E-02	1.21E-01	1	6.53E-02	2.23E-01	1	6.53E-02	4.12E-01	1	6.53E-02	2.60E+00
2	1.21E-01	2.23E-01									
3	2.23E-01	4.12E-01	2	2.23E-01	7.61E-01						
4	4.12E-01	7.61E-01				2	4.12E-01	2.60E+00			
5	7.61E-01	1.41E+00	3	7.61E-01	2.60E+00						
6	1.41E+00	2.60E+00									



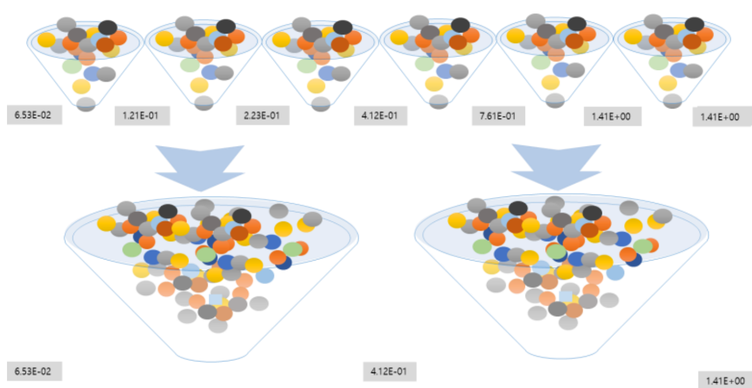
No	Source Term Category	Time			Population- weighted early fatality risk (0~80Km)			Population-weighted cancer fatality risk (0~80Km)		
		Base case (sec)	3 BINS (sec)	%	Base Case	3 BINS	%	Base Case	3 BINS	%
1	STC01	2217.7	2212.0	99.7%	100%	100%	0.0%	100%	101.5%	1.5%
2	STC02	2170.4	2171.7	100.1%	100%	100%	0.0%	100%	102.8%	2.8%
3	STC03	1214.0	1204.9	99.3%	100%	100%	0.0%	100%	102.2%	2.2%
4	STC04	2439.5	2416.1	99.0%	100%	100%	0.0%	100%	102.3%	2.3%
5	STC05	1747.2	1737.7	99.5%	100%	100%	0.0%	100%	101.8%	1.8%
6	STC06	2418.3	2407.0	99.5%	100%	101.5%	1.5%	100%	101.8%	1.8%
7	STC08	948.5	943.2	99.4%	100%	100%	0.0%	100%	100.7%	0.7%
8	STC09	433.0	429.3	99.1%	100%	100%	0.0%	100%	100.9%	0.9%
9	STC10	946.1	942.5	99.6%	100%	100%	0.0%	100%	101.2%	1.2%
10	STC12	921.6	913.5	99.1%	100%	100%	0.0%	100%	105.4%	5.4%
11	STC13	372.5	371.0	99.6%	100%	100%	0.0%	100%	101.4%	1.4%
12	STC14	926.5	924.2	99.7%	100%	100%	0.0%	100%	102.0%	2.0%
13	STC17	1337.1	1331.3	99.6%	100%	100%	0.0%	100%	100.7%	0.7%
14	STC18	1563.2	1552.5	99.3%	100%	100%	0.0%	100%	101.0%	1.0%
15	STC19	2608.0	2590.1	99.3%	100%	99.0%	1.0%	100%	101.2%	1.2%
16	STC20	2506.7	2506.6	100.0%	100%	101.1%	1.1%	100%	100.7%	0.7%
17	STC21	814.8	811.2	99.5%	100%	100.7%	0.7%	100%	101.6%	1.6%
		Average		99.5%			0.3%			1.7%

S.H. Kim and S.Y. Kim, **Feasibility Study on the Optimization of Offsite Consequence Analysis by Particle Size Distribution Setting and Multi-Threading,** *Journal of the Korean Society of Safety*, 39(1), pp. 96-103, February 2024.

Particle Size Distribution Setting

- Impact of setting: 6 bins → 2 bins

6 Bins (Base case)			3 Bins			2 Bins			1 Bin		
Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)
1	6.53E-02	1.21E-01	1	6.53E-02	2.23E-01	1	6.53E-02	4.12E-01	1	6.53E-02	2.60E+00
2	1.21E-01	2.23E-01									
3	2.23E-01	4.12E-01	2	2.23E-01	7.61E-01						
4	4.12E-01	7.61E-01				2	4.12E-01	2.60E+00			
5	7.61E-01	1.41E+00	3	7.61E-01	2.60E+00						
6	1.41E+00	2.60E+00									

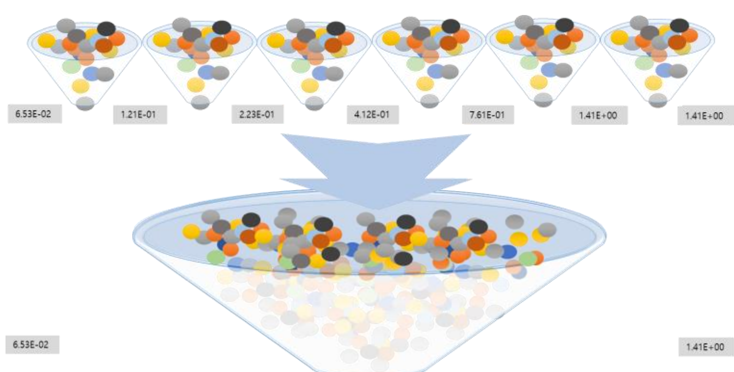


No	Source Term Category	Time			Population- weighted early fatality risk (0~80Km)			Population-weighted cancer fatality risk (0~80Km)		
		Base case (sec)	2 BINS (sec)	%	Base Case	2 BINS	%	Base Case	2 BINS	%
1	STC01	2217.7	2201.4	99.3%	100%	100%	0.0%	100%	104.2%	4.2%
2	STC02	2170.4	2168.5	99.9%	100%	100%	0.0%	100%	106.7%	6.7%
3	STC03	1214.0	1205.9	99.3%	100%	100%	0.0%	100%	108.9%	8.9%
4	STC04	2439.5	2413.9	98.9%	100%	100%	0.0%	100%	107.1%	7.1%
5	STC05	1747.2	1737.9	99.5%	100%	100%	0.0%	100%	104.0%	4.0%
6	STC06	2418.3	2405.5	99.5%	100%	105.0%	5.0%	100%	107.2%	7.2%
7	STC08	948.5	938.6	99.0%	100%	100%	0.0%	100%	101.4%	1.4%
8	STC09	433.0	431.6	99.7%	100%	100%	0.0%	100%	102.1%	2.1%
9	STC10	946.1	942.3	99.6%	100%	100%	0.0%	100%	103.3%	3.3%
10	STC12	921.6	916.4	99.4%	100%	100%	0.0%	100%	103.1%	3.1%
11	STC13	372.5	373.4	100.2%	100%	100%	0.0%	100%	103.9%	3.9%
12	STC14	926.5	918.8	99.2%	100%	100%	0.0%	100%	102.9%	2.9%
13	STC17	1337.1	1337.7	100.0%	100%	100%	0.0%	100%	112.5%	12.5%
14	STC18	1563.2	1550.9	99.2%	100%	100%	0.0%	100%	102.4%	2.4%
15	STC19	2608.0	2590.0	99.3%	100%	98.0%	2.0%	100%	104.1%	4.1%
16	STC20	2506.7	2490.0	99.3%	100%	105.9%	5.9%	100%	102.9%	2.9%
17	STC21	814.8	816.6	100.2%	100%	102.4%	2.4%	100%	103.9%	3.9%
	Average			99.5%	100.0%	100.9%	0.9%	100.0%	104.7%	4.7%

