DEVELOPMENT OF IN-VESSEL SOURCE TERM ANALYSIS CODE, TRACER

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Abstract

Analyses of radionuclide transport in fuel failure accidents (generally referred to source terms) are considered to be important especially in the severe accident evaluation. The TRACER code has been developed to realistically predict the time dependent behavior of FPs and aerosols within the primary cooling system for wide range of fuel failure events. This paper presents the model description, results of validation study, the recent model advancement status of the code, and results of check out calculations under reactor conditions.

1. INTRODUCTION

In an event of fuel failure accident including core disruptive accident in FBRs, fission products (FPs) released from the failed fuel will be transported into a cover gas space through a coolant liquid sodium in a rector vessel. In such event, behavior of FPs is strongly affected by sodium related phenomena in FBRs. For example, the FPs transport in a sodium pool is governed by gas bubble behavior and its interaction with sodium. The species and quantities of radionuclides transported into the cover gas; so-called in-vessel source term, are dominated by many physical and chemical phenomena related to the release and transport behavior in a primary cooling system as illustrated in Fig. 1 schematically. From the viewpoint of FBR safety, mechanistic analysis of radionuclide transport in the primary cooling system during accidents is required for evaluating the source term realistically. To meet this requirement, in-vessel source term code TRACER (Transport phenomena of Radionuclide for Accident Consequence Evaluation of Reactor) has been developed.

2. ANALYTICAL FUNCTIONS AND REQUIREMENTS FOR CODE IMPROVEMENT

2.1. Analytical functions of TRACER

The TRACER code is intended to treat mechanistically the FP release and transport behavior in consideration of a variety of the physical and chemical characteristics of FPs. The behaviors modeled in the code are; a) release from the failed fuel into sodium, b) transport into cover gas through the sodium in the form of gas bubbles and aerosols in connection with the bubble dynamic behavior and the sodium flow, and c) transport within the cover gas space. Figure 2 summarizes the analytical models used in the code.

TRACER is intended to analyze the transport behavior through coolant liquid sodium in detail because this behavior plays an important role to attenuate the in-vessel source term due to the high retention capability for volatile FPs of the sodium. Especially FP gas bubble behavior is very important because less retention effects can be expected if volatile FPs are carried by gas bubbles.

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Figure 3 shows the schematic illustration of analytical model for FP gas bubble behavior considered in the code. In addition to the transport due to the bubble behavior, evaporation into the cover gas and deposition onto structure wall are also considered as other important transport and attenuation mechanisms. The source term into the cover gas is obtained by summing up the sources due to the bubble behavior and evaporation.

2.2. Validation study using the TRACER code

The code validation was performed by comparing the TRACER predictions with two experimental results for the in-vessel source term that were obtained from the SABER experiment by PNC [1] and the MOL7C/6 in-pile local blockage experiment by KfK and SCK/CEN [2]. Figures 4 and 5 show the experimental geometries, the calculational models, and the comparison of results for SABER and MOL7C/6, respectively.

In the former case, the average mass flux of iodine transferred from xenon-iodine mixed gas bubble rising through a sodium pool was compared between the TRACER predictions and the SABER experimental results as a function of the initial iodine concentration in the bubbles. As shown in Fig. 4, the predictions show good agreement with the experimental results.

In the latter case, as shown in Fig. 5, radionuclide activity concentration changes in sodium near the interface between the sodium and cover gas were calculated by using the integrated models of the code. Although the increase of activity concentration in the early phase could not be reproduced by the calculation, the rest of code prediction explains the trend of measured data well including the oscillation of concentration change after 30 s. The oscillation was attributed to the circulation behavior of FP gas bubbles with radionuclides in the experimental loop.

2.3. Requirements for the calculation under reactor condition

From above calculational results, it has been confirmed that the TRACER code would be capable of simulating appropriately the radionuclide transport behavior in the small scaled experimental condition. Nevertheless, through the results for wide range of parameter sensitivity analyses for FP transport into the cover gas under the large scaled fuel failure conditions including core disruptive accident, additional functions required for the TRACER code were clarified.

