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SALUS 사고해석을 위한 FAI 상관식-기반 에어로졸 모델의 특성 연구

Remarks on the FAI Correlation-based Aerosol Model for SALUS Accidemt Analysis

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Introduction

SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR)

- KAERI is developing a design and analysis technique for a pool-type sodium-cooled fast reactor called SALUS(Small, Advanced, Long-cycled and Ultimate Safe SFR), which will generate 100MWe with a long refueling period more than 20 years.
- Despite the extremely low probability of a severe accident expected in SALUS NPPs(Nuclear Power Plants), 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.

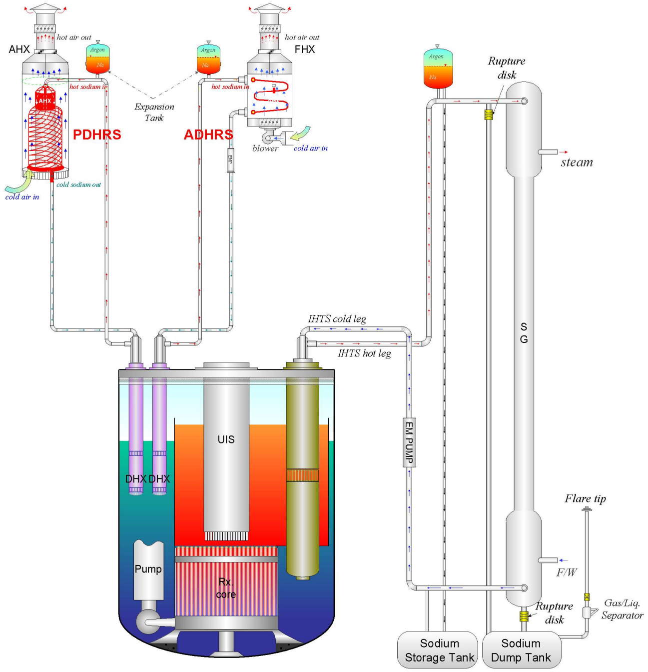


Fig. SALUS schematic diagram

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(Prototype Gen-IV Sodium-cooled Fast Reactor) 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.

Purposes & Contents

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

Purpose of this study: To characterize the transition behavior between the steady-state and the decaying modes, and to compare the CPU times between the correlation-based model and the MAEROS sectional numerical method.

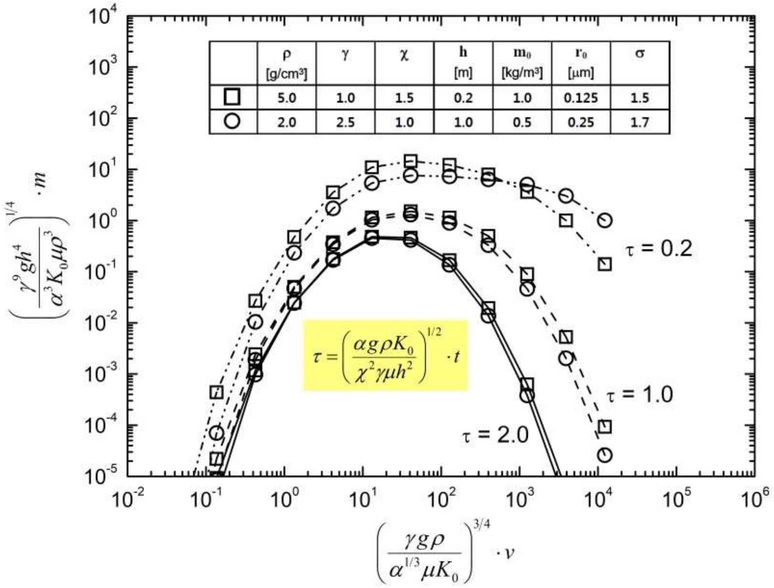
CONTENTS :

- Introduction
- Purposes & Contents
- Correlation-based Aerosol Model
- Transition between Steady-State and Decaying modes
- CPU Time Comparison
- Conclusions

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.**



	ρ [g/cm³]	γ	χ	h [m]	m_0 [kg/m³]	r_0 [μm]	σ
□	5.0	1.0	1.5	0.2	1.0	0.125	1.5
○	2.0	2.5	1.0	1.0	0.5	0.25	1.7

