SIMULATION OF POOL SCRUBBING EXPERIMENTS USING BUSCA

A. Dehbi, S. Guentay

ABSTRACT

BUSCA-PSI is a computer code which predicts the aerosol scrubbing taking place when gas bubbles containing fission products rise through stagnant pools of water after a postulated severe accident. A Lagrangian formulation is adopted to follow the path of a bubble as it rises toward the surface of the pool. The BUSCA model includes most aerosol removal mechanisms which are thought to be significant, namely: Jet Impaction at the orifice, Convection/Diffusiophoresis during steam condensation, Thermophoresis, Sedimentation, Centrifugal Impaction during bubble rise, and Brownian Diffusion. The hydraulic modelling offers a variety of options for the initial globule volume, the stable bubble size, the bubble rise velocity, and the bubble shape. The heat and mass transfer part of the model uses correlations found in the relevant literature.

BUSCA simulations were performed to determine the decontamination factor (DF) dependence on key aerosol and thermal hydraulic parameters. The decontamination factor increases with height, pool temperature subcooling, and steam content. The decontamination factor exhibits a parabolic dependence on the particle radius. At low particle sizes, the DF is high due to Brownian Diffusion which is the dominant removal mechanism. The DF hits a minimum and then increases with particle size as Centrifugal Impaction and Sedimentation become important.

In separate calculations, BUSCA was used to the simulate the aerosol scrubbing experiments performed by EPRI. For cold pool tests, the predicted scrubbing efficiencies were in a good, conservative agreement with the data for both Tin and CsI, and the discrepancies were within the reported measurement errors. For hot pool tests, the code systematically underpredicted the scrubbing DF's; this is potentially due to condensation in the gas space above the pool, a situation not currently modelled by BUSCA. The code was also tested against data produced by the Tepco-Toshiba-Hitachi experiments. The predicted DF factors were again in good, conservative agreement with the data.

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1 INTRODUCTION

When a nuclear reactor severe accident occurs, fission products are expected to be released from the degraded fuel in the core. Analyzing the release, transport, and retention of these fission products is a fundamental step toward quantifying the amount of radioactivity which would ultimately make its way to the environment.

In most LWR's severe accident scenarios, the transport paths of aerosols include passages through stagnant pools of water. For instance, in BWR's, the steam-gas-fission product mixture is directed towards the suppression pool where steam is condensed to prevent overpressurization of the wetwell space. In PWR's, the mixture could pass through the pressurizer quench tanks before reaching the containment; in other instances, the fission product carrying gas could leak into the secondary-side pool of a steam generator following a hypothetical tube rupture. Hence, it is important to design models and experiments to simulate the aerosol removal taking place in water pools.

BUSCA (Bubble Scrubbing Analysis) is a computer code which predicts the aerosol decontamination factors in water pools during degraded core accidents. The code was developed jointly by AEA, GRS, and PSI. A short summary of BUSCA will follow, while an extensive description of the code's models and validation can be found in reference [1] and [2].

2 THERMAL-HYDRAULIC MODELS

When the carrier gas is forced in a water pool through an injector orifice, it forms an initial globule whose volume depends on the orifice size as well as on the gas velocity. Because it is too large to be stable, the globule subsequently breaks up into a multitude of smaller bubbles which rise as a swarm towards the pool surface. Past experimental investigations showed that even though the bubbles break up and coalesce continuously, the bubble size distribution remains nearly constant along the depth of the pool. The EPRI experiments [3] showed that the distribution is adequately described by a log-normal frequency function while the mean bubble size is near 5.6 mm at low steam fractions and shrinks as the steam content increases.

When the bubble rises through the pool, it exchanges mass and energy with the surrounding water. BUSCA uses standard correlations which estimate the heat and mass transfer rates between a solid sphere and an infinite surrounding medium [4]. Condensation as well as evaporation into the bubble are allowed to take place depending on the difference in temperature and vapor pressure between the bubble and the water pool [5].

BUSCA adopts a Lagrangian formulation whereby a bubble of known shape and initial diameter is followed as it rises in a pool of water. At each time step (vertical location), the program computes the net transport of mass and energy in or out of the bubble. The bubble size, composition, and thermal state are thus updated for the next time-step. For the bubble rise velocity, BUSCA allows various theoretical and empirical options to be selected [6], [7].

The exchange of mass and energy between the bubble and the pool results in the removal of aerosols by some known mechanisms such as Diffusiophoresis or Thermophoresis. Hence, at each time step, the thermal-hydraulic information is fed into BUSCA's aerosol module which, in turn, calculates the rate of aerosol removal.

