Integration of Source Term in Multi-Unit Accident Scenario

Sung-yeop Kim and Dong-San Kim

Korea Atomic Energy Research Institute

sungyeop@kaeri.re.kr

2019 IMUG Meeting

US NRC Headquarters, North Bethesda, MD

June 10-11, 2019

Korea Atomic Energy Research Institute

Table of Contents

Characteristics of Multi-Unit Level 3 PSA

Characteristics of Multi-Unit Level 3 PSA

- Accidents at Multiple Units
  - Different sources released from each NPP unit
  - Exponentially increasing number of multi-unit accident scenarios by the number of STCs (n) and the number of units (k) on a site:
    - When accidents happen at all k units
      ex) Accidents happen at 6 units in the site comprised of 6 units

$$n^k$$

    - When accidents happen at some units (include subset)
      ex) Accidents happen at 1, 2, 3, 4, 5, or 6 units in the site comprised of six units

→ Adding zero release source term can be a simple solution

$$(n+1)^k$$

*Fukushima 2011/Photo: AFP

Characteristics of Multi-Unit Level 3 PSA

- Number of Multi-Unit Accident Scenarios
  - Different reactor type (exactly: Different core inventory)
    - Different contents of STCs for each unit
    - Multiplication of the number of STCs of each unit, regardless of identical release location or multiple release locations
  - Identical reactor type (exactly: Identical core inventory)
    - Identical Release Location: Nothing to do with order = Combination
    - Identical reactor type: Allow repetition = Combination with repetition

	Multiple Release Locations	Identical Release Location
Different Core Inventory (The Number of STCs of Each Unit: p, q, …, x, y)	$p \times q \times \cdots \times x \times y$	$p \times q \times \cdots \times x \times y$
Identical Core Inventory	n^k (Related to Order)	${}_nH_k = {}_{n+k-1}C_k = \frac{(n+k-1)!}{k!\,(n-1)!}$ (Unrelated to Order, Allow Repetition)

※ *If zero-release STC is added, +1 for every parameters excluding k*

Characteristics of Multi-Unit Level 3 PSA

- Number of Multi-Unit Accident Scenarios

  - $(n+1)^k$

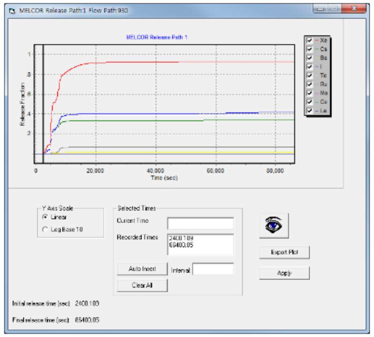
Number of STCs	Number of Units							
	1	2	3	4	5	6	7	8
5	6	36	216	1,296	7,776	46,656	279,936	1,679,616
10	11	121	1,331	14,641	161,051	1,771,561	19,487,171	214,358,881
15	16	256	4,096	65,536	1,048,576	16,777,216	268,435,456	4,294,967,296
20	21	441	9,261	194,481	4,084,101	85,766,121	1,801,088,541	37,822,859,361

  - One point release: ${}_{n+1}H_k$

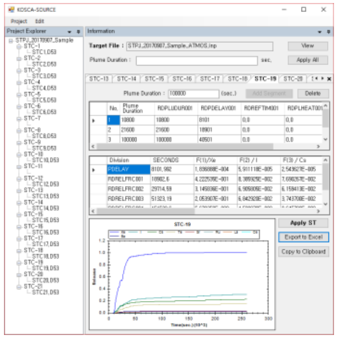
Number of STCs	Number of Units							
	1	2	3	4	5	6	7	8
5	6	21	56	126	252	462	792	1,287
10	11	66	286	1,001	3,003	8,008	19,448	43,758
15	16	136	816	3,876	15,504	54,264	170,544	490,314
20	21	231	1,771	10,626	53,130	230,230	888,030	3,108,105

