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ISFRA SFR 중대사고 해석 프로그램 안에 MAEROS 에어로졸 모델의 구현 및 검증

Implementation and Validation of the MAEROS Aerosol Model in ISFRA SFR Severe Accident Analysis Program

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Churl Yoon* & Seok Hun Kang

KAERI
한국원자력연구원
Korea Atomic Energy Research Institute

Introduction

❑ PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor)

- KAERI developed a design and analysis technique for a **pool-type sodium-cooled fast reactor** called PGSFR, since 1987.
- PGSFR design focuses on the inherent safety characteristics of **metal fuel** and **passive cooling using natural circulation and thermal expansion**.
- Despite the extremely low probability of a severe accident expected in the PGSFR, the analytical capabilities and tools to **predict radioactive fission products (FPs) releases** to the environment under postulated nuclear power plant accidents are required for public acceptance and licensing.

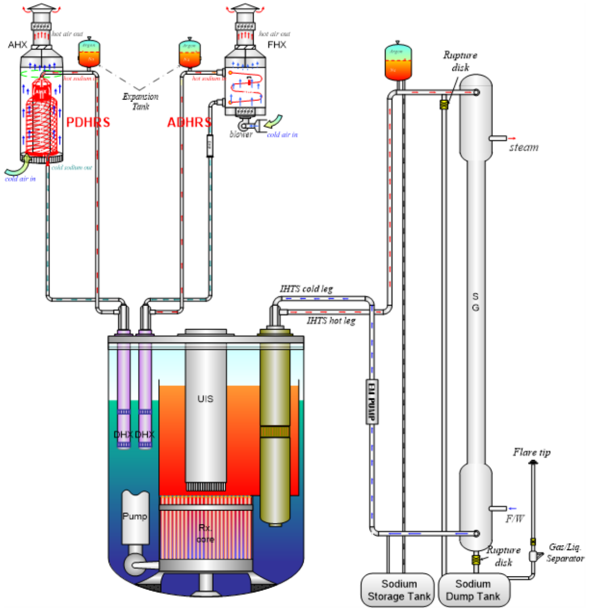


Fig. PGSFR schematic diagram

❑ ISFRA (Integrated SFR Analysis Program for PSA)

- KAERI and Fauske & Associates, LLC (FAI), jointly developed ISFRA computer program to simulate the response of the PGSFR pool design with metal fuel during a severe accident.
- ISFRA was designed to be a fast-running simulation software, used for the Level II PSA of PGSFRs.
- ISFRA adapted **FAI's correlation-based aerosol analysis model**, as like MAAP or APRIL code.

Correlation-based Aerosol Model (1/2)

FAI's Correlation-based Aerosol Model

- **Aerosol similarity assumed.**
  - As time increase, the **particle size distribution becomes the same**, independent of the initial distribution of sizes.
  - Two steady-state aerosols or two aging aerosols (after the initial conditions are forgotten) are similar, if their dimensionless densities *M* are the same. (See **Figure I**)
  - By **similarity analysis**, variables concerning aerosol behavior can be non-dimensionalized, as in **Table 1**.

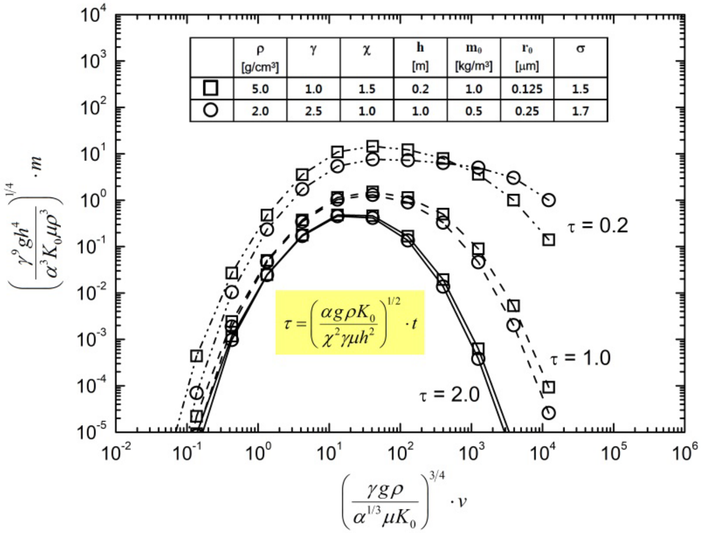


Fig. I: Particle mass distribution of two different aging aerosols undergoing Brownian and gravitational coagulation and settling