3 AEROSOL REMOVAL MODELS

BUSCA-PSI considers the removal of aerosols by the following mechanisms: Jet Impaction at the orifice, Diffusiophoresis, Thermophoresis, Sedimentation, Centrifugal Impaction during Bubble Rise, and Brownian Diffusion. At the start of the calculation, BUSCA calculates the removal due to Jet Impaction at the orifice. The computation is based on empirical correlations ([8], [9]) which give the removal efficiency as a function of the particle Stokes number. This step allows the computation of the aerosol mass remaining inside the bubble immediately after it leaves the orifice.

Except for Jet Impaction, each removal mechanism has an associated removal velocity which depends on the aerosol and/or the bubble characteristics. The removal velocities are obtained from theoretical or empirical formulations. Occasionally, there exist several alternatives for modelling the same mechanism. In such cases, BUSCA offers options which allow the user to select the desired model. The respective removal velocities are calculated at each time step, then summed up vectorially to obtain an effective deposition velocity. This net velocity is subsequently integrated over the surface of the bubble to obtain the local aerosol removal rate and by the same token update the bubble aerosol inventory for the next time step. The standard aerosol velocities used in BUSCA are:

- The Diffusiophoretic velocity:

$$v_{cond} = \frac{X_s}{X_s + \sum\limits_{i \neq s} X_i (\frac{M_i}{M_s})^{0.5}} \frac{-\frac{dm_s}{dt}}{m_s} \frac{V}{A}$$

- The Centrifugal Impaction velocity:

$$v_{imp} = \frac{9}{4} U_B^2 v_g(r) \frac{sin^2\theta}{R_c g}$$

- The Thermophoretic velocity:

$$v_{th}(r) = 1.5\frac{\eta_G}{\rho_G T_B \chi} k_h (T_B - T_p) K_G C(L/r) Br(\frac{L}{r})$$

where the Brock factor $Br(r)$ is defined as:

$$Br(L/r) = \frac{K_G/K_p + 2.48L/r}{(1 + 3L/r)(1 + 2(K_G/K_p + 2.48L/r))}$$

and $C(L/r)$ is the Cunningham correction factor.

- Sedimentation velocity:

$$v_g(r) = \frac{4\pi}{3} \rho_p g r^3 B(r)$$

where the particle mobility function $B(r)$ is defined as:

$$B(r) = \frac{1}{6\pi\chi\eta_G r} C(L/r)$$

- The Brownian Diffusion velocity:

$$v_d(r) = 1.8(\frac{D_p U_B}{R_c^3})^{0.5} \frac{V}{A_d}$$

where:

$$D_p = kT_B B(r)$$

4 PARAMETRIC CALCULATIONS

BUSCA-PSI simulations were performed to determine the decontamination factor (DF) dependence on key aerosol and thermal hydraulic parameters, namely: the particle size, the steam content in the carrier gas, the water pool temperature, the gas temperature, and the gas flowrate. CsI was selected as the aerosol material for the simulations. The selected pool height of 5 m corresponds to BWR suppression pools, while the carrier gas temperature of 500 K is typical of severe accident conditions.

4.1 Effect Steam Fraction, Aerosol Size, and Pool Temperature

Figure 1 shows the dependence of the DF on the aerosol geometric radius for various steam fractions at cold pool conditions. The parabolic shape of the curve is due to the competing mechanisms which are responsible for the scrubbing process. For the finest particles, Brownian Diffusion is the dominant removal mechanism, and hence the DF is very large. Likewise, for the heaviest particles, Sedimentation and Centrifugal Impaction are dominant, resulting in high decontamination. For mid-size particles, no removal mechanism overwhelms the others, and hence the curve is somewhat flat near a radius of $0.1 \mu m$. Figure 1 also displays the strong dependence of the DF on the carrier-gas steam fraction, a fact which confirms the experimental findings. For hot pools (Figure 2), the trends are similar except that the magnitude of the DF is smaller because evaporation into the bubble occurs with a subsequent reduction in the aerosol removal rate.

