

Using Calibrated Sodium Data for Preliminary Validation of the SRT Code for Advanced Reactors

prepared by

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ABSTRACT

Various types of non-light water reactors are currently engaged in the U.S. licensing process. Because of inherent differences compared with well-established large light water reactors, appropriate assessment tools are needed. Specifically, source term analysis, which determines environmental dose impacts from potential accident scenarios, is a crucial part of design and licensing. The U.S. Nuclear Regulatory Commission has emphasized the importance of mechanistic source term analysis for advanced reactor deployments. To align with these needs, Argonne National Laboratory has developed the Simplified Radionuclide Transport (SRT) source term analysis code for metal fuel Sodium-cooled Fast Reactors (SFRs) and microreactors. SRT conducts time-dependent radionuclide transport and retention in SFRs for core and ex-core radionuclide source accident sequences. The main objective of SRT is to provide rapid sensitivity and uncertainty analyses, incorporating parametric uncertainties and summarizing probabilistic results. As part of the code validation process, a study focused on the bubble scrubbing module was performed using an experiment recently carried out by the University of Wisconsin-Madison. Based on the analysis, the modeling approach in SRT provides accurate results for small and large aerosols, while slight underprediction of radionuclide aerosol removal are observed for medium sized aerosols. However, the deviation is minor, considering the highly uncertain phenomenon and range of results, and is in the conservative direction. In addition, uncertainty information derived from the experiments is further implemented, reflecting the actual span of parameters, which leads to enhanced agreement with code predictions. The results demonstrate that SRT provides reasonable predictions for the bubble scrubbing process in sodium pool.

KEYWORDS

SRT; Source term; SFR; Bubble scrubbing; Sodium

1. INTRODUCTION

With the increasing global interest in deploying advanced reactors, the licensing process is evolving to reflect the specific characteristics of new reactor concepts. Among the safety evaluations, the mechanistic behavior of radionuclides is essential, as unique trends and mechanisms are expected in non-light water reactor types. To address the need for source term analysis in metal fuel Sodium-cooled Fast Reactors (SFRs) and microreactors, Argonne National Laboratory (Argonne) developed the Simplified Radionuclide Transport (SRT) code, a mechanistic source term analysis code. Argonne has also extensively evaluated the knowledge of source term phenomena in SFRs, to support licensing [1-3]. Ref [3] identified the bubble scrubbing process in the sodium pool as highly uncertain and under-investigated phenomenon, with insufficient supportive data directly applicable to sodium environments. Therefore, modeling approaches for the pool scrubbing phenomenon with corresponding sodium data were limited. The Power reactor and Nuclear fuel development Corporation (PNC) in Japan previously tracked iodine gas removal rates in sodium using the SABER test facility, with following model development and analyses [4, 5]. Argonne has recently analyzed the SABER test data, introducing new models and concepts [6, 7]. However, data on *aerosol* removal rate within noble gas bubbles in a sodium environment remained limited. To address this, the University of Wisconsin-Madison (UW) conducted relevant tests through the U.S. Department of Energy Nuclear Energy University Program (NEUP). These tests covered both water and sodium conditions, and the results have been assessed by both UW and Argonne [8-10]. In this study, the sodium data is assessed, as part of ongoing validation of the SRT, focusing on the SRT bubble transport model and incorporating parametric uncertainties. Through the uncertainty analyses, possible prediction ranges are derived, which provides insights and demonstrates SRT's capabilities. Among various parametric values, this study focuses on the bubble size effect, with additional details provided in the following sections.