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 ṽ
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⁻³s⁻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:**

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

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

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

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

  - **Functional relationships of $\Lambda(M)$ are obtained based on many exact numerical solutions by running a sectional analysis tool, MAEROS.**

α	density correction factor [-]
χ	particle settling shape factor [-]
ε(v, ṽ)	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

SYMBOL	h [m]	$\dot{m}_p$ [kg/m^3/s]	ρ [kg/m^3]	γ	χ	σ	r$_0$ [μm]
□	3.1017	9.1549E-7	2450	2.25	1.5	2.0	0.125
△	10.0	8.2160E-6	4000	2.5	1.0	1.55	0.136
○	3.1017	5.9038E-6	2130	2.25	1.5	2.0	0.25
◇	5.0	2.3122E-4	5000	1.0	1.0	1.55	0.27
▽	3.1017	1.1737E-4	3670	2.25	1.5	2.0	0.5
X	2.0	2.9343E-5	2000	1.0	1.0	2.5	1.0
⬡	1.0	1.1737E-4	1000	1.0	1.0	1.5	0.5

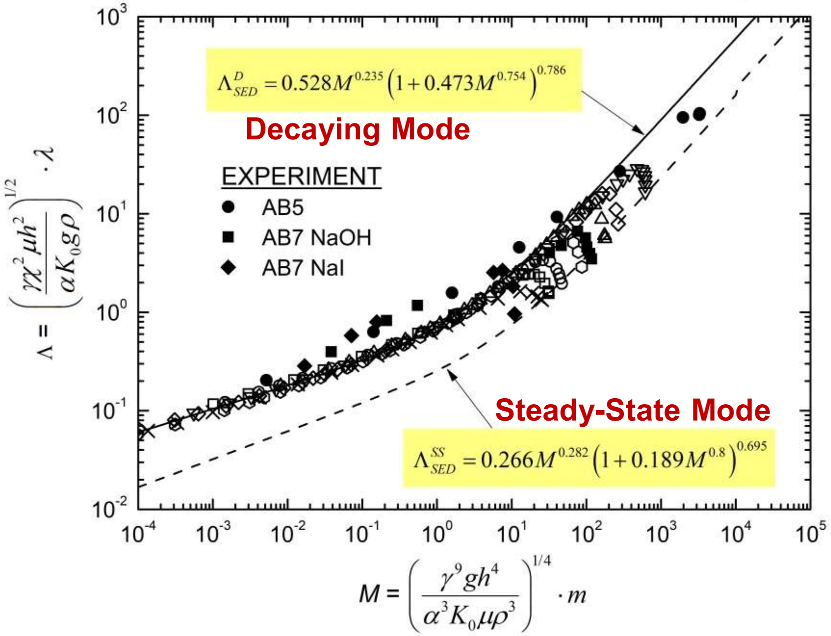


Fig. II: Dimensionless aerosol removal rate constant for sedimentation as a function of dimensionless suspended mass concentration.

Transition btwn S.S. and Decaying (1/2)

Aerosol Removal Rate Constant, λ_{SED}

- Execution procedure to calculate suspended aerosol masses
  1) Dimensionless suspended aerosol mass M is calculated from the suspended aerosol mass m by using the equations of Table 1,
  2) The dimensionless decay constant Λ is calculated depending on the situation of steady-state or decaying aerosol,
  3) Dimensionless decay constant Λ is transformed into an aerosol removal rate constant λ by using the equations of Table 1, and
  4) The suspended aerosol mass m is finally calculated by

$$\frac{dm(t)}{dt} = -\lambda_{SED} m(t) + \dot{m}_p$$

- In the ABCOVE AB5 simulation,
  - Λ_{SED} follows Λ_{SED}^{SS} until 872s, with aerosol sources
  - Λ_{SED} jumps from Λ_{SED}^{SS} to Λ_{SED}^{D} immediately at 872s
  - then Λ_{SED} follows Λ_{SED}^{D} after 872s, without any aerosol source