Pending Issue on Multi-Unit Level 3 PSA

- **Interfacing between Level 2 & 3 PSA**
  - Dependent on severe accident analysis code (MELCOR / MAAP)
    - Interfacing of MELCOR-MACCS: **MELMACCS**
    - Interfacing of MAAP-MACCS: **KOSCA-SOURCE**
      - Only compatible with MAAP5→MACCS2
      - Only 4 plume segments applicable
  - Necessary update
    - Applying dynamic property of source release
    - Considering multi-unit accident



MELMACCS



KOSCA-SOURCE

- **Consequence Analysis of Multi-Unit Accident**
  - Approach to deal with enormous number of multi-unit accident combinations with a practical amount of effort

Severe Accident Code	Single- / Multi-Unit	Interfacing between L2-L3	Tool to Interface between L2-L3	Consequence Analysis Code	Approach to Handle Enormous Number of Multi-Unit Accident Scenarios Applying Dynamic Source Release
MELCOR	Single	Same Radionuclides Group	MELMACCS	MACCS	N/A
	Multi-Unit	Same Radionuclides Group and Use WinMACCS Multi-Unit Option	-	MACCS	**Necessary**
MAAP	Single	Different Radionuclides Group	**KOSCA-SOURCE (Update Needed)**	MACCS	N/A
	Multi-Unit	**New SW** or Use WinMACCS Multi-Unit Option	**This Study**	MACCS	**Necessary**

Current Status of R&D in KAERI

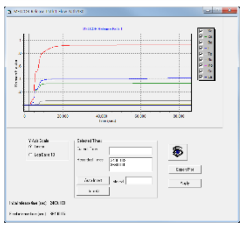
- Multi-Unit Level 3 PSA -

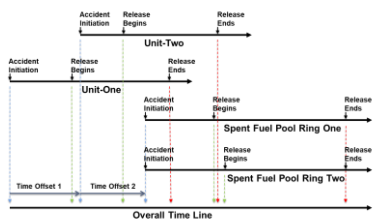
Current Status of R&D in KAERI

Interfacing
Level 2-3 PSA
(Applying Dynamic
Property of Single Unit)

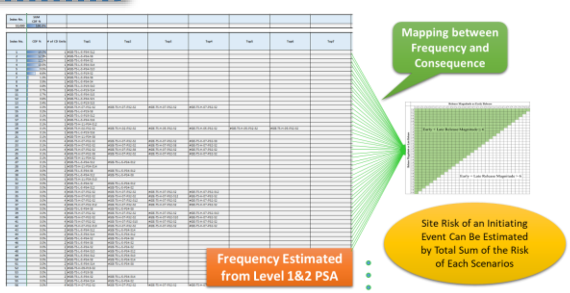
Consequence
Analysis
(Applying Dynamic
Property of Multi-Unit)

MELCOR → MELMACCS → WinMACCS → Analysis of Each Multi-Unit Accident Scenario





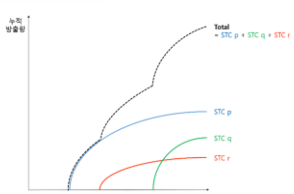
Look-Up Table Approach → Deal with Every Multi-Unit Accident Scenario

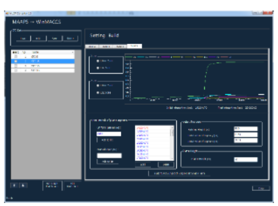


Interfacing
Level 2-3 PSA
(Applying Dynamic
Property of Single or
Multi-Unit)

Consequence
Analysis
(Applying Dynamic
Property of Multi-Unit)

MAAP → MUST Converter → WinMACCS → Analysis of Each Multi-Unit Accident Scenario





Interfacing MAAP-MACCS

- Applying Dynamic Property of Multi-Unit Accident -

Dynamic Property of Source Release

- STC Expression by Accident Progression
  - Amount of release
    - Cumulative release amount by time
    - Cumulative release fraction by time
      - Converted to release amount by applying core inventory
  - Manner of release
    - Delay and duration of release
    - Energy accompanied with release
    - Release height
  - Manner of release