1.1. Mechanistic Source Term Analysis Code (SRT) at Argonne

SRT was developed to support the design and licensing of metal fuel SFRs and microreactors. The code tracks time-dependent radionuclide transport and retention, from in-pin behavior to offsite dose, further assessing parametric uncertainties and deriving key parameters. Radionuclide distribution within the pin is first estimated, and the inventory released after cladding failure is simulated. Radionuclides released from the pin boundary are continuously tracked in the subsequent sodium pool, cover gas, containment (or additional reactor building compartments), and environment. Offsite dose values are also calculated based on inventory trends. SRT primarily adopts a data-driven approach based on historical database, supplemented with mechanistic models. SRT does not model the transient scenario itself, but utilizes the output of systems analysis codes, such as SAS4A/SASSYS-1 [11], or input conditions postulated by the user.

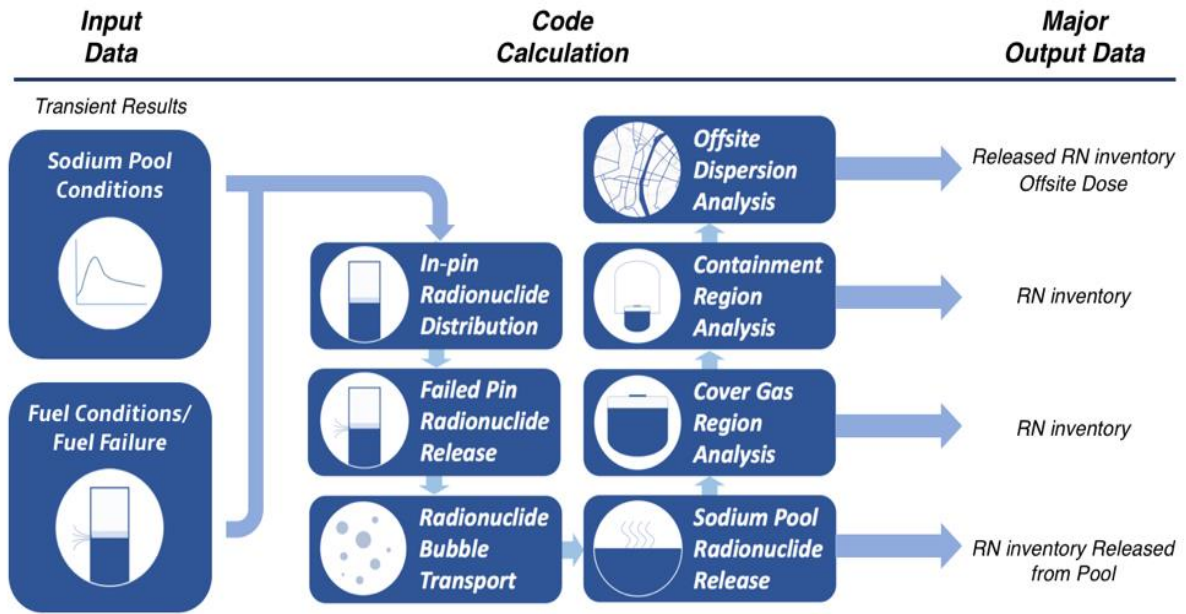


Figure 1. SRT Flow in SFR Application.

1.2. Sodium Pool Scrubbing Data by UW

After pin failure, radionuclides are released from the fuel pin and dispersed within the sodium pool and rising noble gas bubbles. While the bubbles rise through the pool, radionuclide aerosols trapped within the bubble can be effectively removed at the bubble interface. To secure the relevant data in sodium, UW thoroughly assessed the pool scrubbing phenomenon in sodium with various parametric effects (Figure 2 and Table 1). The decontamination factor (DF), which describes the degree of aerosol retention in the sodium pool (eq 1), was determined from the amounts of surrogate aerosols injected into and escaped from the sodium system.

$$DF = \frac{\text{Amount of aerosols injected}}{\text{Amount of aerosols escaped}} \quad (1)$$

The parametric range was selected based on preceding SRT simulations, identifying the lowest performance region, which provided conservative results. Due to the opaqueness of the sodium pool, an X-ray machine was used to determine bubble geometry and rise velocity. A specific nozzle type was developed to generate large, single bubbles, all observed to be spherical caps. In this study, the bubble size effect on DF values is focused on, considering four bubble sizes and uncertainties.