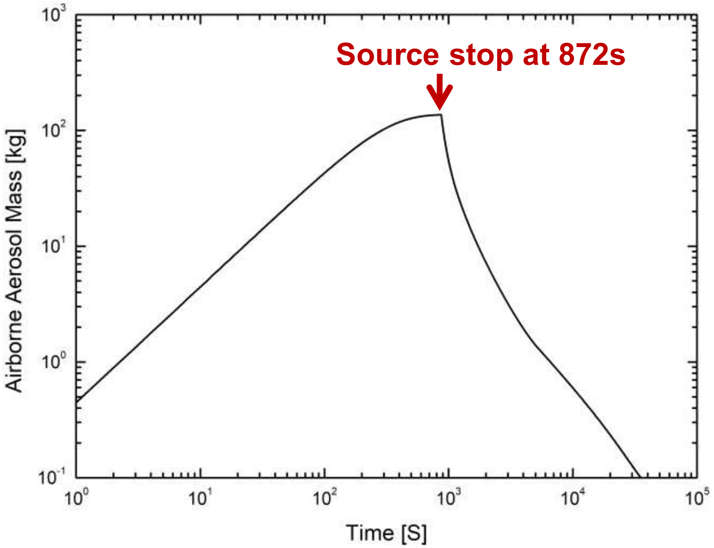


Fig. III: AB5 airborne aerosol mass

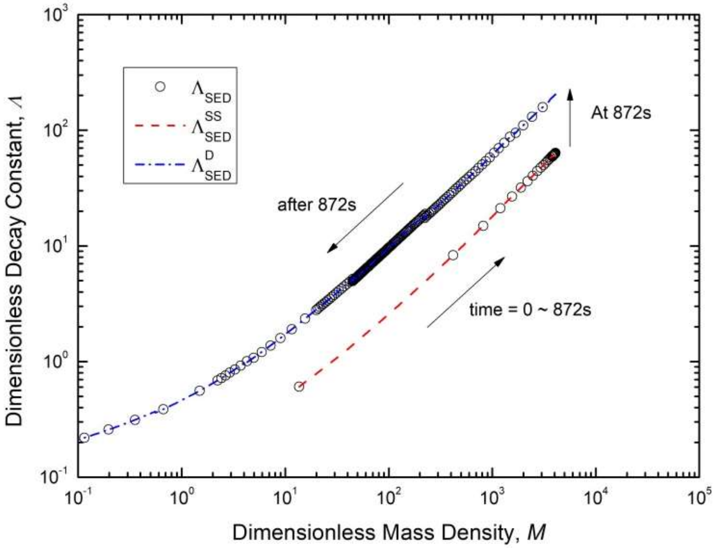


Fig. IV: Aerosol removal rate constant Λ_{SED} for AB5 simulation

Transition btwn S.S. and Decaying (2/2)

- ❑ **How to control λ_{SED} (or Λ_{SED}) in the transition phases?**
  - ❍ **Determination logic of aerosol removal constant λ_{SED} :**

I. Without aerosol source;

$$\boxed{\lambda_{SED} = \lambda_{SED}^{D}}$$

II. With aerosol sources;

II-1) If $m(t)/M_{SS} < 1.0$;

$$\boxed{\lambda_{SED} = \lambda_{SED}^{SS}}$$

II-2) If $m(t)/M_{SS} > 1.0$;

$$U \equiv \frac{m(t) - M_{SS}}{(f_{SS} - 1) M_{SS}}$$

Steady-state airborne aerosol mass

$$M_{SS} = \dot{m}_p / \lambda_{SED}$$

Interpolation factor *FSEDDK*

$$FSEDDK = 4 * U^3 - 6 * U^2 + 3 * U$$

Then,

$$\boxed{\lambda_{SED} = FSEDDK * \lambda_{SED}^{D} + (1 - FSEDDK) * \lambda_{SED}^{SS}}$$

Multiplier to the expected steady-state mass, above which the new source will not affect the removal rate. (> 1.0)