Items specified for the code advancement were implementation of more generalized coolant flow network model, and addition of analytical models related to the aerosol behavior such as formation by homogeneous and heterogeneous nucleations, growth due to ambient volatile vapor condensation in a bubble, attenuation due to collision of aerosol particle and coolant droplet in the sub-assembly (S/A) region, and agglomeration and deposition on structural surfaces in the cover gas space.

3. IMPROVED MODEL DESCRIPTIONS

3.1. Generalized flow network model

In the original TRACER code, it was impossible to model complicated primary coolant system. Therefore generalized flow network model, including pipe and tank components, was implemented.

The flow network model is constituted from mass conservation equations in consideration of the mass changes due to coolant flow effect, interaction between bubbles and coolant, deposition or adsorption onto the structural surface, transport into the cover gas, and source term.

3.2. Aerosol model

Additional aerosol behavior models were developed to perform more realistic estimation of the FP retention capability under fission gas ejection condition. After fuel pin failure, volatile FPs will be released associated with a large amount of inert gas. It is thought that the retention capability depends on the release mode of fission gas from fuel pins, bubble behavior, and mass transfer within a bubble. Therefore, in the new TRACER version, analytical models of aerosol attenuation in the S/A region, and aerosol nucleation and growth in a bubble, were added. In addition to above advancement, the multi-component aerosol model to evaluate the attenuation due to agglomeration and deposition on structural surfaces in the cover gas space was implemented.

3.2.1. Aerosol attenuation model in the S/A region

In the aerosol attenuation model in the S/A region, entrainment of coolant droplet due to gas jet, and interaction between the droplet and aerosol particle were modeled as shown in Fig.6. The equation of the aerosol concentration change at mesh j is written by

$$\partial Cc(j) / \partial t = -\Sigma(Cc(i)\ u(i)\ A(i)) / Vg(j) - E\ \pi\ r_d^2\ Cd(j)\ u_r Cc(j) \quad , \qquad (1)$$

where Cc(j) is the aerosol concentration, u(i) is the gas velocity in channel i, A(i) is the cross sectional area of coolant channel, Vg(j) is the volume of mesh j, E is the collision efficiency between aerosol and droplet, r_d is the droplet radius, Cd(j) is the droplet concentration, and u_r is the relative velocity between gas and droplet. Decontamination factor (DF) , which is the measure of the aerosol attenuation capability, in the coolant channel mesh j, is obtained by Cc(j) /Cc(j+1) . The entrainment velocity of droplet is obtained based on the empirical relation [3-5].

3.2.2. Aerosol nucleation and growth model in a bubble

Aerosol nucleation was modeled by the conventional nucleation relations. The homogeneous nucleation model was based on the relations of critical nucleus creation and ambient vapor pressure, and the heterogeneous model was based on the particle growth due to condensation of vapor.

Aerosol growth behavior was modeled for three typical phases, such as continuous, free molecule motion and transition, characterized by particle radius and mean free path. For transition phase, the model based on Fuchs and Sutugin formula [6] was used.

3.2.3. Aerosol deposition model in the cover gas space

For the transport within the cover gas space, the behavior of multi-component aerosols which consist of sodium mist and radionuclides was modeled in the code. The code calculates the aerosol processes such as agglomeration, deposition, leakage, and source term from the coolant sodium with spatially homogeneous confined atmosphere. The aerosol model of TRACER is based on the ABC-INTG code [7].

4. CHECK OUT CALCULATION

4.1. Calculation to check out the generalized flow network model

In-vessel radionuclides transport behavior after the single fuel pin failure assumed under prototype reactor condition was selected to check out the generalized flow network model. In this calculation, the primary cooling system was modeled by 20 coolant cells as shown in Fig.7, and released FP inventories were assumed to be 100% and 20% of noble gas and volatile species accumulated in the fuel pin gap, respectively. Mass transfer mode from the sodium coolant into the cover gas was assumed to be equilibrium mode between both phases, and typical radionuclides in the cover gas were calculated after the single fuel pin failure until about 24 h. Figure 8 shows the time dependent behavior of radionuclide in the cover gas. From results for noble gas and volatile species transported into the cover gas, it was confirmed that the generalized flow network model was capable of simulating the FP transport phenomena in the primary cooling system under reactor conditions.