Particle Size Distribution Setting

- Impact of setting: 6 bins → 1 bins

6 Bins (Base case)			3 Bins			2 Bins			1 Bin		
Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)	Bin No	Min (μm)	Max (μm)
1	6.53E-02	1.21E-01	1	6.53E-02	2.23E-01	1	6.53E-02	4.12E-01	1	6.53E-02	2.60E+00
2	1.21E-01	2.23E-01									
3	2.23E-01	4.12E-01	2	2.23E-01	7.61E-01						
4	4.12E-01	7.61E-01				2	4.12E-01	2.60E+00			
5	7.61E-01	1.41E+00	3	7.61E-01	2.60E+00						
6	1.41E+00	2.60E+00									



No	Source Term Category	Time			Population- weighted early fatality risk (0~80Km)			Population-weighted cancer fatality risk (0~80Km)		
		Base case (sec)	1 BIN (sec)	%	Base Case	1 BIN	%	Base Case	1 BIN	%
1	STC01	2217.7	2205.5	99.5%	100%	100%	0.0%	100%	106.5%	6.5%
2	STC02	2170.4	2174.9	100.2%	100%	100%	0.0%	100%	110.4%	10.4%
3	STC03	1214.0	1218.4	100.4%	100%	100%	0.0%	100%	115.1%	15.1%
4	STC04	2439.5	2433.4	99.8%	100%	100%	0.0%	100%	112.0%	12.0%
5	STC05	1747.2	1739.5	99.6%	100%	100%	0.0%	100%	105.3%	5.3%
6	STC06	2418.3	2405.6	99.5%	100%	107.5%	7.5%	100%	111.7%	11.7%
7	STC08	948.5	940.0	99.1%	100%	100%	0.0%	100%	104.3%	4.3%
8	STC09	433.0	429.5	99.2%	100%	100%	0.0%	100%	102.7%	2.7%
9	STC10	946.1	941.6	99.5%	100%	100%	0.0%	100%	105.6%	5.6%
10	STC12	921.6	919.6	99.8%	100%	100%	0.0%	100%	117.8%	17.8%
11	STC13	372.5	370.2	99.4%	100%	100%	0.0%	100%	105.0%	5.0%
12	STC14	926.5	921.4	99.4%	100%	100%	0.0%	100%	109.8%	9.8%
13	STC17	1337.1	1332.3	99.6%	100%	100%	0.0%	100%	121.3%	21.3%
14	STC18	1563.2	1556.6	99.6%	100%	100%	0.0%	100%	102.9%	2.9%
15	STC19	2608.0	2597.3	99.6%	100%	97.3%	2.7%	100%	106.7%	6.7%
16	STC20	2506.7	2496.9	99.6%	100%	109.8%	9.8%	100%	104.7%	4.7%
17	STC21	814.8	809.8	99.4%	100%	102.6%	2.6%	100%	104.5%	4.5%
		Average		99.6%		101.3%	1.3%		108.6%	8.6%

S.H. Kim and S.Y. Kim, **Feasibility Study on the Optimization of Offsite Consequence Analysis by Particle Size Distribution Setting and Multi-Threading,** *Journal of the Korean Society of Safety*, 39(1), pp. 96-103, February 2024.

Spatial Grid Setting

Various Spatial Grid Settings

- Method to define radial rings
  - Define rings only for important boundaries
  - Define additional rings between important boundaries
    - Arbitrarily
    - By mathematical approach
      - Arithmetic (equal difference)
      - Geometric (equal ratio): Exponential or Logarithmic
      - Fibonacci

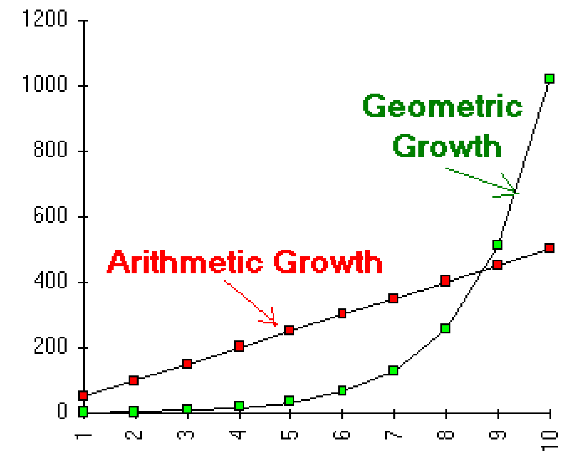


*Image from: https://www.biology.iupui.edu/biocourses/N100/2k4ch39pop.html

- Air concentration profile
  - Exponential rather than linear
  - Geometric method is expected to be appropriate

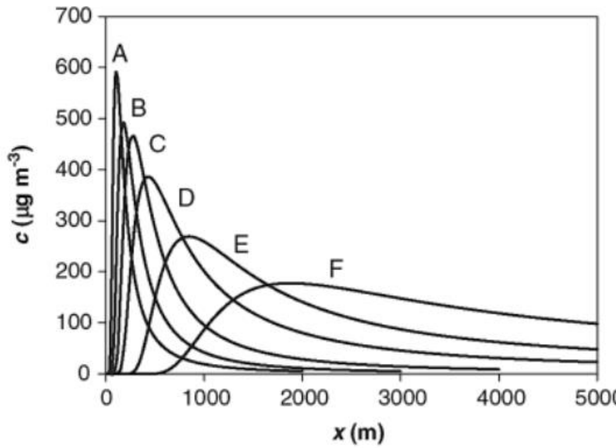
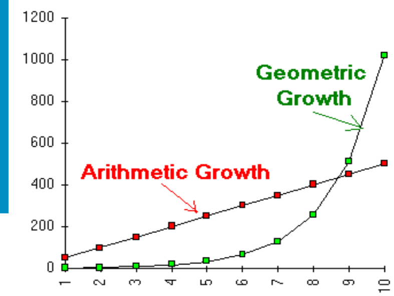
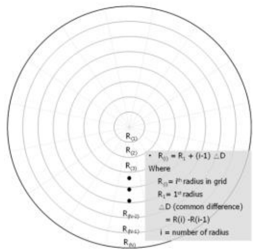