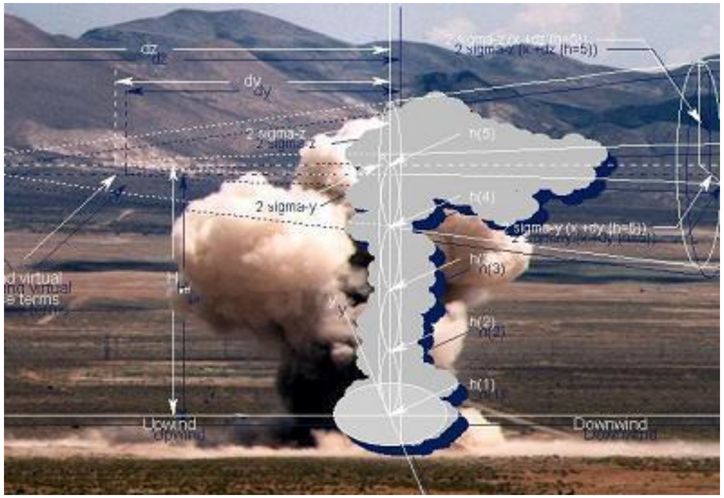


*Image from HotSpot code homepage: https://narac.llnl.gov/hotspot

- Gaussian Plume Model
  - Most commonly used model of atmospheric dispersion in consequence analysis
  - Not easy to apply dynamic property of release
- Gaussian Plume Segment Model
  - Express source release by multiple plumes (Time-discretization)
    - Enable semi-dynamic modeling of source release

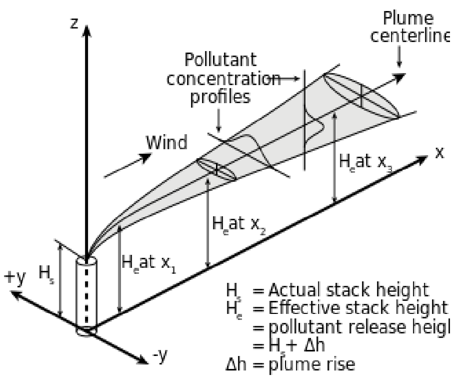
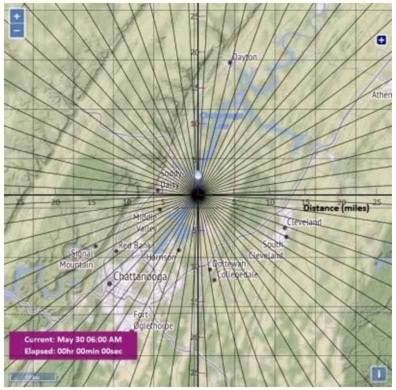


*Image from https://en.wikipedia.org/wiki/Outline_of_air_pollution_dispersion



*Ref: N. E. Bixler, "Overview of MACCS Code Development and Applications," International MACCS User Group (IMUG) 2018 Meeting, Bethesda, MD, June 11-12, 2018.

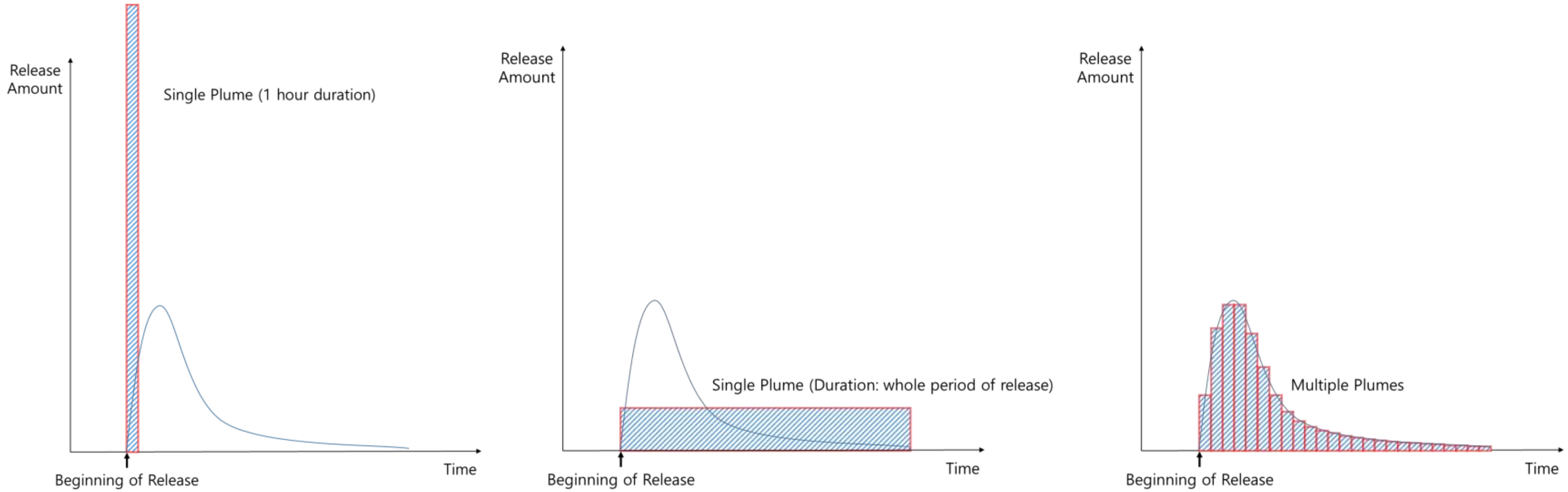
Importance of Applying Multiple Plume Segments