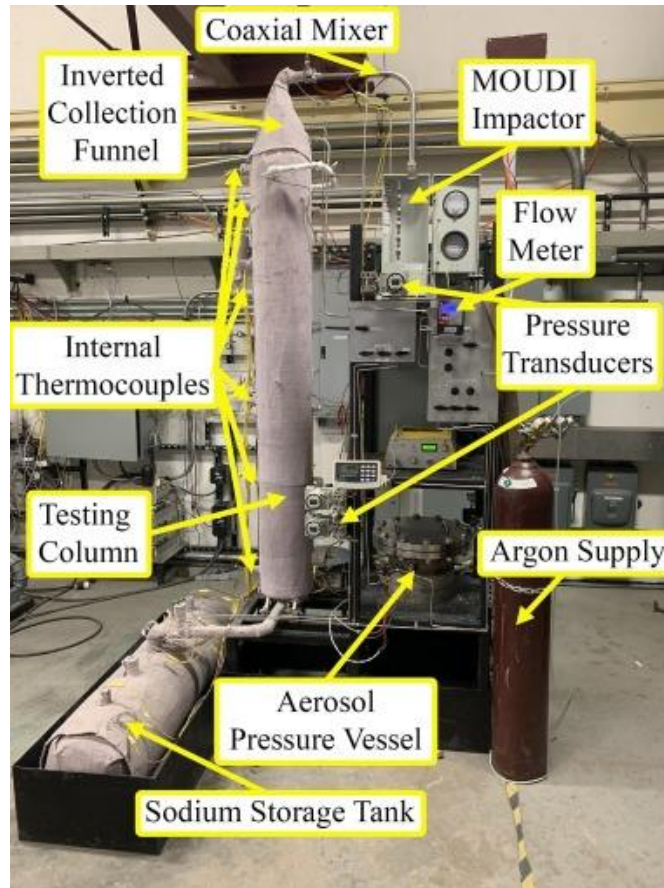


Figure 2. Sodium Test Facility by UW.

Table 1. Parametric conditions in UW sodium tests¹

Parameter	Unit	Value
Bubble size	cm	2.36 / 2.86 / 3.63 / 4.11
Aerosol size	μm	0.018 – 18
Aerosol density	g/cm^3	2.7 (Al) / 8.9 (Ni) / 19.3 (W)
Aerosol concentration	g/m^3	15.3 / 5.4
Pool depth	m	1.829 / 0.914
Pool temperature	$^{\circ}\text{C}$	150 / 200 / 250 / 300

¹ Summary on the bubble size effect is addressed in this paper, with other parametric effects planned to be separately assessed later. Parameter variations considered in this analysis are emphasized in bold.

1.3. Pool Scrubbing Model in SRT

SRT bubble transport model assumes equilibrium states for the bubble scrubbing phenomenon, ignoring transient conditions like temperature and concentration variations during rise. Also, SRT adopts the Powers and Sprung approach [12], where Brownian diffusion, inertial impaction, and gravitational sedimentation are considered. Relevant equations are summarized in eqs 2-5. An eccentricity (bubble axis ratio) concept was used in the equations, describing bubble shape distortion from the spherical shape. In SRT, the Tadaki number (Ta) criterion is adopted for deriving eccentricity (eq 6). Also, multiple options on the bubble rise velocity are provided in SRT, including a user-defined function for specific conditions, providing flexibility to users. As the velocity sensitively influences decontamination performance, evaluations with data measured in real sodium conditions are crucial. On this basis, the correlation options are further evaluated in this study, using the UW data measured in the sodium environment.