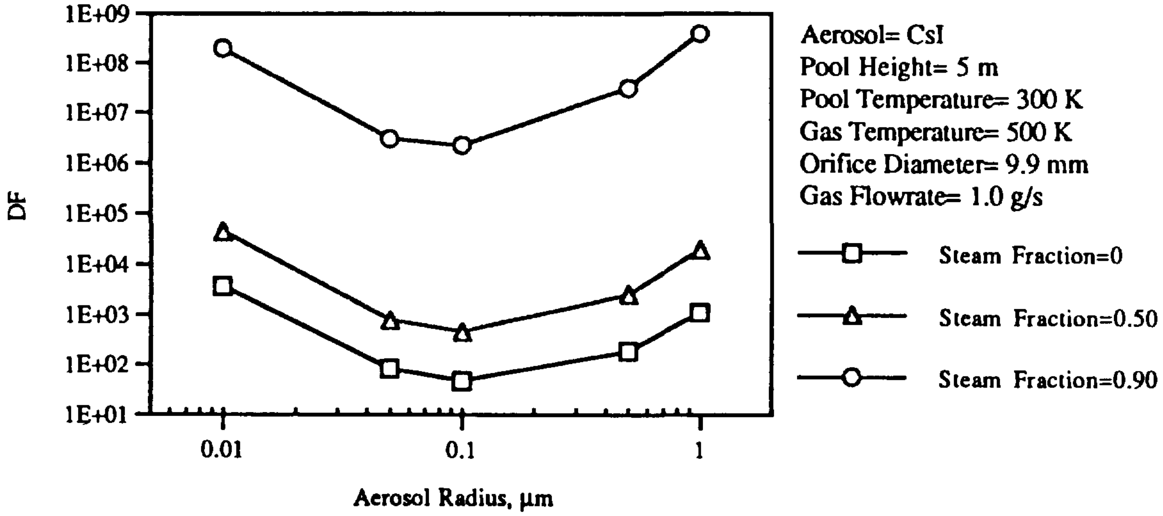

Figure 1: Effect of the Steam Fraction and Aerosol Size, Cold Pool

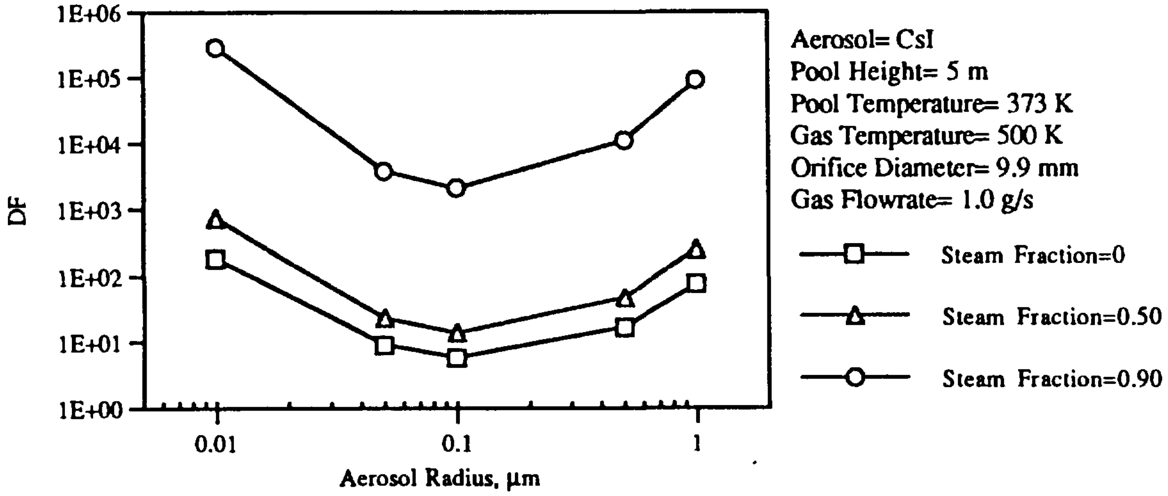

Figure 2: Effect of the Steam Fraction Aerosol Size, Hot Pool

4.2 Effect of the Gas Temperature

Thermophoresis can be an important removal mechanism for severe accidents because the carrier gas is typically very hot while the water pool is comparatively cool. Since the bubble comes into thermal equilibrium with the pool within a few orifice diameters, the simulations were performed at a modest pool height (0.20 m) to minimize the contribution of other inertial removal mechanisms. As shown in Figure 3, the thermophoretic effect is more pronounced at low steam fractions. At high steam fractions, Thermophoresis becomes negligible as Diffusiophoresis dominates the removal process.