*Image from "Air Dispersion Modeling," De Visscher A. (2014). Wiley & Sons, USA

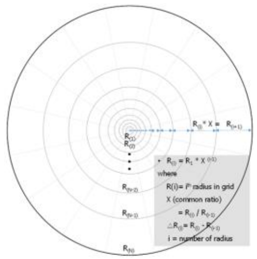
Various Spatial Grid Settings



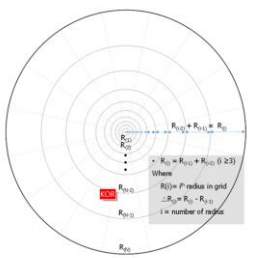
- This study: Arithmetic growth / Geometric growth / Fibonacci growth
- Further study: Logarithmic and another optimized method
- Comparison of ground level concentration, health effects (early and cancer fatalities), and calculation time



(a) Arithmetic Growth



(b) Geometric Growth



(c) Fibonacci Growth

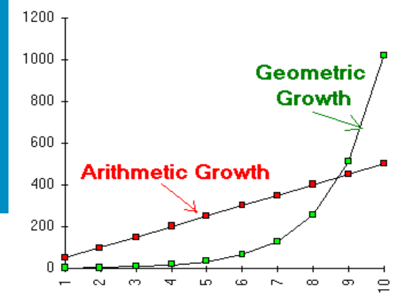
Near-Field (PAZ)

Arithmetic Growth			Radius (km)		Geometric Growth			Radius (km)		Fibonacci Growth (km)
Common Difference (d=)	0.20	0.25	0.50	1.00	Common Ratio (r=)	1.25	1.50	1.75	2.00	
1	0.50	0.50	0.50	0.50	1	0.50	0.50	0.50	0.50	0.50
2	0.60	0.75	1.00	1.00	2	0.67	0.66	0.93	1.25	0.60
3	0.80	1.00	1.50	2.00	3	0.84	0.99	1.63	2.50	0.75
4	1.00	1.25	2.00	3.00	4	1.05	1.48	2.86	5.00	0.90
5	1.20	1.50	2.50	4.00	5	1.31	2.22	5.00		1.15
6	1.40	1.75	3.00	5.00	6	1.64	3.33			1.55
7	1.60	2.00	3.50		7	2.05	5.00			2.20
8	1.80	2.25	4.00		8	2.56				3.25
9	2.00	2.50	4.50		9	3.20				5.00
10	2.20	2.75	5.00		10	4.00				
11	2.40	3.00			11	5.00				
12	2.60	3.25								
13	2.80	3.50								
14	3.00	3.75								
15	3.20	4.00								
16	3.40	4.25								
17	3.60	4.50								
18	3.80	4.75								
19	4.00	5.00								
20	4.20									
21	4.40									
22	4.60									
23	4.80									
24	5.00									

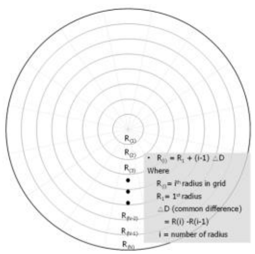
Far-Field (NPZ)

Arithmetic Growth			Radius (km)		Geometric Growth			Radius (km)		Fibonacci Growth (km)
Common Difference (d=)	1.00	2.00	3.00	5.00	Common Ratio (r=)	1.25	1.50	1.75	2.00	
1	0.50	0.50	0.50	0.50	1	0.50	0.50	0.50	0.50	0.50
2	1.00	2.00	3.00	5.00	2	0.68	0.78	1.04	0.94	0.60
3	2.00	4.00	6.00	10.00	3	0.84	1.17	1.83	1.88	0.75
4	3.00	6.00	9.00	15.00	4	1.06	1.76	3.20	3.75	0.90
5	4.00	8.00	12.00	20.00	5	1.32	2.63	5.60	7.50	1.15
6	5.00	10.00	15.00	25.00	6	1.65	3.95	9.80	15.00	1.55
7	6.00	12.00	18.00	30.00	7	2.06	5.93	17.14	30.00	2.20
8	7.00	14.00	21.00		8	2.58	8.89	30.00		3.25
9	8.00	16.00	24.00		9	3.22	13.33			4.95
10	9.00	18.00	27.00		10	4.03	20.00			7.70
11	10.00	20.00	30.00		11	5.03	30.00			12.15
12	11.00	22.00				6.29				19.35
13	12.00	24.00				7.86				30.00
14	13.00	26.00				9.83				
15	14.00	28.00				12.29				
16	15.00	30.00				15.36				
17	16.00					19.20				
18	17.00					24.00				
19	18.00					30.00				
20	19.00									
21	20.00									
22	21.00									
23	22.00									
24	23.00									
25	24.00									
26	25.00									
27	26.00									
28	27.00									
29	28.00									
30	29.00									
31	30.00									

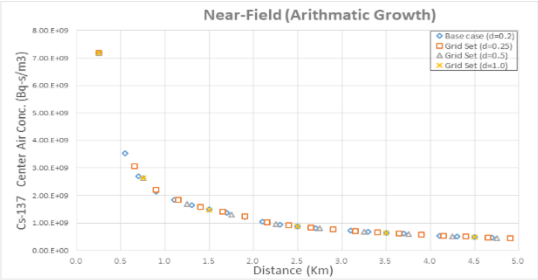
Effect of Spatial Grid Setting

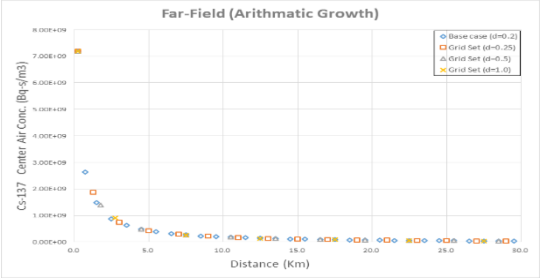


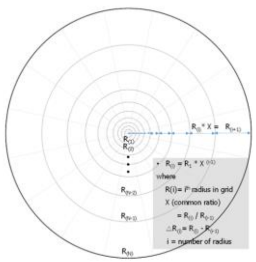
- Ground-level concentration
  - No effect: Just calculated by Gaussian plume model at distances