Table 1: Dimensionless major variables for aerosols undergoing Brownian and gravitational coagulation and settling

Time, τ	Particle volume, υ	Particle number density, N
$\left(\frac{\alpha g \rho K_0}{\chi^2 \gamma \mu h^2}\right)^{1/2} \cdot t$	$\left(\frac{\gamma g \rho}{\alpha^{1/3} \mu K_0}\right)^{\frac{3}{4}} \cdot v$	$\left(\frac{\gamma^3 K_0^5 \mu^5 h^4}{\alpha g^5 \rho^5}\right)^{1/4} \cdot n$
Mass density, M	**Decay constant, Λ**	**Particle production rate, $\dot{N}_p$**
$\left(\frac{\gamma^9 g h^4}{\alpha^3 K_0 \mu \rho^3}\right)^{\frac{1}{4}} \cdot m$	$\left(\frac{\gamma \chi^2 \mu h^2}{\alpha K_0 g \rho}\right)^{1/2} \cdot \lambda$	$\left(\frac{\gamma^5 \chi^4 K_0^3 \mu^7 h^8}{\alpha^3 g^7 \rho^7}\right)^{\frac{1}{4}} \cdot \dot{n}_p$

- h effective height for aerosol deposition [m]
- k Boltzmann constant
- $K(v, \tilde{v})$ kernel representing the frequency of binary collisions between particles of volume v and $\tilde{v}$
- K_0 normalized Brownian collision coefficient
- m total mass concentration of the suspended aerosols [kg/m³]
- M dimensionless total suspended aerosol
- $\dot{M}_p$ mass dimensionless source rate
- N particle size distribution function [m^{-3}]
- $\dot{n}_p$ source rate of particles [$m^{-3}s^{-1}$]

Correlation-based Aerosol Model (2/2)

FAI's Correlation-based Aerosol Model

- **Aerosol dynamic equation is transformed into a simpler equation by using dimensionless parameters.**
  - **Total Aerosol Mass Variation:**

$$m(t)=\rho\int_0^\infty vn(v,t)dv \quad \text{with} \quad \dot{m}_p(t)=\rho\int_0^\infty v\dot{n}_p(v,t)dv$$

$$\lambda(t)=\frac{\int_0^\infty vn(v,t)u(v)dv}{h\int_0^\infty vn(v,t)dv}$$

  - **In dimensionless form, steady-state and decaying conditions are expressed as follows:**

$$\frac{dM}{d\tau}=-\Lambda_{SED}^{SS}(M)\cdot M+\dot{M}_p=0 \quad \& \quad \frac{dM}{d\tau}=-\Lambda_{SED}^{D}(M)\cdot M$$

  - **Functional relationships of $\Lambda(M)$ are obtained based on many exact numerical solutions by running a sectional analysis tool, MAEROS. (Fig. II)**
- **Limitations of FAI's Aerosol Model**
  - **The aerosol correlation technique is restricted to single-component aerosols.**
  - **Aerosol coagulation and deposition depend on particle sizes. Therefore, with a strong source or sink of specific aerosol size, the aerosol similitude would not be maintained.**

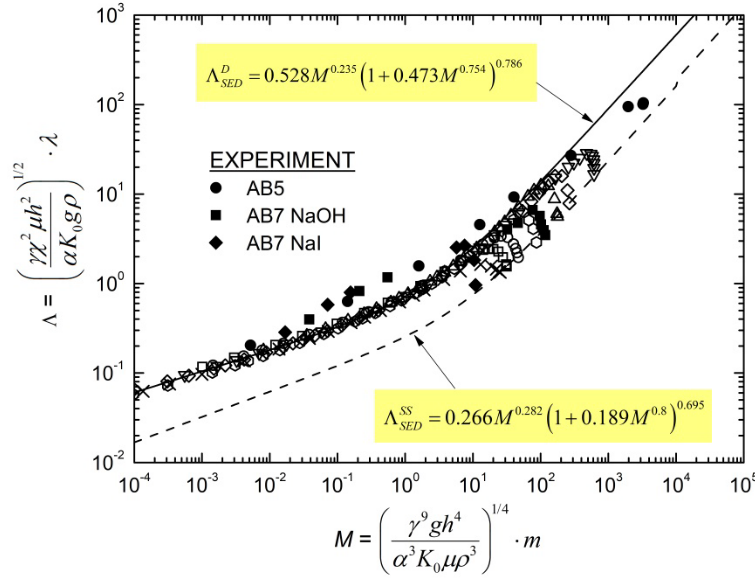


Fig. II: Dimensionless aerosol removal rate constant for sedimentation as a function of dimensionless suspended mass concentration.