$f_{SS} \equiv 8.0$ in ISFRA code

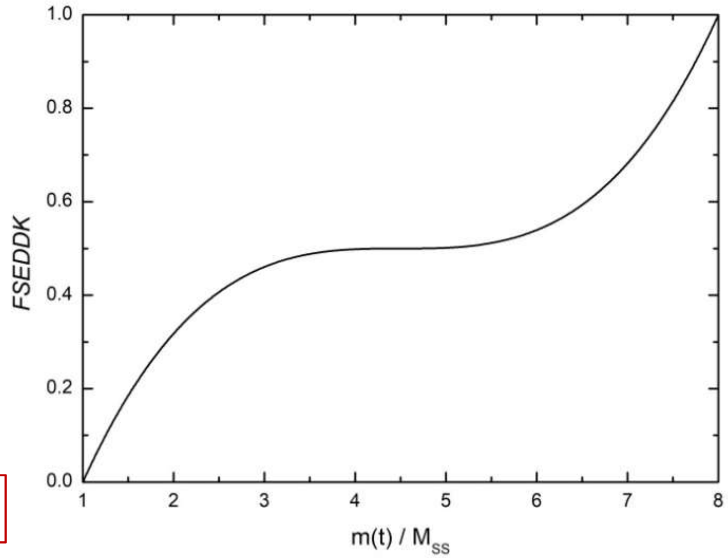


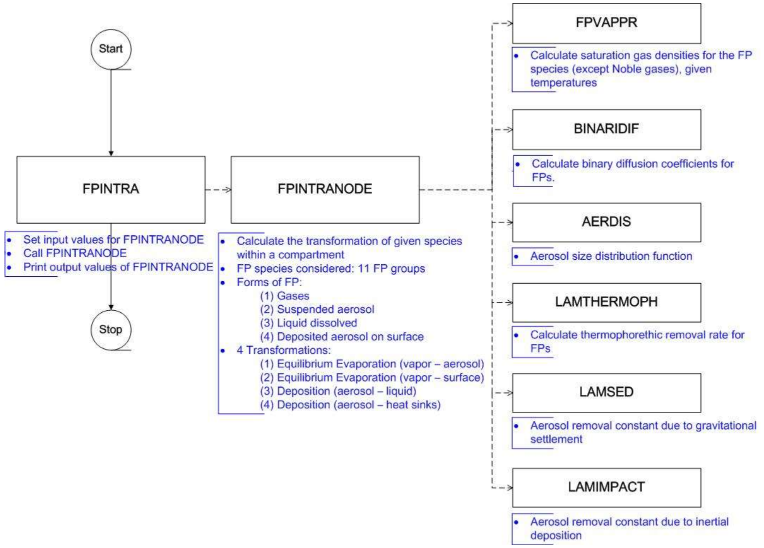
Fig. V: *FSEDDK* as a function of the ratio of suspended aerosol mass *m*(t) to the steady-state airborne aerosol mass M_{SS} (with f_{SS} = 8.0)

CPU Time Comparison (1/2)

❑ Preparation of CPU Time Comparison

- FAI correlation-based aerosol model
  - Stand-alone aerosol module of ISFRA code
    - Subroutines for aerosol FP analysis were extracted from the ISFRA code, and
    - A driver(FPINTRA) was created to impose the appropriate boundary condition of the experiment

- MAEROS sectional method
  - MAEROS model was developed by Gelbard et al. in early '80, and adapted in CONTAIN and MELCOR codes.
  - Numerical solution - the general aerosol kinetic equation is transformed into the sectionalized governing equation, assuming that coagulation and condensation occurs in series and that any two mechanisms cannot occur simultaneously.
  - MAEROS code was obtained from the IAEA code bank system.



Start

FPINTRA
- Set input values for FPINTRANODE
- Call FPINTRANODE
- Print output values of FPINTRANODE

Stop

FPINTRANODE
- Calculate the transformation of given species within a compartment
- FP species considered: 11 FP groups
- Forms of FP:
  - (1) Gases
  - (2) Suspended aerosol
  - (3) Liquid dissolved
  - (4) Deposited aerosol on surface
- 4 Transformations:
  - (1) Equilibrium Evaporation (vapor – aerosol)
  - (2) Equilibrium Evaporation (vapor – surface)
  - (3) Deposition (aerosol – liquid)
  - (4) Deposition (aerosol – heat sinks)

FPVAPPR
- Calculate saturation gas densities for the FP species (except Noble gases), given temperatures

BINARIDIF
- Calculate binary diffusion coefficients for FPs.