- Single Plume or Multiple Plumes for Source Release
  - Not many plumes were employed to model source release before
  - Increased interest after Fukushima accident
    - Long-duration release
    - Change of release by time
- S/W (MACCS) Support for Realistic Modeling
  - Longest duration of emergency phase: 7 days → 40 days
  - Maximum number of plume segments: 4 → 200 → 500
- ASME/ANS RA-S-1.3-2017:
  Standard for Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Applications
  - [RE-A3] **Multiple Plumes**

Capability Category I	Capability Category II	Capability Category III
DEVELOP a single plume for each release category.	DEVELOP multiple plumes for each release category (e.g., to reflect significant changes in the source term as a function of time, to capture meteorological changes).	DEVELOP multiple plumes for each release category at the same resolution as the underlying meteorological data (e.g., to reflect significant changes in the source term as a function of time, to capture meteorological changes).

Importance of Applying Multiple Plume Segments

- Comparison between Single Plume and Multiple Plumes

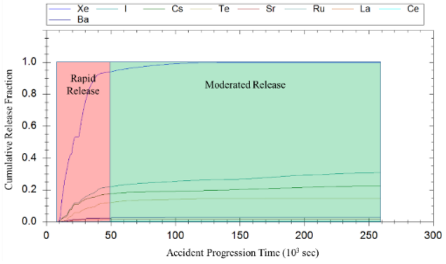


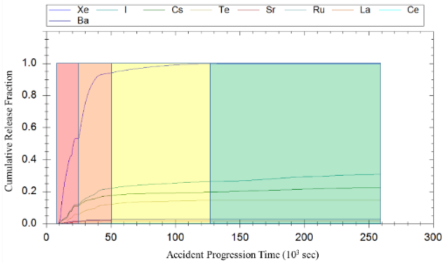
- Number of Plumes Applied in NUREG-1150 Study and SOARCA Study

	NUREG-1150 (Peach Bottom)	Sample Problem A (Surry)	SOARCA (Surry)	SOARCA (Peach Bottom)
Number of Plumes	2	2	28 (LTSBO) 24 (STSBO) 24 (ISLOCA) 49 (TISGTR Mitigated) 24 (TISGTR Unmitigated)	29 (LTSBO) 33 (STSBO with RCIC Blackstart) 86 (STSBO without RCIC Blackstart)

Importance of Applying Multiple Plume Segments

- **Sensitivity of Off-Site Consequence to Time-Discretization of Plume Release**
  - Duration of accident progression: 72 hours
  - 4 sensitivity cases
    - **Case 1**: 1-hour Duration of Single Plume for 72-hour Release Amount
    - **Case 2**: 24-hour Duration of Single Plume for 72-hour Release Amount
    - **Case 3**: Two Plume Segments: One for Early Rapid Release / The Other for Late Moderated Release
    - **Case 4**: Four Plume Segments: Relatively Realistic
  - Conclusion of sensitivity study
    - Excessively simplified modeling such as a single plume release is possibly over- or under-estimate human health effects, especially for early release with a large amount of radioactive materials.
    - The health effect can be seriously over- or under-estimated, if it is combined with emergency response due to the overlapped duration between source release and emergency response.