4.2. Calculations to check out the added aerosol model

Check out calculations were performed by assuming the typical situation to confirm the capability of simulation of nucleation and growth in a bubble, attenuation in the S/A region, and agglomeration and deposition on structural surfaces in the cover gas region.

Figure 9 illustrates calculational geometry for droplet entrainment and aerosol attenuation calculation. In this case, the S/A outlet region length and the equivalent diameter of coolant channel was 0.5 m and 0.1 m, respectively. The typical calculational results were shown in Figs.10-12. From these results, it was found that the aerosol attenuation rate was strongly affected by the fission gas ejection velocity, and DF increased as gas ejection velocity increased.

The calculational geometry using the integrated models for the transport behavior during FP release with inert gas was shown in Fig. 13. In this calculation, coherent release of CsI of 4 mol% at 1000℃ from failed fuel pins in 40 subassemblies was assumed. Aerosol concentration in the cover gas space as a function of time was shown in Fig. 14. Although the increase of aerosol concentration in the early phase was observed, its concentration decreased due to agglomeration and deposition on structural surfaces in the cover gas space after about 1000 s.

Through several check out calculations, it was confirmed that model implementation and numerical calculation were performed exactly, and under the gas ejection condition the attenuation behavior in the S/A region was very important.

5. CONCLUDING REMARKS

Improvement of analytical models in the TRACER code has been performed toward applying to realistic in-vessel source term evaluation.

Improved model performance was confirmed through several check out calculations for the in-vessel aerosol transport behavior after the fuel failure under reactor conditions, such as aerosol attenuation in the S/A region, aerosol nucleation in a bubble, the growth during bubble rising, and integral behavior including aerosol deposition within cover gas. Further verification and applicability study using experimental results are required for more realistic evaluation of in-vessel source term in FBRs.

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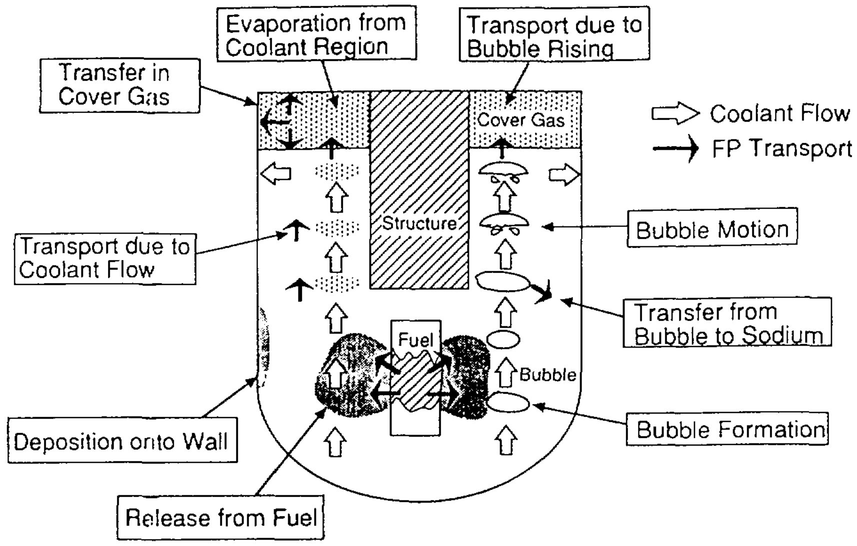
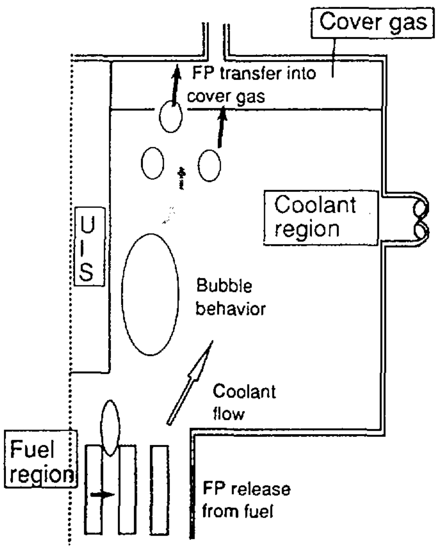