$N(v,\tau)$	dimensionless particle distribution function
α	density correction factor [-]
χ	particle settling shape factor [-]
$\varepsilon(v,\tilde{v})$	capture coefficient [-]
γ	collision shape factor [-]
λ	aerosol removal rate constant [s^{-1}]
Λ	dimensionless decay constant
μ	viscosity of the carrier gas [kg/m/s]
ρ	density of the aerosol material [kg/m^3]
τ	dimensionless time
N	dimensionless particle volume

Purposes & Contents

Ultimate Goal: Improvement in Confidence in the ISFRA Severe Accident Source Term Analysis Tool for PGSFRs

Purpose of this study: To overcome the previously mentioned limitation of ISFRA's aerosol correlation technique, the sectional method aerosol program, MAEROS, was implemented into ISFRA program as an optional model for aerosol analysis in this study. And, the implemented model was verified and validated.

CONTENTS :

MAERES Sectional Aerosol Model

MAEROS Aerosol Model

- **MAEROS model was developed by Gelbard et al. in early ’80, and adapted in CONTAIN and MELCOR codes.**
- **Assuming that coagulation and condensation occurs in series and that any two mechanisms cannot occur simultaneously, the general aerosol kinetic equation is transformed into the sectionalized governing equation:**

$$\frac{dQ_{l,k}}{dt} = \frac{1}{2}\sum_{i=1}^{l-1}\sum_{j=1}^{l-1}\left[{}^{1a}\overline{\beta}_{i,j,l} Q_{j,k} Q_i + {}^{1b}\overline{\beta}_{i,j,l} Q_{i,k} Q_j \right] - \sum_{i=1}^{l-1}\left[{}^{2a}\overline{\beta}_{i,l} Q_i Q_{l,k} - {}^{2b}\overline{\beta}_{i,l} Q_i Q_{l,k} \right]$$
$$- \frac{1}{2}\,{}^{3}\overline{\beta}_{l,l} Q_l Q_{l,k} - Q_{l,k}\sum_{i=l+1}^{m} {}^{4}\overline{\beta}_{i,l} Q_i + \overline{F}_{l,k} Q_l + {}^{1}\overline{G}_{l,k} Q_l$$
$$- \sum_{i=1}^{s}\left[{}^{2}\overline{G}_{l,i} Q_{l,k} - {}^{2}\overline{G}_{l-1,i} Q_{l-1,k} \right] + {}^{3}\overline{G}_{l-1,k} Q_{l-1} + \overline{S}_{l,k} - \overline{R}_{l,k}$$

with

$$Q_l(t) = \sum_{k=1}^{s} Q_{l,k}(t) = \int_{v_{l-1}}^{v_l} v\,n(v,t)\,dv$$

Here, $Q_{l,k}(t)$ is the total mass concentration of aerosol component k per unit volume of fluid in section l at time t, s is the total number of components, $\overline{\beta}$ ’s are sectional coagulation coefficients, $\overline{F}$ is sectional coefficient for intra-particle chemical reaction, $\overline{G}$’s are sectional growth coefficients due to gas-to-particle conversion, $\overline{S}$ is a source and $\overline{R}$ is a removal rate.