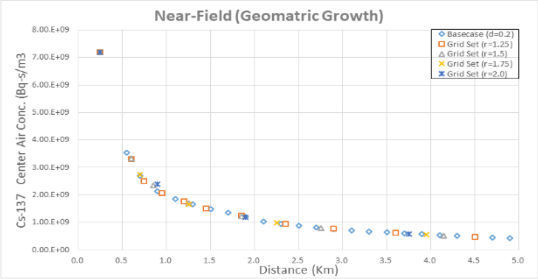
(a) Arithmetic Growth

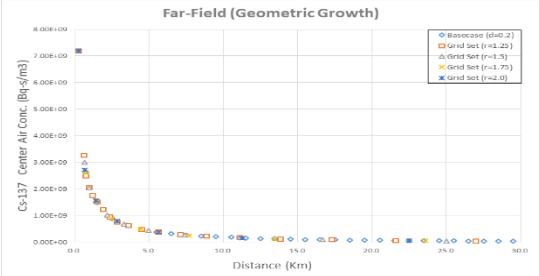


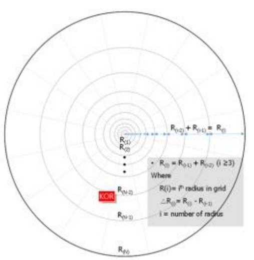




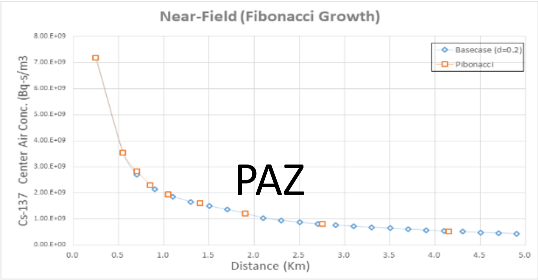
(b) Geometric Growth

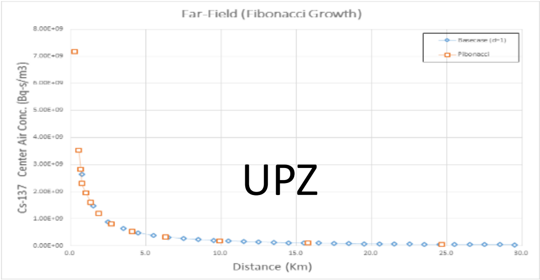




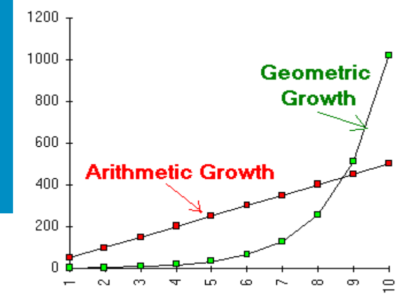


(c) Fibonacci Growth



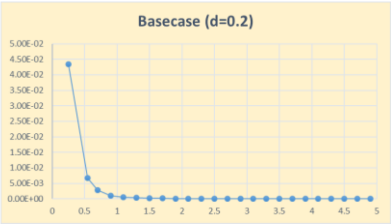


Effect of Spatial Grid Setting

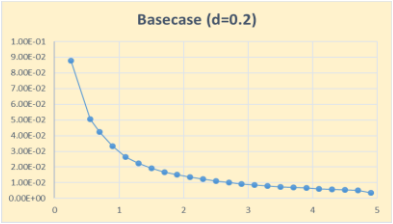


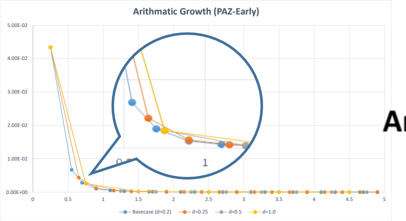
- Health effects (Near-field)
  - Decreasing number of radial rings → Increasing relative error

Early Fatality Risk

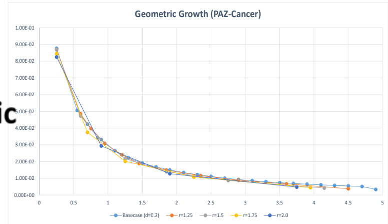


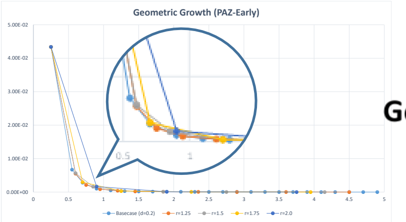
Cancer Fatality Risk



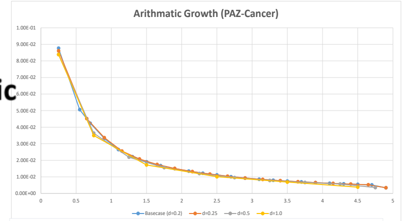


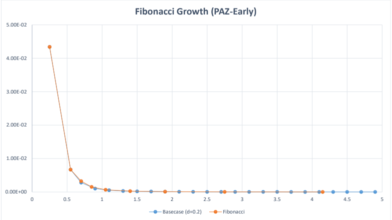
Arithmetic



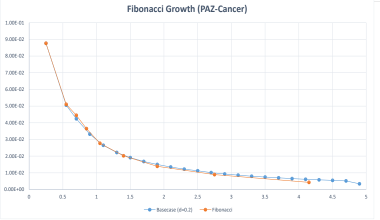


Geometric





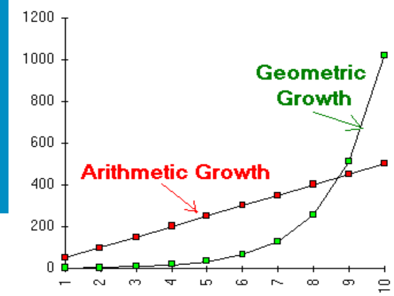
Fibonacci



				Number of Radial Rings	Relative Error(%)
Near Field (PAZ) (0.5~5km)	Early Fatality	Basecase	d=0.2	24	0.0%
		Arithmetic Growth	d=0.25	19	0.8%
			d=0.5	10	0.8%
			d=1.0	6	4.6%
		Geometric Growth	r=1.25	11	1.5%
			r=1.5	7	3.8%
			r=1.75	5	6.1%
			r=2.0	4	9.2%
		Fibonacci Growth	Fibonacci	9	3.1%
	Cancer Fatality	Basecase	d=0.2	24	0.0%
		Arithmetic Sequence	d=0.25	19	1.0%
			d=0.5	10	5.7%
			d=1.0	6	12.2%
		Geometric Sequence	r=1.25	11	8.2%
			r=1.5	7	14.9%
			r=1.75	5	19.1%
			r=2.0	4	21.7%
		Fibonacci Growth	Fibonacci	9	14.3%

< Results in PAZ >

Effect of Spatial Grid Setting



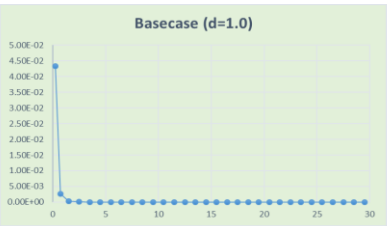
▪ Health effects (Far-field)