$$DF = e^{(\alpha_D + \alpha_I + \alpha_G)H_{pool}} \quad (2)$$

$$\alpha_D = \sqrt{\frac{288\theta}{\pi U_B D_B^3} \left[\frac{(E^2 - 1)F}{1 + \sqrt{4 + 2(E^2 - 1)}} \right]} \quad (3)$$

$$\alpha_I = \frac{6U_B \tau G}{D_B^2} \quad (4)$$

$$\alpha_G = \frac{1.5g\tau E^{2/3}}{D_B U_B} \quad (5)$$

$$E = 1$$

$$Ta \leq 1$$

$$E = 1/[0.81 + 0.206 \times \tanh\{2 \times (0.8 - \log_{10} Ta)\}]^3$$

$$1 < Ta \leq 39.8 \quad (6)$$

$$E = 1/0.62^3$$

$$Ta > 39.8$$

$$Ta = ReMo^{0.23} \quad (7)$$

2. RESULTS AND DISCUSSION

This section utilizes sodium data from the UW bubble transport tests to assess (or validate) the approaches implemented in SRT. First, the bubble rise velocity in sodium is addressed, selecting the best correlation option in SRT for this study's range of interest. Also, DF values measured in sodium are compared with the SRT-predicted results, including the uncertainty effect. The uncertainty analysis selects 10,000 samples with two standard deviations, using a standard Gaussian distribution. In addition, discretized uncertainty values are interpolated and extrapolated to produce continuity.

2.1. Bubble Rise Velocity in Sodium

Rise velocity options in SRT are assessed over the data measured in sodium by UW (Davies and Taylor [13], Peebles and Garber [14], Wallis [15], and Wallis [16]). Also, another correlation (Lehrer [17]) developed for intermediate and high Reynolds numbers and adopted in the recent study by UW is added for an extensive assessment. According to Figure 3, both Wallis regime maps provide reasonable predictions, with the Lehrer correlation giving the best prediction for the sodium environment within the range considered. The Davies and Taylor correlation shows increasing deviations, especially at small bubble sizes. The Peebles and Garber regime map continuously underestimates for all bubble scales considered.

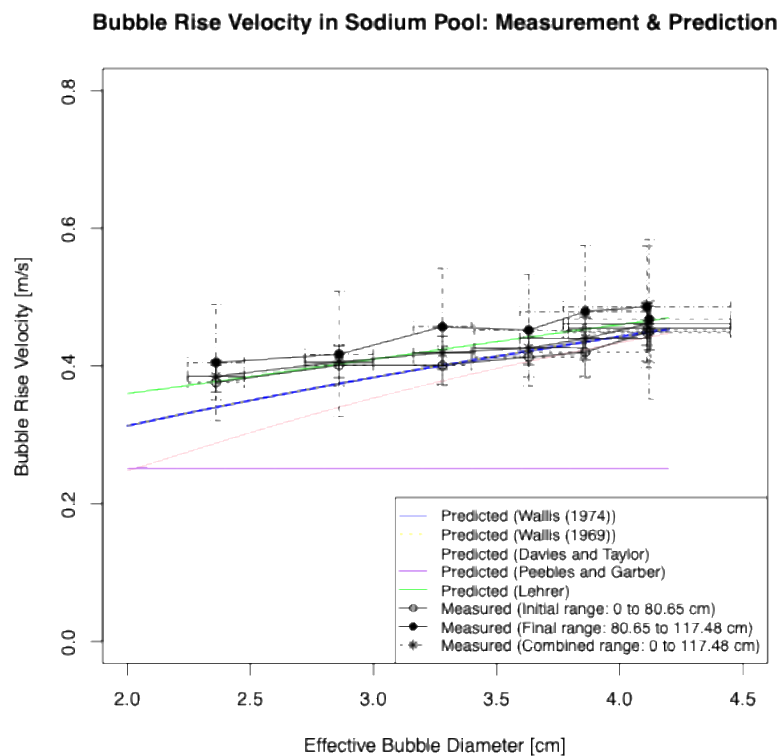


Figure 3. Prediction of Bubble Rise Velocity over Measurement Data in Sodium.