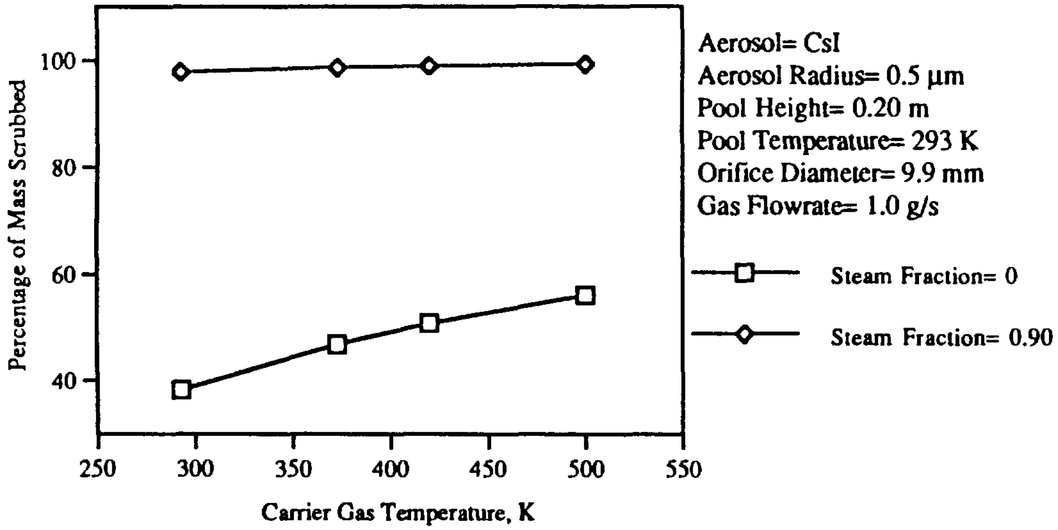

Figure 3: Effect of the Gas Temperature

4.3 Effect of the Gas Flowrate

At the injection point, some aerosol particles may impinge against the water in a way similar to that encountered in impactors. In fixed orifice geometries, the removal efficiency depends primarily on the aerosol inertia and on the carrier gas velocity. Figure 4 shows the DF versus gas flowrate for particles with radii of 0.1 and 0.5 μm, respectively. As the gas flowrate is increased, the DF increases noticeably for the larger particles, and rather mildly for the smaller ones.

4.4 Effect of the Pool Height

BUSCA was used to assess the DF dependence on the pool height. To that effect, the input parameters were chosen so as to eliminate aerosol removal by Thermophoresis and Diffusiophoresis. As shown in Figure 5, the decontamination factor increases with pool height in an exponential fashion, a fact which confirms the experimental findings reported in references [11] and [12]. As expected, the heaviest particle is more efficiently scrubbed then the lighter one.