- Decreasing number of radial rings → Increasing relative error

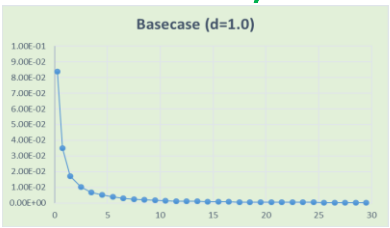
				Number of Radial Rings	Relative Error(%)
Far Field (UPZ) (0.5~30km)	Early Fatality	Basecase	d=1.0	31	0.0%
		Arithmetic Sequence	d=2.0	16	18.8%
			d=3.0	11	40.6%
			d=5.0	7	66.2%
		Geometric Sequence	r=1.25	19	3.1%
			r=1.5	11	3.1%
			r=1.75	8	4.5%
			r=2.0	7	8.8%
		Fibonacci Growth	Fibonacci	13	0.3%
	Cancer Fatality	Basecase	d=1.0	31	0.0%
		Arithmetic Sequence	d=2.0	16	5.5%
			d=3.0	11	10.0%
			d=5.0	7	16.9%
		Geometric Sequence	r=1.25	19	7.5%
			r=1.5	11	16.2%
			r=1.75	8	21.6%
			r=2.0	7	24.5%
		Fibonacci Growth	Fibonacci	13	17.1%

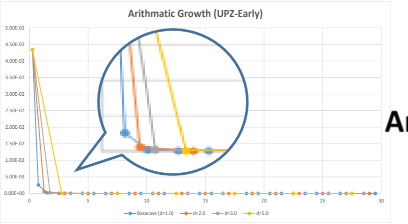
< Results in UPZ >

Early Fatality Risk

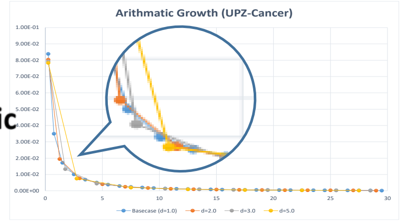


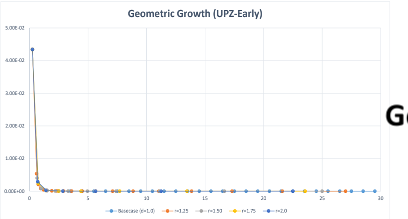
Cancer Fatality Risk



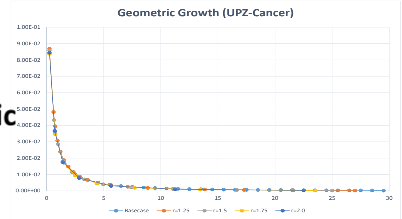


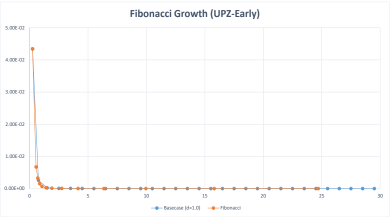
Arithmetic



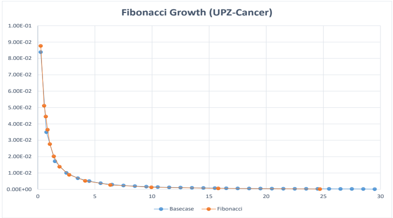


Geometric

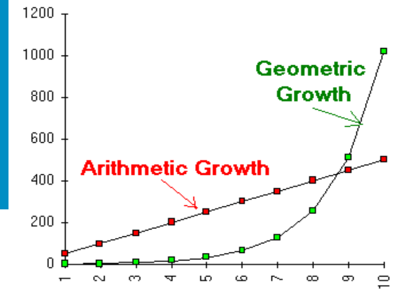




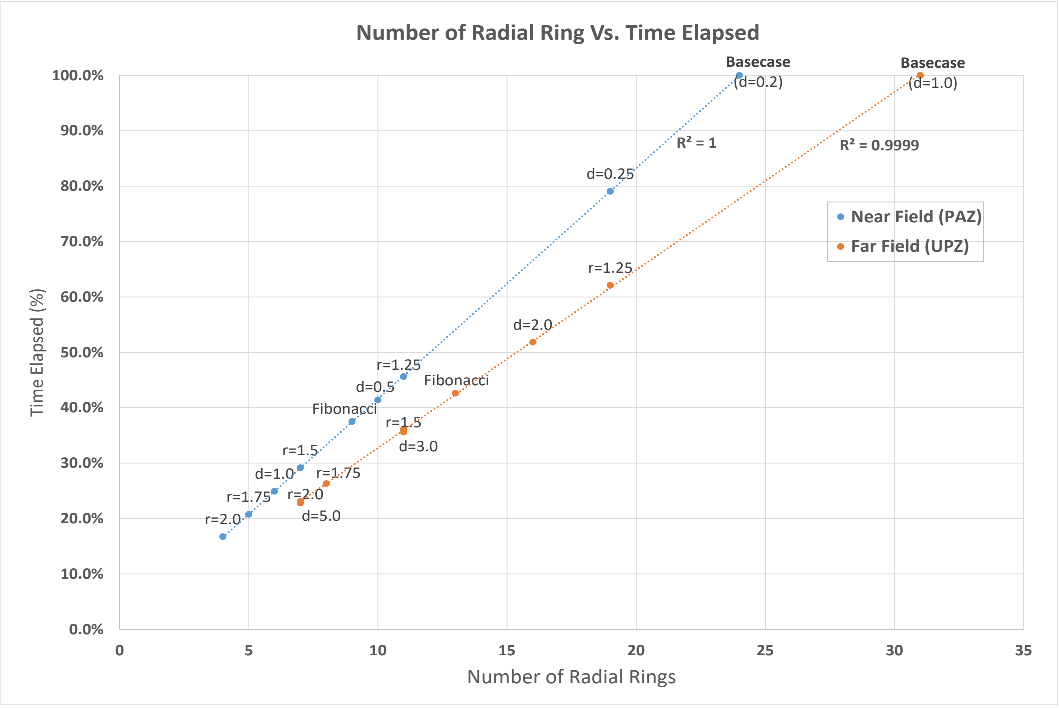
Fibonacci



Effect of Spatial Grid Setting



- Number of radial rings and calculation time



< Number of Radial Rings Vs. Calculation Time >

				Number of Radial Rings	Time
Near Field (PAZ) (0.5~5km)	Early Fatality	Basecase	d=0.2	24	100.0%
		Arithmetic Growth	d=0.25	19	79.1%
			d=0.5	10	41.4%
			d=1.0	6	24.9%
		Geometric Growth	r=1.25	11	45.6%
			r=1.5	7	29.2%
			r=1.75	5	20.8%
			r=2.0	4	16.7%
		Fibonacci Growth	Fibonacci	9	37.5%
	Cancer Fatality	Basecase	d=0.2	24	100.0%
		Arithmetic Sequence	d=0.25	19	79.1%
			d=0.5	10	41.3%
			d=1.0	6	24.9%
		Geometric Sequence	r=1.25	11	45.9%
			r=1.5	7	29.2%
			r=1.75	5	20.9%
			r=2.0	4	16.9%
		Fibonacci Growth	Fibonacci	9	37.6%