2.2. DF with Bubble Size Effect

Since bubble rise velocity dominantly affects bubble scrubbing efficiency by determining bubble residence time and geometry, previous correlations in SRT and an additional correlation are further assessed. The rising velocity correlations, which tracked the overall trends in Figure 3, are implemented for the evaluation. Figure 4 to Figure 6 show that the Wallis approach and the Davies and Taylor correlation provide reasonable results within the range of interest (minimum DF range), even though some conservative predictions occur at the lowest performance region (where aerosolized radionuclides escape mostly from the sodium pool). Still, the Wallis correlation provides a clearer bubble size effect and better predictions at large aerosols, along with better predictions on bubble dynamics observed in the previous section (Figure 3). The Lehrer correlation, on the other hand, gives overestimations at large aerosols due to interrelated equations for the DF.

Both predicted and measured results show U-shaped trends with increasing aerosol sizes, generating the lowest performance region, since the main mechanism shifts from Brownian diffusion (for small particles) to inertial impaction and gravitational sedimentation (for large particles). In addition, the bubble size effect is observed over the range, where DF increases with decreasing bubble size. Reduced bubble size generates an increased surface area to volume ratio, providing a higher reaction rate at the interface during rise. Also, a small single bubble tends to show slower velocity, securing elongated time of reaction in the sodium pool. At the lowest performance region and for very small aerosols, SRT underestimates the data; however, it's difficult to precisely measure this range due to limitations of the measurement technique. Specifically, deviation at the lowest performance region is relatively minor, considering the log-scale plot and highly uncertain phenomenon, which generally ranges over several orders of magnitude. The SRT model errors in the conservative direction, underestimated the DF in this region. In comparison, the SRT model tends to be well aligned with the test data for large aerosols.

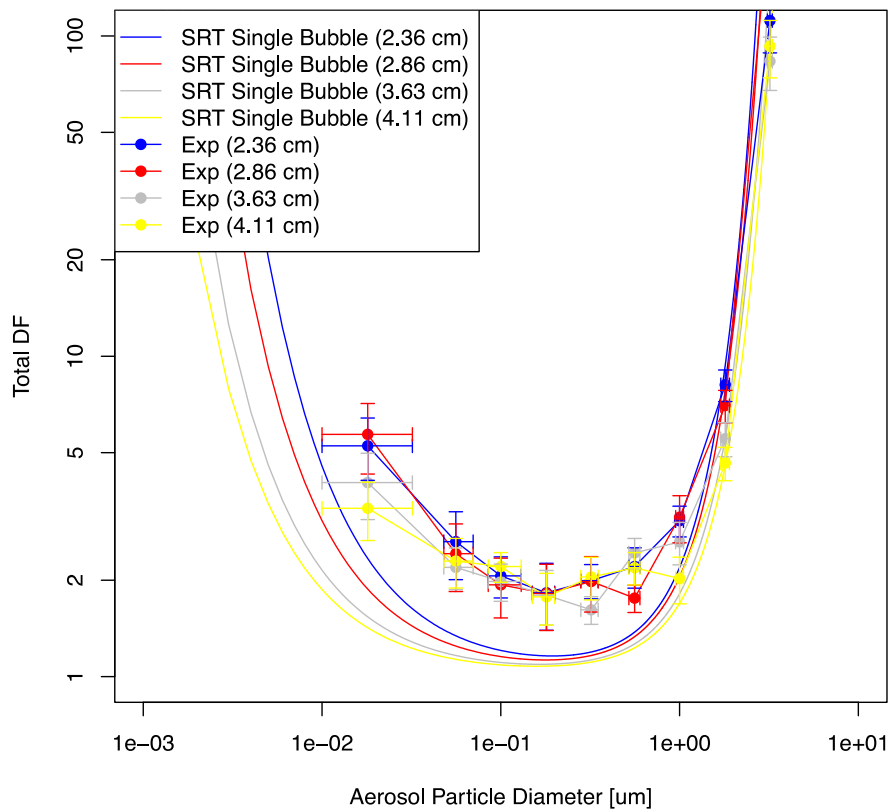


Figure 4. Predictability of DF with Wallis regime map.