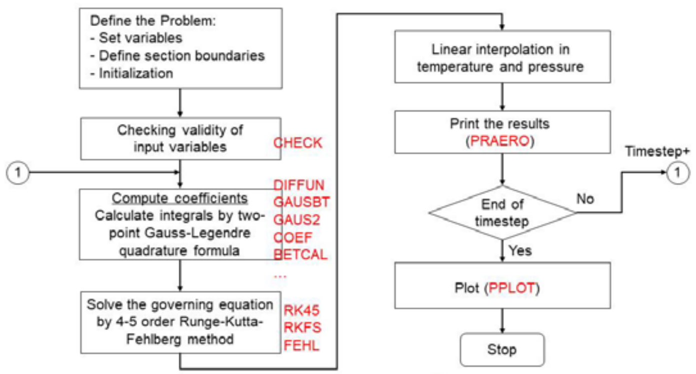


Fig. MAEROS calculation flow chart

Implementation of MAEROS Model

❑ MAEROS Implementation Plan into ISFRA Code:

- Implemented as an optional aerosol analysis model for users to select one proper aerosol model considering required level of uncertainty and computing cost.
- MAEROS model is a zero-dimensional aerosol analysis model which solves macroscopic lumped aerosol behavior inside a single compartment.
- MAEROS implementation procedure:
  - implementation of the original MAEROS model,
  - modification of the FP component treatment from MAEROS's 8-grouping into the 11-grouping, to match with the ISFRA grouping method,
  - implementation of the aerosol transport model between compartments, and
  - registering the new variables into ISFRA I/O data structure system and modification of ISFRA I/O module

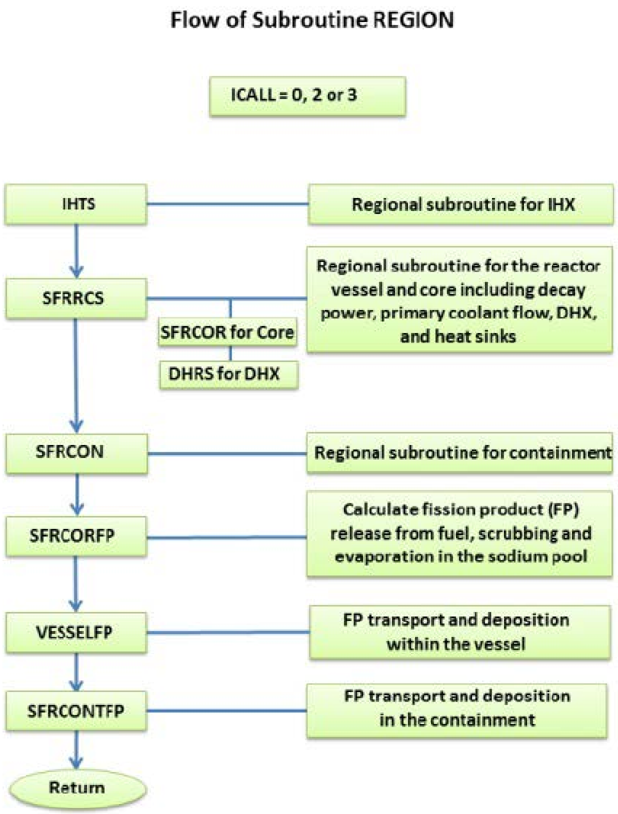


Fig. ISFRA region calculation code structure; SFRCONTFP and VESSELFP subroutines call the aerosol module

Verification and Validation Plan

❑ V&V Plan:

- According to the implementing procedures in previous slide,
  1) Validation of the implemented MAEROS model against ABCOVE AB5 experiment,
  2) Validation of the interaction model between aerosol components against ABCOVE AB6 and AB7 experiments,
  3) Verification of the aerosol transport model against a conceptual problem, and
  4) Validation of the model for PGSFR severe accident analyses.

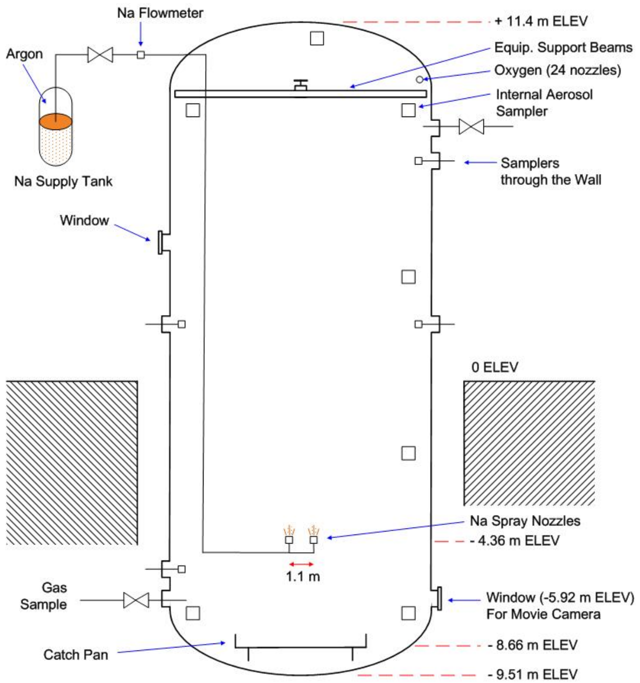


Fig. Schematic view of CSTF vessel

❑ Aerosol Behavior Code Validation and Evaluation (ABCOVE) experiments:

- A series of large-scale confirmatory tests were performed in the Containment Systems Test Facility (CSTF) vessel in the Hanford Engineering Development Laboratory (HEDL)
  - Test AB5 is a single-species aerosol test that involves spraying sodium at a high rate into an air atmosphere, while AB6 and AB7 are experiments for the case of a two-component aerosol simulating the FP releases in the presence of a sodium fire.

Validation of Original MAEROS Model

- **Validation of the implemented model against ABCOVE Experiment**
  - **Validation of the single-component aerosol model against AB5 experiment (Figure A)**
    - In the ABCOVE AB5 test, performed in 1982, a single-species aerosol was generated by spraying sodium at high rate into an air atmosphere for initial 872s.
  - **Validation of the multi-component aerosol model against AB6 & AB7 experiments (Figs. B & C)**
    - In the AB6 test, performed in 1983, a NaI aerosol was released in the presence of a sodium spray fire.
    - In the AB7 test, performed in 1984, the NaI aerosol was released after the end of a small sodium pool fire.

The ISFRA calculations with MAEROS model give the similar transient suspended aerosol masses as the ISFRA calculation with FAI's correlation-based aerosol model, and additional information of aerosol size distributions at all transient time.

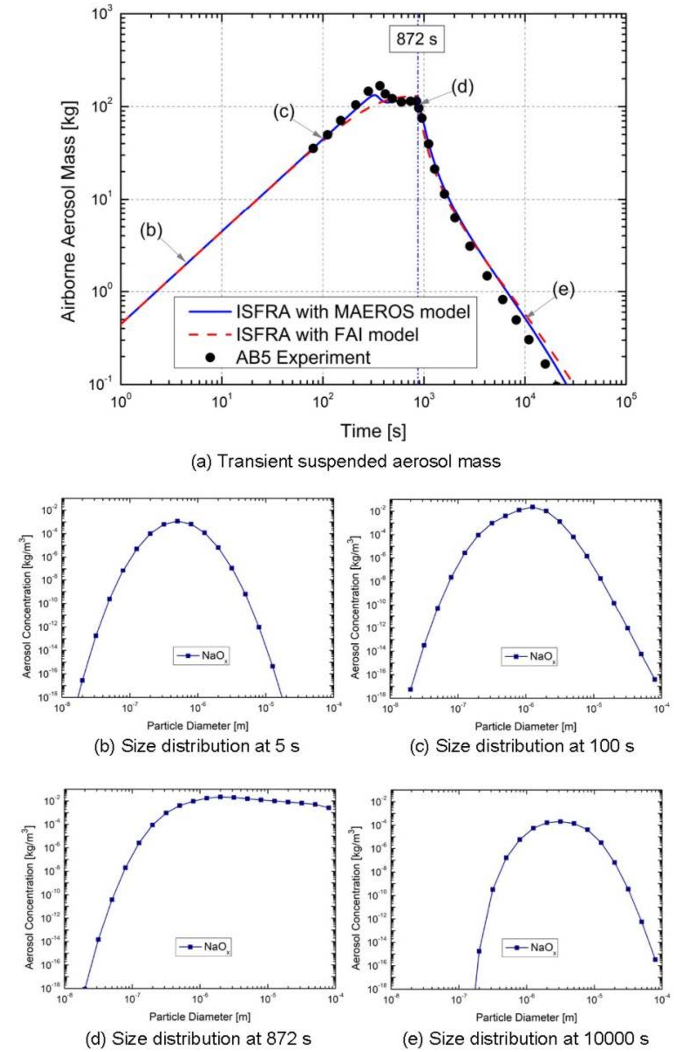
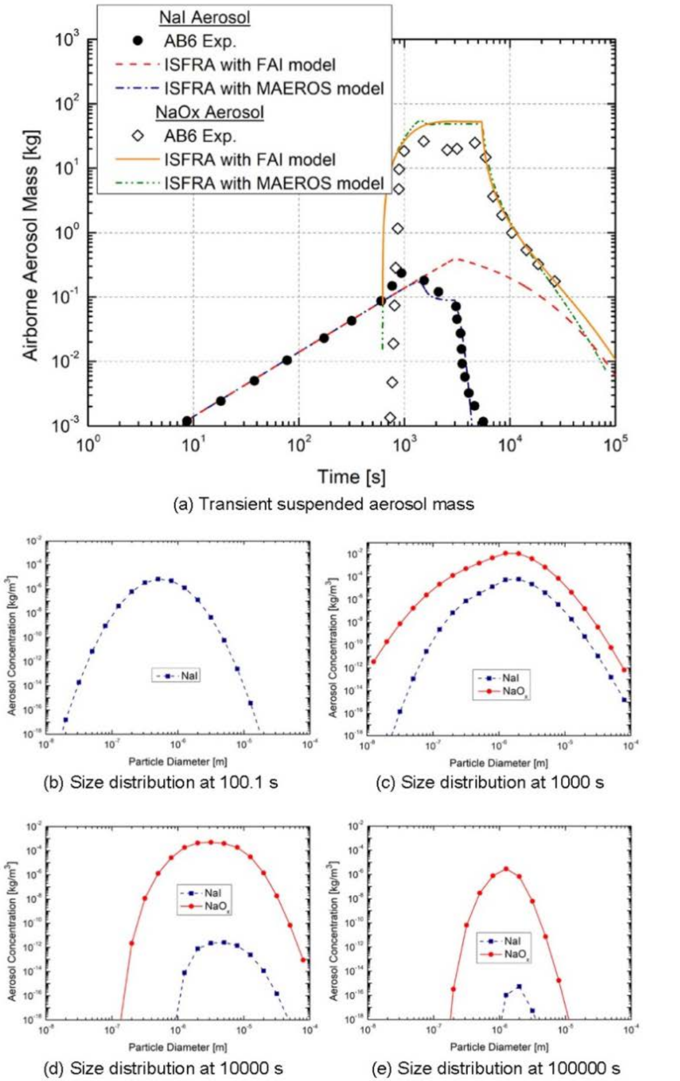