				Number of Radial Rings	Time
Far Field (PAZ+UPZ) (0.5~30km)	Early Fatality	Basecase	d=1.0	31	100.0%
		Arithmetic Sequence	d=2.0	16	51.9%
			d=3.0	11	35.6%
			d=5.0	7	22.8%
		Geometric Sequence	r=1.25	19	62.1%
			r=1.5	11	36.1%
			r=1.75	8	26.3%
			r=2.0	7	23.1%
		Fibonacci Growth	Fibonacci	13	42.6%
	Cancer Fatality	Basecase	d=1.0	31	100.0%
		Arithmetic Sequence	d=2.0	16	51.8%
			d=3.0	11	35.5%
			d=5.0	7	22.7%
		Geometric Sequence	r=1.25	19	62.1%
			r=1.5	11	36.0%
			r=1.75	8	26.2%
			r=2.0	7	23.0%
		Fibonacci Growth	Fibonacci	13	42.7%

Logarithmic Spacing on Delta Radius

- An approach to choose radii
  - Choose inner (R(1)) and outer (R(N)) radii appropriate for problem
  - Use logarithmic spacing on delta radius to define boundaries in grid

    $R(i) = R(n)*X^{(i-n)}$

    where

    R(i): i^{th} radius in grid

    n: integer corresponding to inner radius

    N: integer corresponding to outer radius

    X: logarithmic factor
  - Modify a few of the radii to be at specific boundaries of interest (e.g., site boundary)
  - Repeat process over multiple intervals

Grid #	Delta Radius (km)		Radius (km)	
1	0.10	0.10	0.10	0.10
2	0.12	0.12	0.22	0.22
3	0.15	0.14	0.37	0.37
4	0.18	0.17	0.55	0.54
5	0.22	0.21	0.78	0.75
6	0.27	0.25	1.05	1.00
7	0.33	0.31	1.38	1.31
8	0.41	0.38	1.79	1.69
9	0.50	0.47	2.28	2.17
10	0.61	0.58	2.89	2.75
11	0.74	0.72	3.63	3.47
12	0.91	0.89	4.54	4.36
13	1.11	1.09	5.65	5.45
14	1.35	1.35	7.00	6.80
15	1.65	1.66	8.65	8.46
16	2.02	2.05	10.67	10.51
17	2.47	2.53	13.14	13.04
18	3.01	3.12	16.15	16.16
19	3.68	3.85	19.83	20.00
20	4.50	4.68	24.33	24.68
21	5.50	5.70	29.83	30.38
22	6.72	6.94	36.55	37.32
23	8.21	8.45	44.76	45.77
24	10.03	10.29	54.79	56.06
25	12.25	12.52	67.04	68.58
26	14.97	15.25	82.01	83.83
27	18.29	18.56	100.31	102.39
28	22.35	22.60	122.66	124.99
29	27.31	27.51	149.96	152.50
30	33.37	33.49	183.33	185.99
31	40.77	40.78	224.10	226.76
32	49.81	49.64	273.91	276.41
33	60.86	60.44	334.77	336.84
34	74.36	73.58	409.14	410.42
35	90.86	89.58	500.00	500.00

X_1	1.221830	1.203000
X_2		1.233250
X_3		1.217449

Logarithmic Spacing on Delta Radius

1) Radial rings defined only for important boundaries

2) Radial rings defined by geometric spacing on delta radius method

Grid #	Delta R (km)	Radius (km)	Radius (km)-BND	Delta R (km)-MOD	R (km)-FIN	R (km)-FIN-MOD	Remarks
1	0.25	0.25	0.25	0.25	0.25	0.25	
2	0.309	0.559		0.320	0.570	0.560	Changes to 0.56 (i.e. EAB)
3	0.382	0.941		0.409	0.979	0.979	
4	0.472	1.413		0.523	1.501	1.501	
5	0.584	1.997	2.17	0.669	2.17	2.17	EAB + 1 mi (for Early Fatalities)
6	0.722	2.719		0.790	2.960	2.960	
7	0.892	3.611		0.935	3.895	3.895	
8	1.103	4.714	5	1.105	5	5	PAZ Boundary
9	1.364	6.078		1.372	6.372	6.372	
10	1.686	7.763		1.705	8.077	8.077	
11	2.084	9.847		2.117	10.194	10	Changes to 10 (for Shadow Evacuation)
12	2.576	12.423		2.630	12.824	12.824	
13	3.184	15.608	16.09	3.266	16.09	16	Changes to 16 (for Cancer Fatalities)
14	3.937	19.544		3.873	19.963	19.963	
15	4.867	24.411		4.592	24.555	24.555	
16	6.016	30.427	30	5.445	30	30	UPZ Boundary
17	7.437	37.864		6.588	36.588	36.588	
18	9.194	47.058		7.972	44.560	44.560	
19	11.365	58.423		9.646	54.206	54.206	
20	14.050	72.473		11.671	65.878	65.878	
21	17.369	89.842	80	14.122	80	80	Reporting
22	21.471	111.314		18.327	98.327	98.327	
23	26.543	137.857		23.783	122.110	122.110	
24	32.813	170.670		30.864	152.975	152.975	
25	40.564	211.233		40.054	193.029	193.029	
26	50.145	261.378		51.979	245.007	245.007	
27	61.990	323.368		67.455	312.462	312.462	
28	76.632	400	400	87.538	400	400	Residual Effect

SUM	400.0

DIFF_BND	SUM_INT	Range
2.17	2.170	(0~2.17 km)
2.83	2.830	(2.17~5 km)
11.09	11.090	(5~16.09 km)
13.91	13.910	(16.09~30 km)
50	50.000	(30~80 km)
320	320.000	(80~400 km)