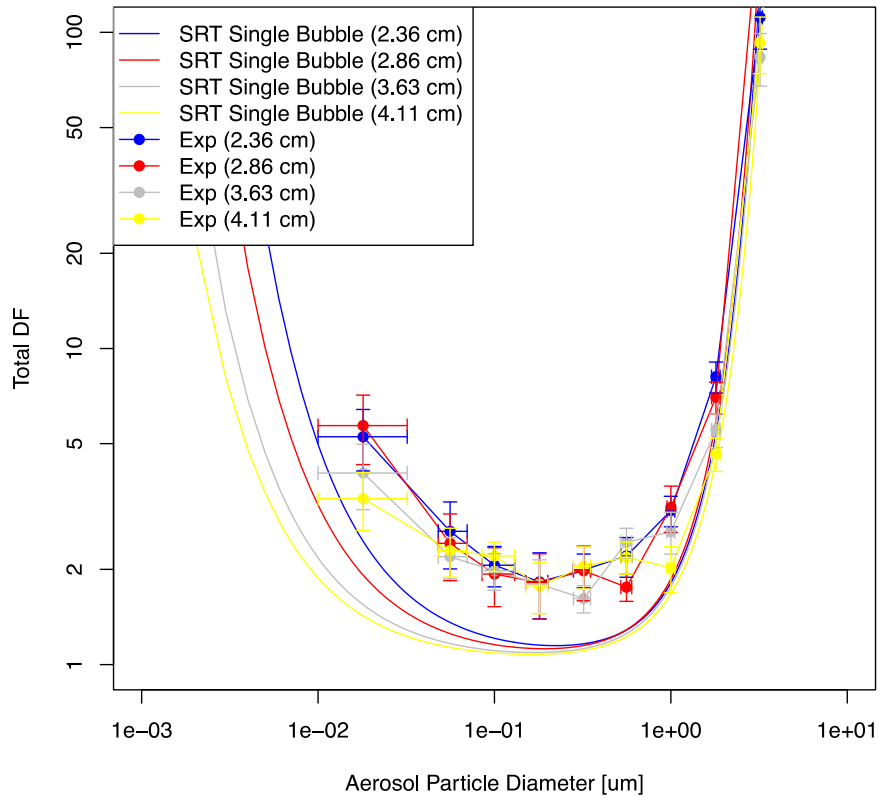


Figure 5. Predictability of DF with Davies and Taylor Correlation.