Fig.1 Dominant Behavior of Radionuclides in Primary Cooling System for In-vessel Source Term Evaluation



Behavior	Analytical model
1. Fuel Pin Temperature	•Input (function)
2. FP release from fuel to coolant	•Direct release (NUREG-0772) •Release from gas plenum •Specify initial bubble size based on gas ejection velocity •Input for gas composition
3. Coolant flow	•Flow network model
4. Bubble behavior a) Components b) Shape c) Size change d) Velocity e) Heat transfer f) EOS g) Diffusion between gas and liquid phases h) Deposition as aerosol	 •Condensable, Noncondensable, Aerosol •Sphere, Ellipsoidal, and Spherical-cap •Variation due to heat transfer, head, and break-up based on instability •One dimensional model •Convection and Radiation •Ideal gas •Mass transfer coefficient in both phases •Considered
5. FP transfer model into cover gas	•Diffusion •Equilibrium evaporation
6. Deposition onto wall	•Considered

Fig.2 Analytical Models in TRACER

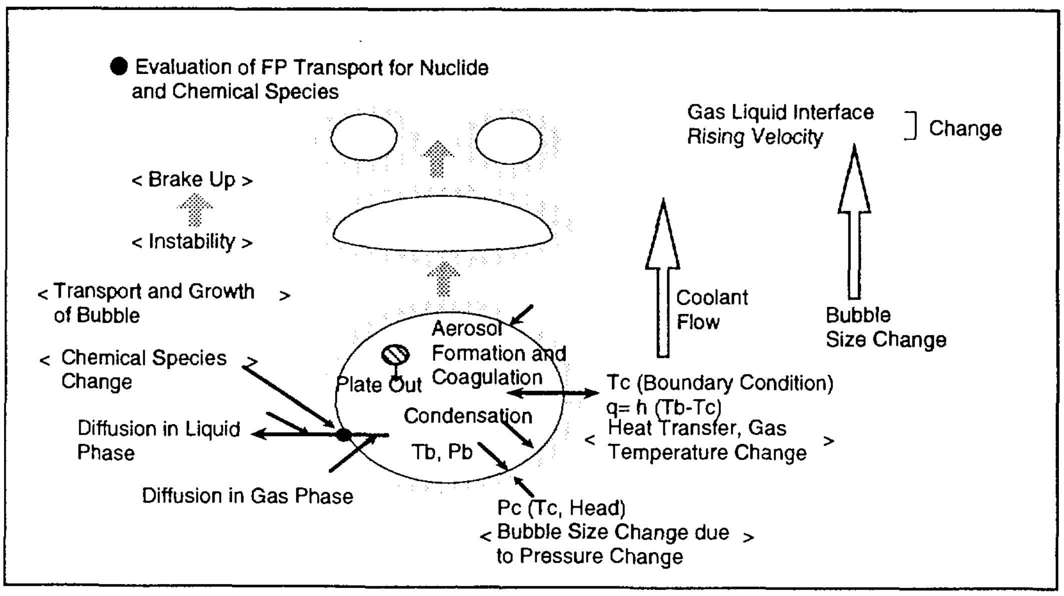


Fig.3 Schematic Illustration of Analytical Model for FP Gas Bubble Behavior

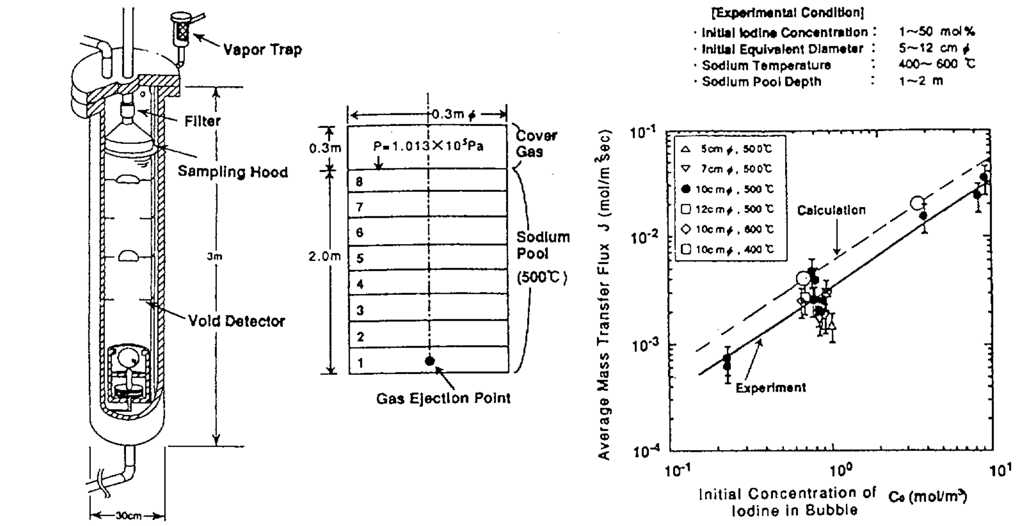
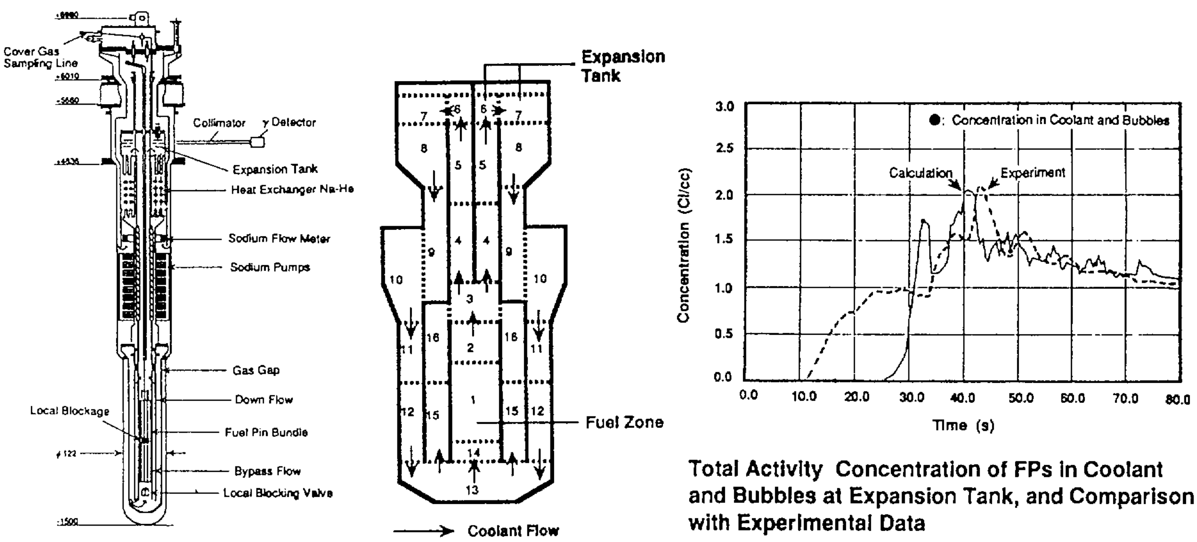


Fig.4 Experimental Geometry of SABER and Calculational Model for TRACER Prediction, and Comparison of their Results



Total Activity Concentration of FPs in Coolant and Bubbles at Expansion Tank, and Comparison with Experimental Data

Fig.5 Experimental Geometry of MOL7C/6 and Calculational Model for TRACER Prediction, and Comparison of their Results