X	1.236207851

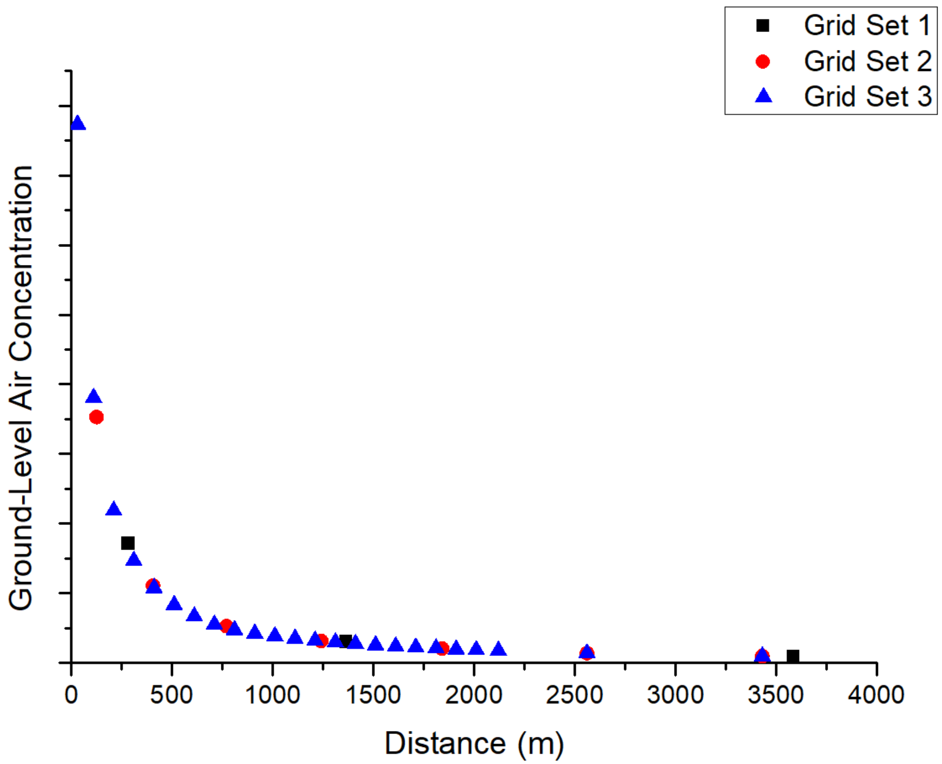
Interval	Geometric Ratio	STD DEV	
X_1 (1~5)	1.27882	0.048	(0~80 km)
X_2 (5~8)	1.18228		
X_3 (8~13)	1.24206		
X_4 (13~16)	1.18573		
X_5 (16~21)	1.20999		
X_6 (21~28)	1.29773	0.041	(0~400 km)

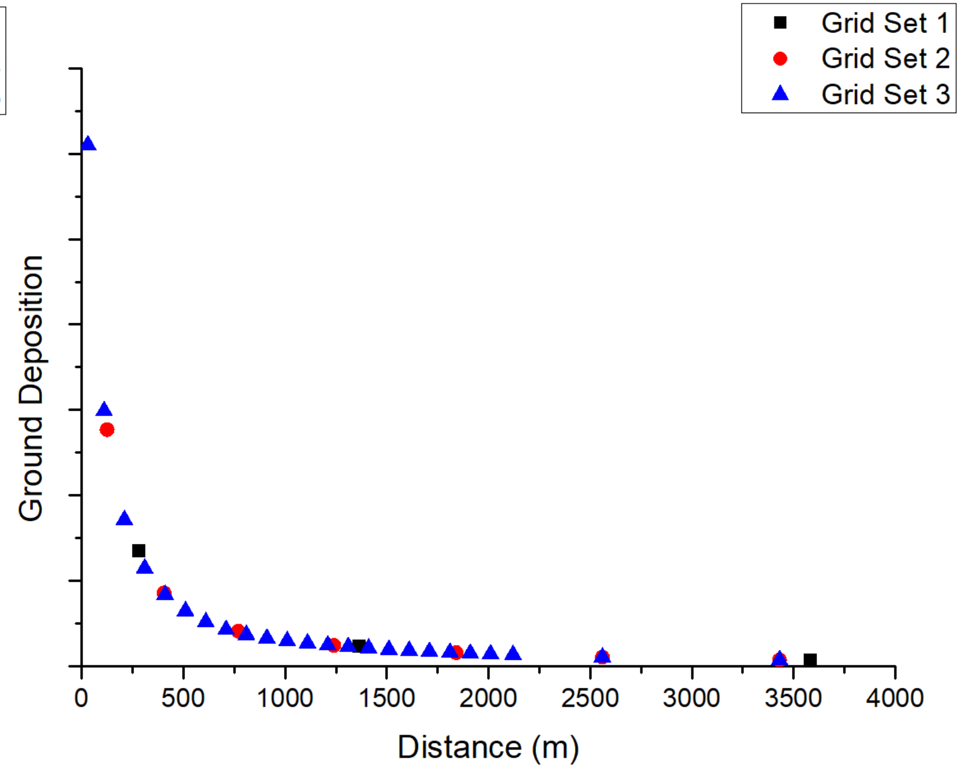
Grid Set 1	Grid Set 2	Grid Set 3	
		0.06	
		0.16	
	0.25	0.26	
		0.36	
		0.46	
0.56	0.56	0.56	EAB
		0.66	
		0.76	
		0.86	
	0.98	0.96	
		1.06	
		1.16	
		1.26	
		1.36	
	1.5	1.46	
		1.56	
		1.66	
		1.76	
		1.86	
		1.96	
		2.06	
2.17	2.17	2.17	EAB + 1 mile
	2.96	2.96	
	3.9	3.9	
5	5	5	PAZ Boundary
	6.37	6.37	
	8.08	8.08	
10	10	10	Shadow Evacuation
	12.82	12.82	
16	16	16	10 miles
	19.96	19.96	
	24.56	24.56	
30	30	30	UPZ Boundary

3) 2) with additional rings inside (EAB + 1 mile)