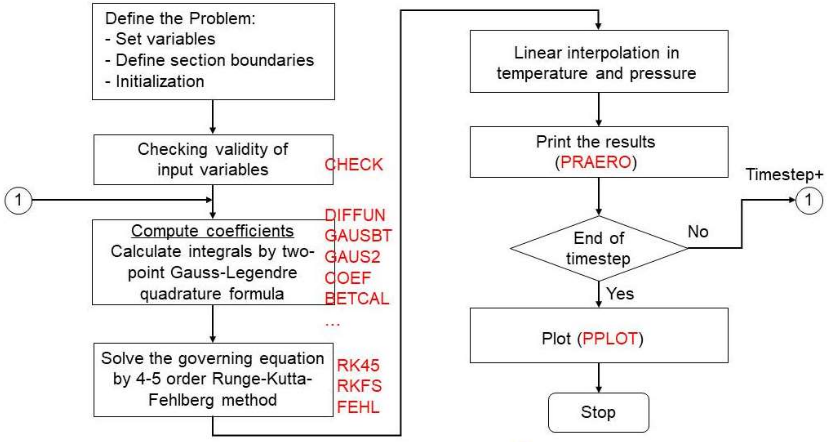
AERDIS
- Aerosol size distribution function

LAMTHERMOPH
- Calculate thermophorethic removal rate for FPs

LAMSED
- Aerosol removal constant due to gravitational settlement

LAMIMPACT
- Aerosol removal constant due to inertial deposition

Fig. VI: Code structure of the stand-alone aerosol module of ISFRA



Define the Problem:
- Set variables
- Define section boundaries
- Initialization

Checking validity of input variables — CHECK

Compute coefficients
Calculate integrals by two-point Gauss-Legendre quadrature formula — DIFFUN, GAUSBT, GAUS2, COEF, BETCAL, ...

Solve the governing equation by 4-5 order Runge-Kutta-Fehlberg method — RK45, RKFS, FEHL

Linear interpolation in temperature and pressure

Print the results (PRAERO)

End of timestep — No: Timestep+ ① — Yes

Plot (PPLOT)

Stop

Fig. VII: MAEROS calculation flow chart

CPU Time Comparison (2/2)

❑ CPU Time Comparison between AB5 Simulations by FAI & MAEROS methods

- In the ABCOVE AB5 test, performed in 1982, single-species aerosol was generated by spraying sodium at high rate for initial 872s.
- Code modification for CPU time comparison
  - Using "CPU_TIME(x)" FORTRAN subroutine - simple & primary, but robust method to measure CPU times
  - Basic logics only - unnecessary procedures were removed
- As a result, the FAI correlation-based aerosol model gives output about 80 times faster than the sectional method in the AB5 simulation
  - Both runs performed on the same PC with the 64-bit WINDOWS operating system on an Intel I7-7700 CPU
  - Simulation times = 300,000 s (for both runs)

	Stand-alone aerosol module of ISFRA code	MAEROS sectional model
Simulation condition	time_end = 3.0E+05 sec	28 particle size sections time_end = 3.0E+05 sec
CPU time	0.6250E-01 sec	0.5000E+01 sec

Table 2: Modification for CPU time measurements (in both ISFRA & MAEROS codes)

```
PROGRAM MAIN
----------------
----------------
call CPU_TIME(time1)
****************
*                *
* Calculation    *
* Procedure      *
*                *
****************
call CPU_TIME(time2)
write(*,*) time2-time1
----------------
STOP
END
```

Conclusions

❑ CONCLUSIONS

- Study on the Transition Behavior of FAI Correlation-based Aerosol Model between the Steady-state and Decaying Modes
  - Aerosol removal rate constants λ_{SED} as a function of time were extracted, and the transition behavior from steady-state to decaying mode was tracked.
  - This transition behavior was found to be controlled by the interpolation factor *FSEDDK*, which is the internal variable of ISFRA code.

- CPU Time Comparison between the AB5 Simulations by FAI Correlation-based Aerosol Model and by MAEROS Sectional Numerical Method
  - FAI correlation-based aerosol model gave output about 80 times faster than the MAEROS sectional method for the single-component aerosol analysis of the AB5 experiment.

- This is the final stage of the research series on FAI correlation-based aerosol model in the ISFRA code. The research results were summarized in the following journal paper.

  Churl Yoon, Sung Il Kim, Sung Jin Lee, Seok Hun Kang, and Chan Y. Paik, "Validation of the correlation-based aerosol model in the ISFRA sodium-cooled fast reactor safety analysis code," *Nuclear Engineering and Technology*, Vol. 53, pp. 3966-3978, 2021.

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