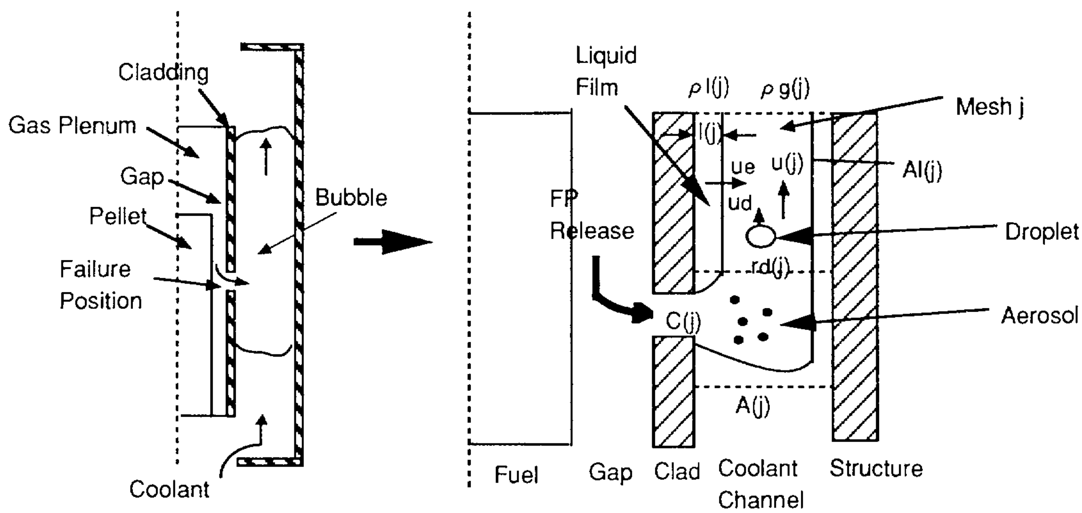


Fig.6 Model Description of Entrainment of Droplets, and Interaction Between Droplets and Aerosol Particles Moved in S/A