Logarithmic Spacing on Delta Radius

- Concentration and deposition

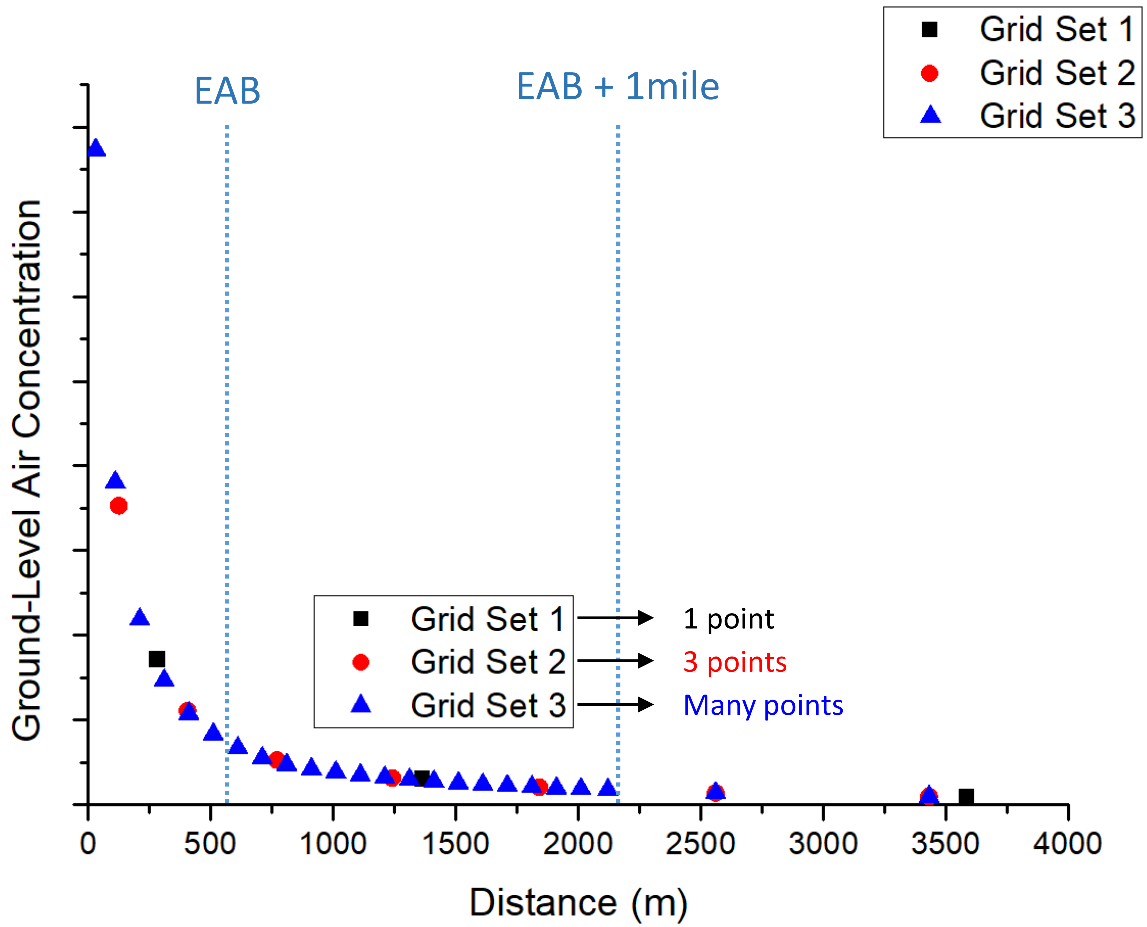




- Concentration and deposition results are on the line of exponential decrease

Logarithmic Spacing on Delta Radius

- Concentration result used to calculate dose and health effects
  - For example: Early fatality within (EAB + 1 mile)



Grid Set 1	Grid Set 2	Grid Set 3	
		0.06	
		0.16	
	0.25	0.26	
		0.36	
		0.46	
0.56	0.56	0.56	EAB
		0.66	
		0.76	
		0.86	
	0.98	0.96	
		1.06	
		1.16	
		1.26	
		1.36	
	1.5	1.46	
		1.56	
		1.66	
		1.76	
		1.86	
		1.96	
		2.06	
2.17	2.17	2.17	EAB + 1 mile
	2.96	2.96	
	3.9	3.9	
5	5	5	PAZ Boundary
	6.37	6.37	
	8.08	8.08	
10	10	10	Shadow Evacuation
	12.82	12.82	
16	16	16	10 miles
	19.96	19.96	
	24.56	24.56	
30	30	30	UPZ Boundary

Logarithmic Spacing on Delta Radius

- Results of health effects

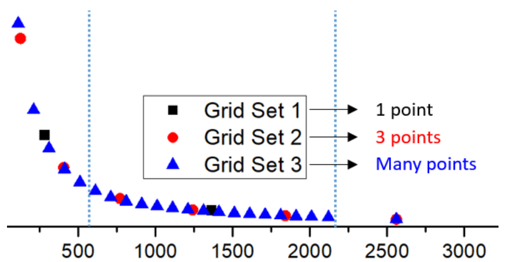
Health Effect Cases		Grid Set 1	Grid Set 2	Grid Set 3
Early Fatality	0.56-2.17 km	-21.88%	0.00%	-0.30%
Early Fatality	2.17-5.0 km	-100.00%	0.00%	0.00%
Early Fatality	5.0-10.0 km	0.00%	0.00%	0.00%
Early Fatality	10.0-16.0 km	0.00%	0.00%	0.00%

Health Effect Cases		Grid Set 1	Grid Set 2	Grid Set 3
Cancer Fatality	0.56-2.17 km	16.33%	0.00%	-1.00%
Cancer Fatality	2.17-5.0 km	0.23%	0.00%	0.00%
Cancer Fatality	5.0-10.0 km	-1.20%	0.00%	0.00%
Cancer Fatality	10.0-16.0 km	2.18%	0.00%	0.00%
Cancer Fatality	16.0-30.0 km	-6.41%	0.00%	0.00%

Population-Weighted Risk		Grid Set 1	Grid Set 2	Grid Set 3
Early Fatality	0.56-2.17 km	-21.93%	0.00%	-0.31%
Early Fatality	0.56-5.0 km	-22.35%	0.00%	-0.00%
Early Fatality	0.56-10.0 km	-22.27%	0.00%	-0.24%
Early Fatality	0.56-16.0 km	-21.95%	0.00%	-0.00%
Early Fatality	0.56-30.0 km	-22.06%	0.00%	-0.21%

Population-Weighted Risk		Grid Set 1	Grid Set 2	Grid Set 3
Cancer Fatality	0.56-2.17 km	16.36%	0.00%	-0.69%
Cancer Fatality	0.56-5.0 km	6.84%	0.00%	0.00%
Cancer Fatality	0.56-10.0 km	3.54%	0.00%	-0.25%
Cancer Fatality	0.56-16.0 km	3.41%	0.00%	0.00%
Cancer Fatality	0.56-30.0 km	0.63%	0.00%	0.00%

Population Dose		Grid Set 1	Grid Set 2	Grid Set 3
L-ICRP60ED	0.56-2.2 km	-1.06%	0.00%	-0.21%
L-ICRP60ED	0.56-5.0 km	-0.52%	0.00%	-0.10%
L-ICRP60ED	0.56-10.0 km	0.00%	0.00%	0.00%
L-ICRP60ED	0.56-16.0 km	0.00%	0.00%	0.00%
L-ICRP60ED	0.56-30.0 km	0.35%	0.00%	0.00%



- Spatial grid setting can influence both early & cancer fatalities especially in near-field
- Threshold dose for early fatalities and DDREF for cancer fatalities can have an influence
- Logarithmic spacing on delta radius can be a good option

Summary and Conclusion

Summary and Conclusion

- Optimization of **Plume Segmentation**
  - The number of plume segments: Linearly proportional to the calculation time
  - Suggested method: **Optimization based on the slope of cumulative release**
    - Reduced analysis time by up to 55% while maintaining the accuracy of the analysis results
- Optimization of **Particle Size Distribution Setting**
  - The number of particle size bin: Not much impact on the calculation speed
    - Can affects the results, but the effect on the analysis time is insignificant.
  - Suggested method: **Set as many particle size bins as possible**, as long as data supports it
- Optimization of **Spatial Grid Setting**
  - The number of spatial grid: Linearly proportional to the calculation time
  - Suggested method: **Logarithmic spacing on delta radius**
    - Works quite well in case study
    - Setting too many rings in near-field does not necessarily improve the results → Optimization is necessary.

Thank you.

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