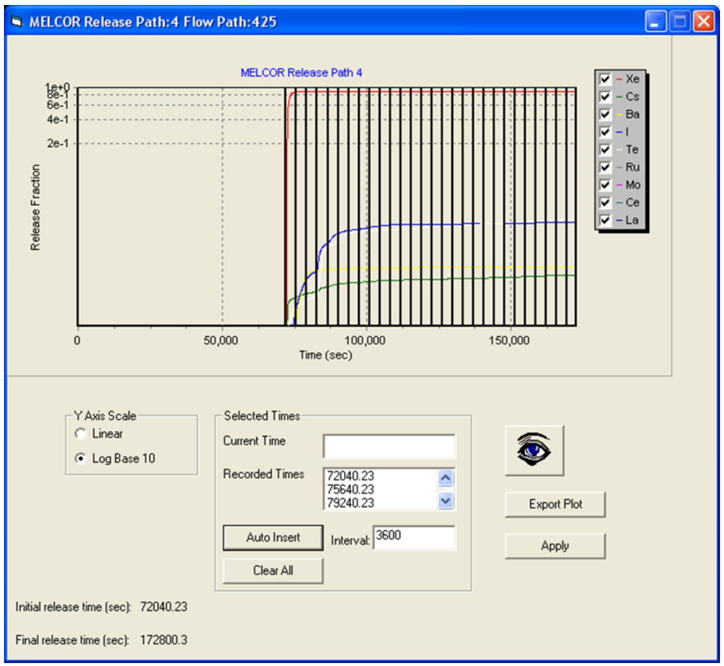




Korea Atomic Energy Research Institute

Interfacing Level 2-3 PSA Applying Multiple Plume Segments

- **MELCOR-MACCS**
  - MELMACCS
    - MELCOR output - (MELMACCS) - MACCS input



*img from: N. E. Bixler, "Overview of MACCS Code Development and Applications," International MACCS User Group (IMUG) 2018 Meeting, Bethesda, MD, June 11-12, 2018.

Group	Name of Group	Representative	Member Elements
1	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	Halogens	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkali Earth	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	I	F, Cl, Br, I, At
5	Chalcogens	Te	O, S, Se, Te, Po
6	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf

Interfacing Level 2-3 PSA Applying Multiple Plume Segments

▪ **MAAP-MACCS**: Different Radionuclide Group

- MAAP Fission Product Group

	Group	Member Elements		Group	Member Elements
MAAP4 & MAAP5	G1	VAPOR (V): Noble gases (Xe + Kr) AEROSOL (A): All non-radioactive inert aerosols	Only MAAP5	G13	Ag (control rod material, not FP)
	G2	V & A: CsI + RbI		G14	V: I2 (iodine in elemental form)
	G3	V & A: TeO2		G15	V: CH3 I (iodine in organic form)
	G4	V & A: SrO		G16	V & A: Cs2MoO4
	G5	V & A: MoO2 + RuO2* + TcO2 + RhO2		G17	V & A: RuO2
	G6	V & A: CsOH + RbOH		G18	V & A: PuO2 (fuel, not fission product)
	G7	V & A: BaO			
	G8	V & A: La2O3 + Pr2O3 + Nd2O3 + Sm2O3 + Y2O3 + ZrO2 + NbO2 + AmO2** + CmO2**			
	G9	V & A: CeO2 + NpO2 + PuO2*			
	G10	V & A: Sb			
	G11	V & A: Te2			
	G12	V & A: UO2 (fuel, not FP)			