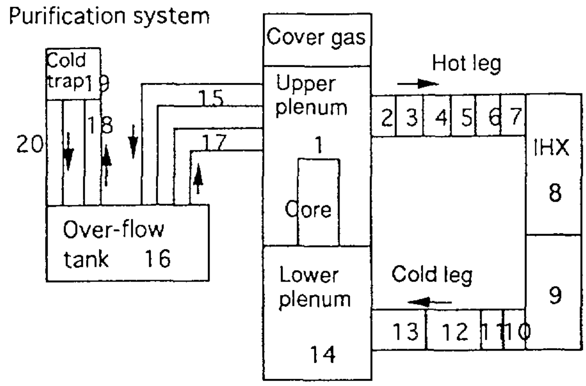


Fig.7 Calculational Geometry to Check out more Generalized Path Model

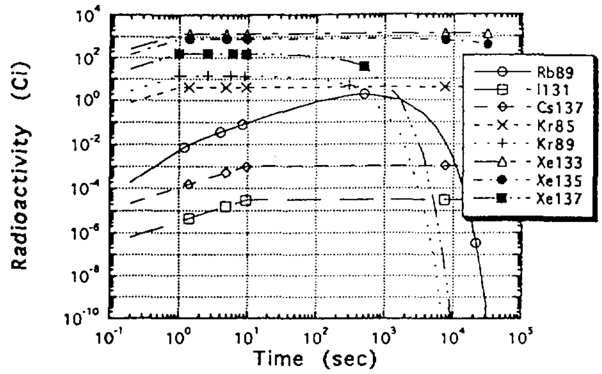


Fig.8 Time Dependent Behavior of Radionucldes in Cover Gas of R/V

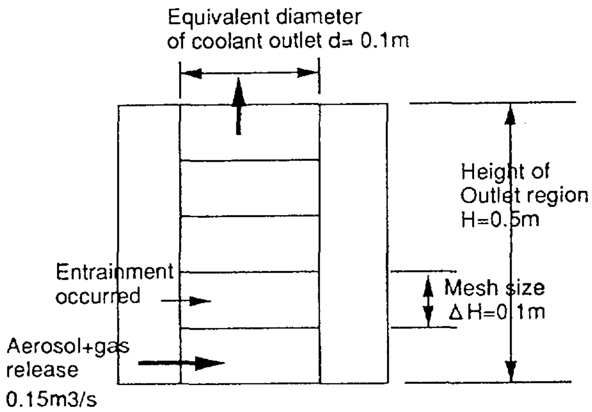


Fig.9 Calculational Geometry for Entrainment and Aerosol Attenuation Models

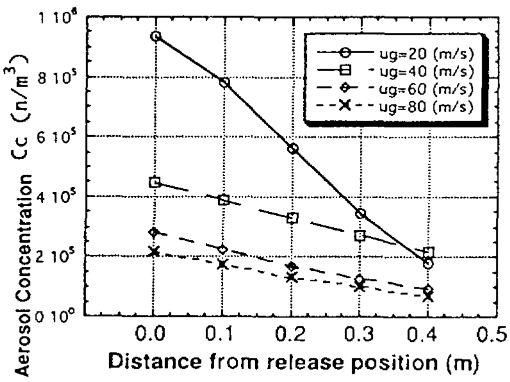


Fig.10 Spatial Distribution of Aerosol Concentration at Time 0.03 s

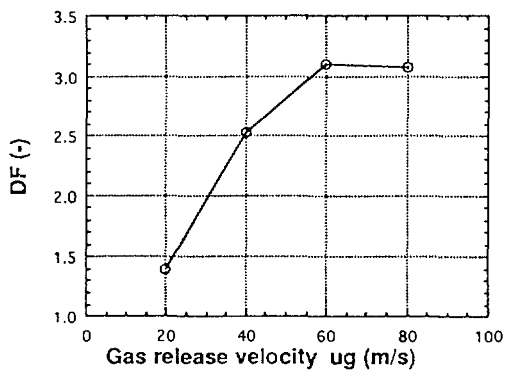


Fig.11 Decontamination Factor(DF) as Function of Inlet Gas Velocity

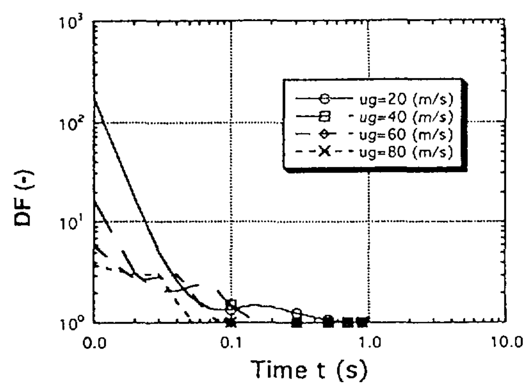


Fig.12 Decontamination Factor as Function of Time

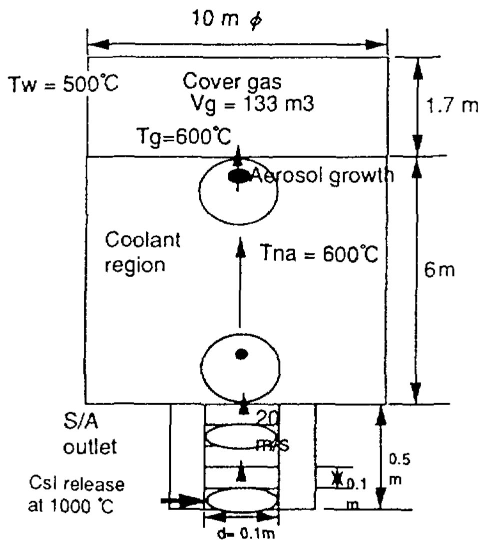


Fig.13 Calculational Geometry for FP Transport Behavior During FP release with Inert Gas

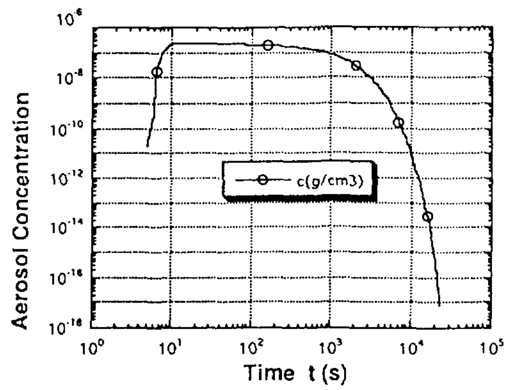


Fig.14 Improved TRACER Prediction of Aerosol Concentration Change in Cover Gas After FP release with Inert Gas