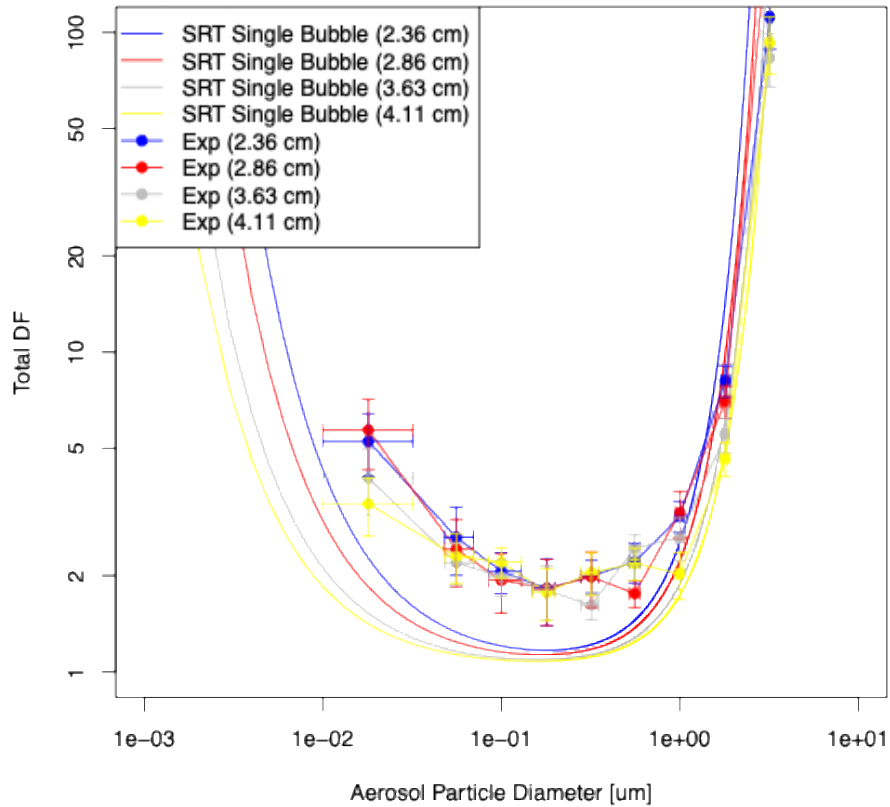


Figure 6. Predictability of DF with Lehrer Correlation.

Reflecting highly uncertain and sensitive characteristics of the pool scrubbing phenomenon, an uncertainty analysis has been conducted, implementing uncertainties for each bubble size in the test matrix. The input parameter uncertainty ranges are based on the measurements performed by UW. For the purpose, 10,000 samples are selected from normal distributions with two standard deviation bands, as an ideal Monte Carlo sampling with infinite boundaries leads to non-physical results for the phenomenon. The tails of the distribution add unrealistic values, such that some cut-off boundaries are needed to derive meaningful results. As a representative plot, mean values of the DF distributions are calculated for each case in Figure 7. According to the plot, the SRT model provides enhanced predictions, especially at the range with high uncertainty and sensitivity (small aerosols in this study), still keeping good predictability for large aerosols. The predicted DF radically increases near the last data point since the parametric uncertainty band includes very large DF values from very small aerosols, leading to well-predicted results. The impact of including the uncertainty is observed in all bubble scales considered in this study, which emphasizes the importance of uncertainty assessments, especially for highly uncertain conditions.