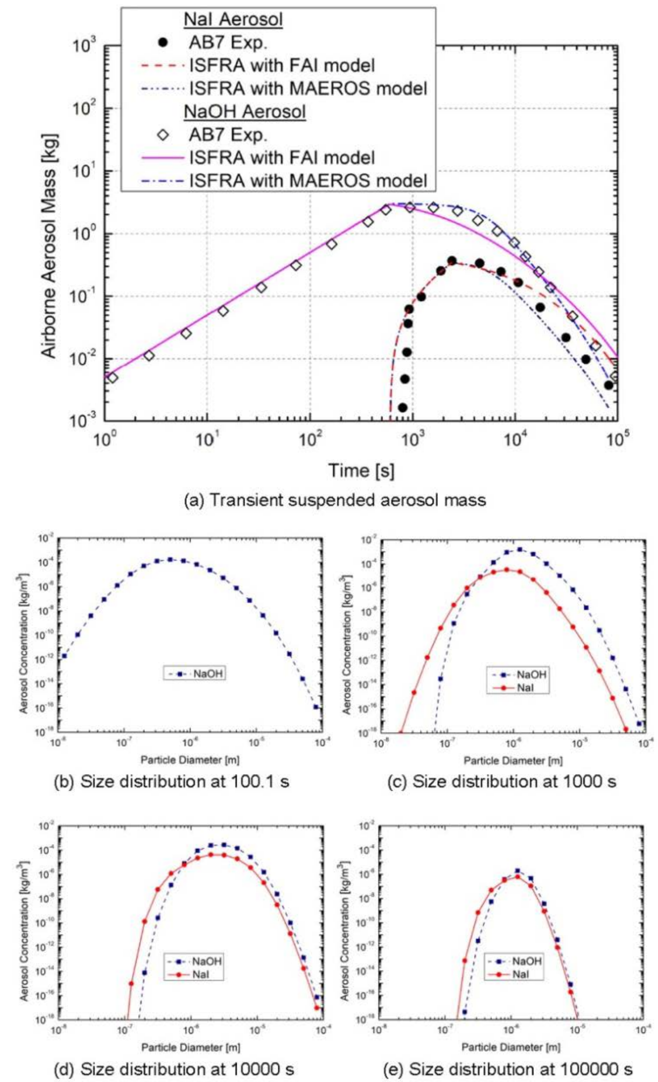
Fig. A: Validation of the ISFRA with MAEROS model against ABCOVE AB5 experiment