* Only MAAP4
** Only MAAP5

- MACCS: NUREG-1150

Group	Name of Group	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	Ba	Ba

- MACCS: SOARCA

Group	Name of Group	Representative	Member Elements
1	Noble Gas	Xe	He, Ne, Ar, Kr, Xe, Rn, H, N
2	Alkali Metals	Cs	Li, Na, K, Rb, Cs, Fr, Cu
3	Alkali Earths	Ba	Be, Mg, Ca, Sr, Ba, Ra, Es, Fm
4	Halogens	I	F, Cl, Br, I, At
5	Chalcogens	Te	O, S, Se, Te, Po
6	Platinoids	Ru	Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni
7	Early Transition Elements	Mo	V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W
8	Tetravalent	Ce	Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
9	Trivalents	La	Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf

Interfacing Level 2-3 PSA Applying Multiple Plume Segments

- **MAAP-MACCS Interfacing**
  by Release Fraction & Release Mass of Each FP Group
  (MAAP: Chemical Compound → MACCS: Element)
  - Release expression of MACCS

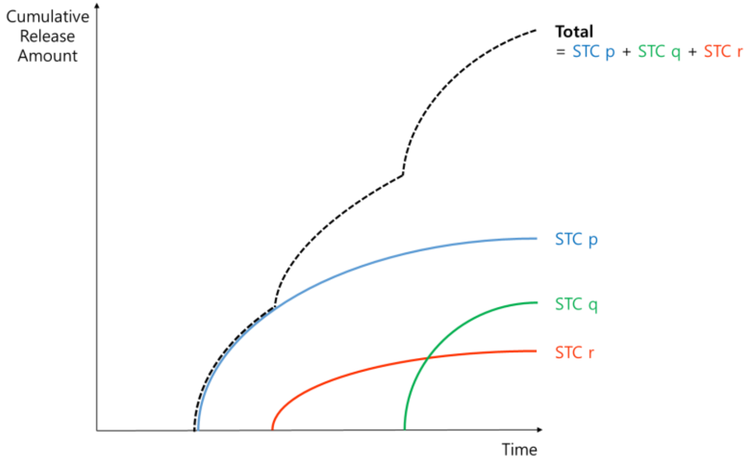
$$Release\ Fraction\ (f) = \frac{Release\ Mass\ (m)}{Core\ Inventory\ (I)}$$

    - Same release fraction for radionuclides in same group
  - Conversion using release fraction and release mass of each FP group of MAAP
    - Considering every element for each group (ex: Cs & Rb for Alkali Metals)
    - Considering representative element for each group (ex: Only Cs for Alkali Metals)

- **MAAP-MACCS Interfacing**
  by Release Mass of Representative Isotope
  (MAAP: Element → MACCS: Element)
  - Considering release mass of representative isotope (ex: Cs-137 for Cs)

Integration of Multi-Unit Source Term

- Advantages
  - Apply dynamic property of each release
  - Integration during interfacing L2-3 PSA
    - Don't need to build multi-unit consequence model
    - Can be supported by automation of making each multi-unit combination
  - Likely to provide useful information
    - By interfacing integrated source term to each multi-unit accident scenario
      - Consequence analysis
      - Regression
      - Machine learning



- Limitations
  - Only applicable to one point release
  - Possible worse accuracy than building multi-unit consequence model
    - Assumptions to integrate units having different core inventory
    - Assumptions to integrate heat of each release

Integration of Multi-Unit Source Term

- Method
  - In case of identical core inventory for each unit
    - Integrate release fraction of each unit
    - Total sum of release fraction can be above 100%
      - Can avoid using core scaling factor (CORSCA)

Release Amount = Σ(Core Inventory × Release Fraction)

= Core Inventory × Σ(Release Fraction) (∵ Due to identical core inventory)

= (Core Inventory × Number of Units (CORSCA))×(Σ(Release Fraction) / Number of Units (CORSCA))

  - In case of different core inventory for each unit
    - Integrate release mass of each unit
    - Total core inventory