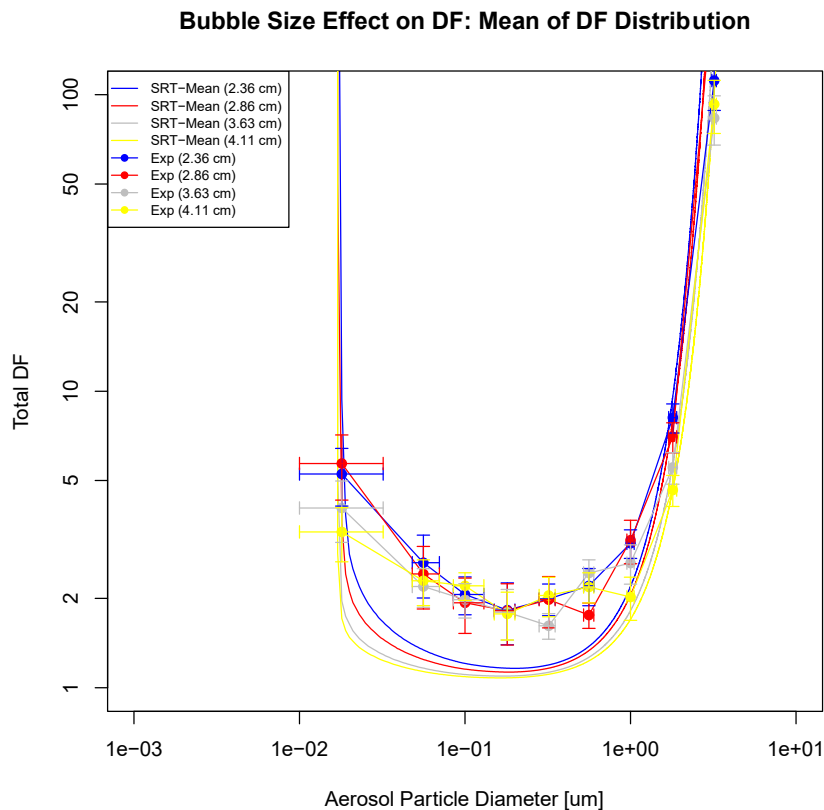


Figure 7. Uncertainty Analysis over Bubble Size Effect Data

3. CONCLUSIONS

The SRT code, developed at Argonne, is currently utilized by industry to assess source term behavior in metal fuel SFRs and microreactors. As part of the active validation process of the SRT code, the recent sodium data on pool scrubbing phenomenon has been considered and thoroughly assessed.

Bubble size effect is considered in the current analysis, demonstrating realistic predictions for bubble dynamics and decontamination performance, based on data acquired under sodium environments. Specifically, the pool scrubbing module in SRT provides reasonable predictions at the lowest DF range, the most significant region with most of radioactive aerosols escaping from the system. Also, the model tracks the bubble size effect, where higher DF values are observed for smaller bubble sizes, mainly due to enlarged surface area and elongated residence period in sodium. When the uncertainties of each condition are implemented, the predictions by the SRT model provide further enhanced results, improving the predictions at the highly uncertain ranges in this study. Based on the validation results, this study emphasizes the importance of uncertainty analysis for more realistic predictions, especially under uncertain and sensitive conditions. This conclusion provides a basis for future probabilistic analysis. Furthermore, the study demonstrates the prediction capability of the current SRT model in sodium environments. Other parametric effects will be included in the following documents, assessing the whole test range UW carried out.

NOMENCLATURE

α_D = Removal coefficient for Brownian diffusion

α_I = Removal coefficient for Inertial impaction

α_G = Removal coefficient for Gravitational sedimentation

$$\theta = \frac{k_B T_B C_n}{3\pi\mu_B d_a}$$

C_n = Cunningham factor $(1 + \frac{2\lambda}{d_a} [1.257 + 0.4e^{-0.55\frac{d_a}{\lambda}}])$

$$\lambda = \frac{k_B T_B}{\sqrt{2}\pi d_{B,mol}^2 P_B}$$

$$F = \left[\frac{1.76E^2}{E^2-1} - \sqrt{2} \right]^{1/2} \left[\frac{E^2 \tan^{-1} \sqrt{E^2-1}}{\sqrt{E^2-1}} - 1 \right]^{-1/2}$$

$$\tau = \frac{\rho_a d_a^2 C_n}{18\mu_B}$$

$$G = \frac{E^{4/3} [(E^2-1)^2 + (E^2-1)^{3/2} (E^2-2) \tan^{-1} \sqrt{E^2-1}]}{[\sqrt{E^2-1} - E^2 \tan^{-1} \sqrt{E^2-1}]^2}$$

U_B = Bubble rise velocity

D_B = Effective bubble diameter

T_B = Gas temperature

P_B = Gas pressure

μ_B = Gas dynamic viscosity

μ_l = Liquid dynamic viscosity

$d_{B,mol}$ = Effective diameter of gas molecules

d_a = Aerosol diameter

ρ_a = Aerosol density

ρ_l = Liquid density

k_B = Boltzmann constant

E = Eccentricity

g = Gravitational acceleration

σ = Surface tension

DF = Decontamination factor

H_{pool} = Pool depth

Re = Reynolds number $\left(\frac{\rho_l U_B D_B}{\mu_l}\right)$

Mo = Morton number $\left(\frac{g \mu_l^4}{\rho_l \sigma^3}\right)$

α_D = Removal coefficient for Brownian diffusion

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