Validation of Multi-component Effect



(a) Transient suspended aerosol mass
(b) Size distribution at 100.1 s
(c) Size distribution at 1000 s
(d) Size distribution at 10000 s
(e) Size distribution at 100000 s

Fig. B: Validation of the ISFRA with MAEROS model against ABCOVE AB6 experiment



(a) Transient suspended aerosol mass
(b) Size distribution at 100.1 s
(c) Size distribution at 1000 s
(d) Size distribution at 10000 s
(e) Size distribution at 100000 s

Fig. C: Validation of the ISFRA with MAEROS model against ABCOVE AB7 experiment

Conclusions

❑ CONCLUSIONS

- In this study, for improving in confidence in the ISFRA severe accident source term analysis tool, MAEROS model using the sectional method has been implemented into ISFRA as an additional aerosol model option.
- From the validation of the implemented MAEROS model against the ABCOVE experiments, it is concluded that ISFRA calculation with the newly implemented MAEROS model provides the similar suspended total aerosol mass as the original ISFRA and experimental data and additional information of aerosol size distributions.
- For the complete V&V procedure, following two additional steps will be performed soon.

❑ FUTURE WORKS

- Firstly, the aerosol transport model will be validated against a simple conceptual problem.
- Then finally, the ISFRA with newly implemented MAEROS aerosol model will be validated for PGSFR severe accident analyses.

Future Validation Plan I

- **Verification of the aerosol transport model against a simple conceptual problem**
  - **Following the implementation of MAEROS model, calculation step of aerosol removal rate constant (λ) from the MAEROS output ($Q_{l,k}(t)$) should be implanted.**

$$\lambda(t) = \frac{\int_0^\infty vn(v,t)u(v)dv}{h\int_0^\infty vn(v,t)dv} \cong \frac{\sum_l QT_l(t)\cdot u_l}{h\sum_l QT_l(t)}$$

k	*aerosol component*
h	effective height [m]
u_d	deposition velocity [m/s]

  - **$QT_l(t) = \sum_k Q_{l,k}(t)$ = sectional total aerosol mass concentration per unit volume of fluid in section *l* at time *t***
  - **Simple conceptual problem for aerosol transport**
    - **A simple 5-compartment passage is considered, where only the first compartment contains initial non-zero aerosol concentration of $Q_I(t=0)$.**
    - **For the case without any aerosol source or sink, the analytic solution exists as below:**

$$Q_I(t) = \prod_{j=1}^{I-1}\alpha_j \cdot Q_1(t=0)\cdot t^{I-1}\exp\left(-\frac{\alpha_I t}{(I-1)!}\right),$$
$$\text{with } \alpha_j = v_j A_j / \mathrm{Vol}_u$$