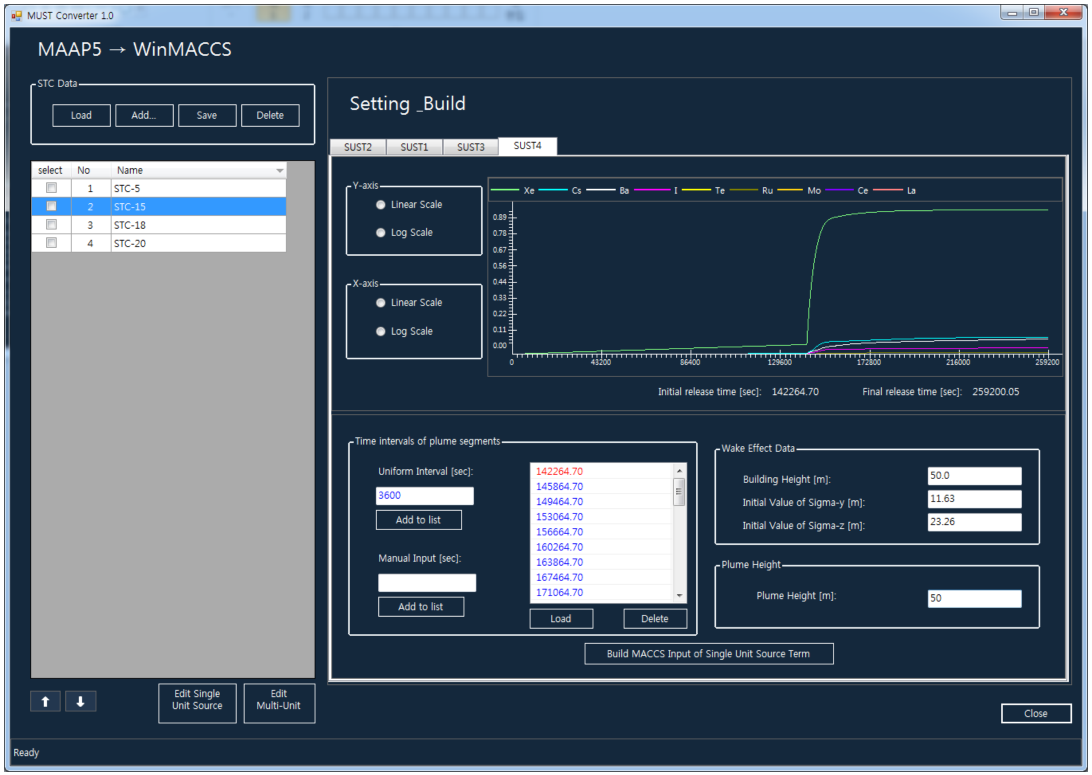
$$\sum_{i=1}^{n} I_i = I_1 + I_2 + I_3 + \cdots + I_n$$

    - Integrated release fraction by core inventory-weighted average

$$\frac{\sum_{i=1}^{n} I_i f_i}{\sum_{i=1}^{n} I_i} = \frac{I_1 f_1 + I_2 f_2 + I_3 f_3 + \cdots + I_n f_n}{I_1 + I_2 + I_3 + \cdots + I_n}$$

Software Interfacing Level 2-3 PSA
Applying Multiple Plume Segments

- **MUST(Multi-Unit Source Term) Converter**
  - Single unit: MAAP-MACCS interfacing with flexible multiple plume segments
    - Flexible time interval input
    - Better version compatibility: MAAP4 or MAAP5 → MACCS2 or WinMACCS
  - Multi-unit: Integration of multi-unit release



Summary and Conclusion

Summary and Conclusion

- **Pending Issue** on Multi-Unit Level 3 PSA
  - Interfacing Level 2-3 PSA (especially MAAP-MACCS) by applying dynamic property of source release
  - Deal with enormous number of multi-unit accident combinations with a practical amount of effort
- **Method** to Interface between MAAP and MACCS
  - **Conversion** by using release fraction & release mass of each FP group
    (**MAAP: Chemical Compound** → **MACCS: Element**)
  - **Direct mapping** by using release mass of representative isotope
    (**MAAP: Element** → **MACCS: Element**)
- **Method** to Integrate Multi-Unit Source Term
  - For both identical or different core inventory
- **Software** to Realize Above Methods
  - **MUST Converter**
- To be Updated to MUST Converter
  - Application of method using direct mapping
  - Application of representative release height
    - Effective release height considering physical height & release energy

Thank you.

Acknowledgement
This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT: Ministry of Science, ICT) (No. 2017M2A8A4015287).