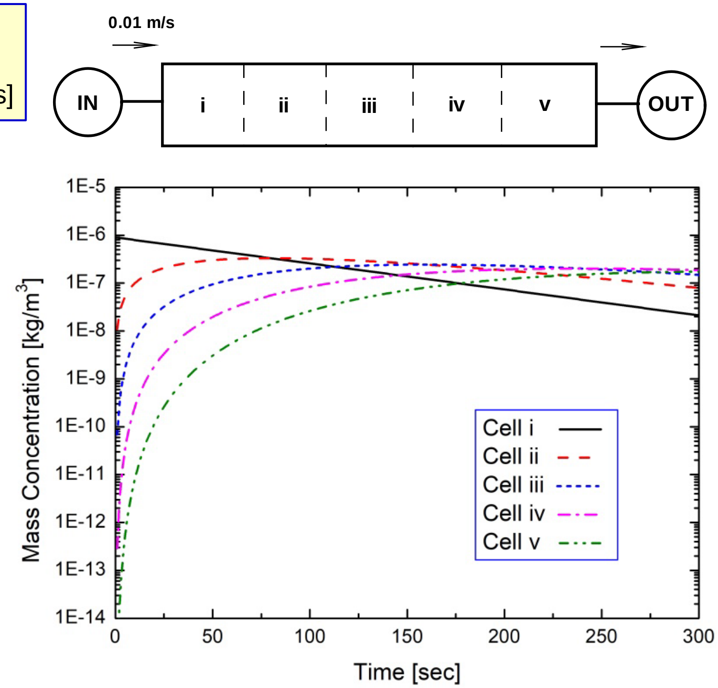


Fig. Schematic diagram and analytic solution of the simple conceptual problem

Future Validation Plan II

- Validation of the ISFRA with newly implemented MAEROS model for PGSFR severe accident analyses
  - Flow Blockage (FB) accident analysis
    - Definition: Near-complete flow blockage of a single fuel assembly
    - Due to the low burnup of the fuel assembly (~0.8 at%), RN inventory of the assembly is generally small. (see Table 2-1)
    - FB – ISFRA calculation assumption (see Table 2-2)
    - Results of the ISFRA with FAI aerosol model:
      - Fig. 2-6: Leakage from the cover gas region to the containment begins at ~35,000s as the cover gas region pressure exceeds that of the containment.
      - Fig. 2-7: Release of RNs (Noble gas, NaI, Te2, Cs, and Sr groups) to the environment begins at ~45,000s.
      - The largest release occurs in the Cs group, with a total release of approximately 5.6E-9 kg.

Table 2-1: FB – RN Mass Released from Fuel

Number	Group	Mass Released from Fuel (kg)
1	Xe, Kr	2.62E-4
2	I_2	Not Modeled
3	NaI	2.13E-4
4	Te_2	3.20E-5
5	Cs, Rb	4.41E-2
6	Na	Not Modeled
7	Ru, Mo, Rh, Tc	1.86E-4
8	Ba	1.73E-4
9	Sr	5.32E-3
10	La, Pr, Nd, Sm, Y, Pm, Zr, Nb, Am, Cm	1.17E-3
11	Ce, Np, Pu, U	3.99E-2

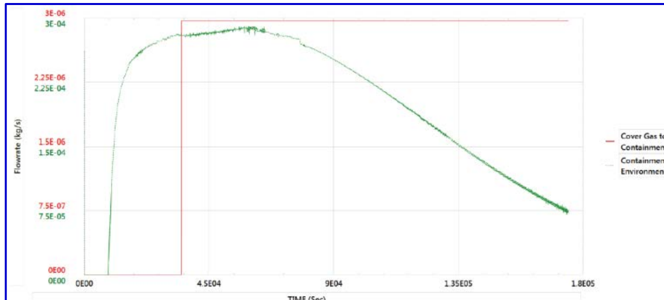


Figure 2-6: FB – Leakage Rates

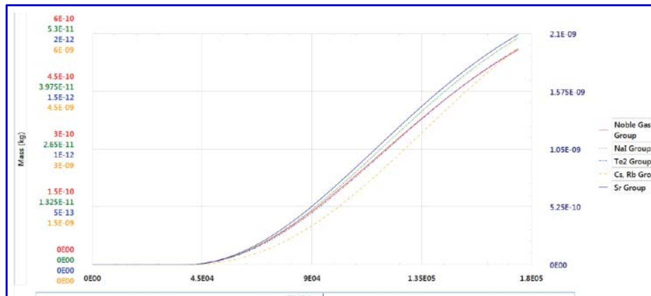


Figure 2-7: FB – RN Mass Released to Environment

Table 2-2: FB – ISFRA-β Simulation Assumptions

Topic	Assumption
Simulation Time	48 hours
Hot/Cold Pool Temperatures	Constant from last SAS4A/SASSYS-1 value (at ~25 seconds)
Heat Transfer	No heat transfer from reactor head to containment
Cover Gas Leakage	Design basis leakage (0.1 %/day – 2.97E-6 kg/s) when cover gas pressure is greater than containment pressure
Containment Leakage	Approximately design basis leakage (0.1 %/day ~2.66E-4 kg/s) when containment pressure is greater than environment pressure

Corresponding Author: Churl Yoon (cyoon@kaeri.re.kr)