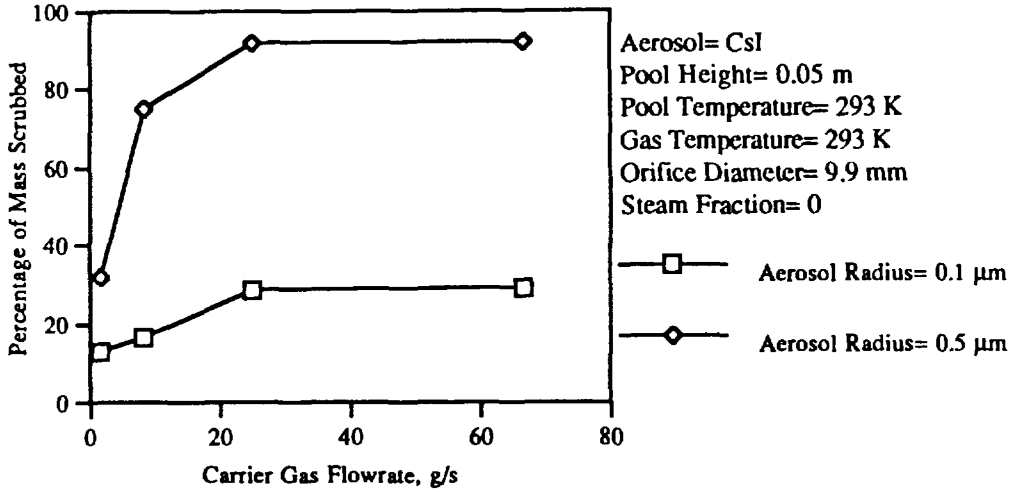

Figure 4: Effect of the Gas Flowrate

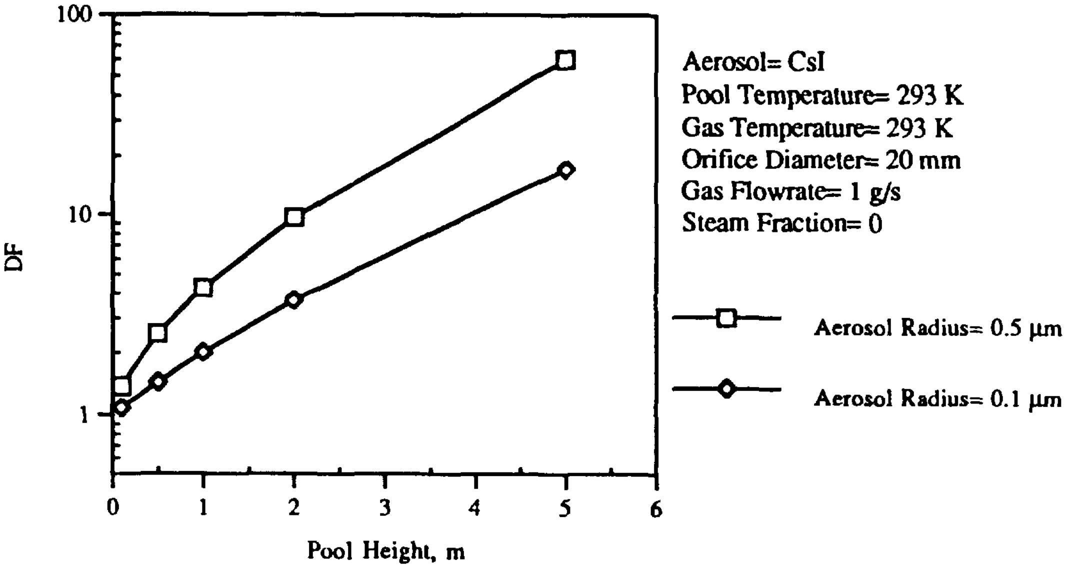

Figure 5: Effect of the Pool Height

5 SIMULATION OF THE EPRI EXPERIMENTS

BUSCA was used to simulate the EPRI tests [10] which constitute the most complete pool scrubbing experiments to date because many significant thermal-hydraulic and aerosol parameters were measured. The EPRI program was undertaken to investigate both the hydrodynamics and the aerosol physics pertinent to pool scrubbing. The purpose of the program

Parameter	Range
Mean geometric radius Sn, μm	0.50
Mean geometric radius CsI, μm	0.09
Orifice diameter, cm	1.27
Steam mass fraction	0-0.96
Gas mass flowrate, g/s	0.23-14.52
Inlet gas temperature, K	282-404
Pool temperature, K	282-373
Pool submergence, m	0.155-1.65

Table 1: Parameters for the EPRI Experiments

was to produce data which would support model development and serve as a benchmark tool for the computer code SUPRA [8]. In the scrubbing experiments, both soluble (CsI, TeO_2) and insoluble (Sn) aerosols were used. The aerosols were carried away by a gaseous mixture whose steam fraction varied from 0 to 0.96. The mixture was forced through a horizontal orifice and injected into a water pool. The range of parameters used in these experiments is summarized in Table 1. In the BUSCA simulations, the stable bubble diameter was assumed to be 5.6 mm, in accordance with the EPRI hydrodynamical experiments [3].

5.1 CsI Scrubbing, Ambient Pool Temperature, No Steam

As displayed in Figure 6, the calculated DF's for pure noncondensable runs are in fair agreement with the data. The comparison on the basis of scrubbed mass in shown in Figure 7.

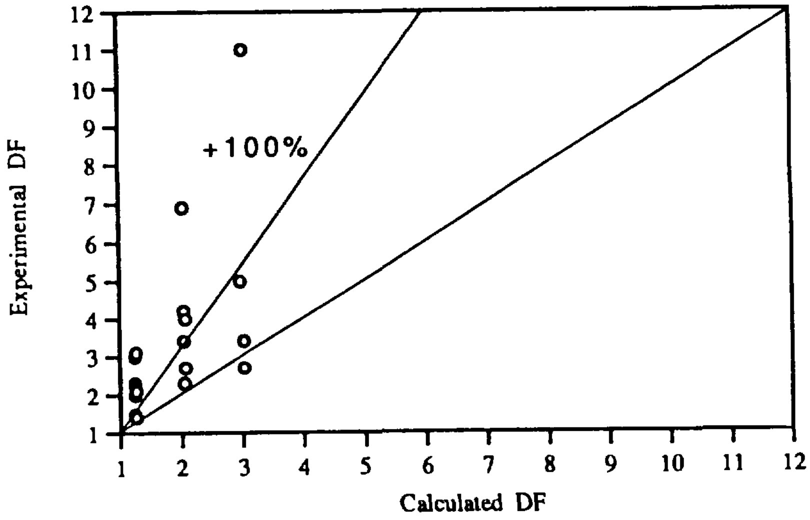

Figure 6: Comparison of DF's for CsI Runs, Ambient Pool Temperature, No Steam

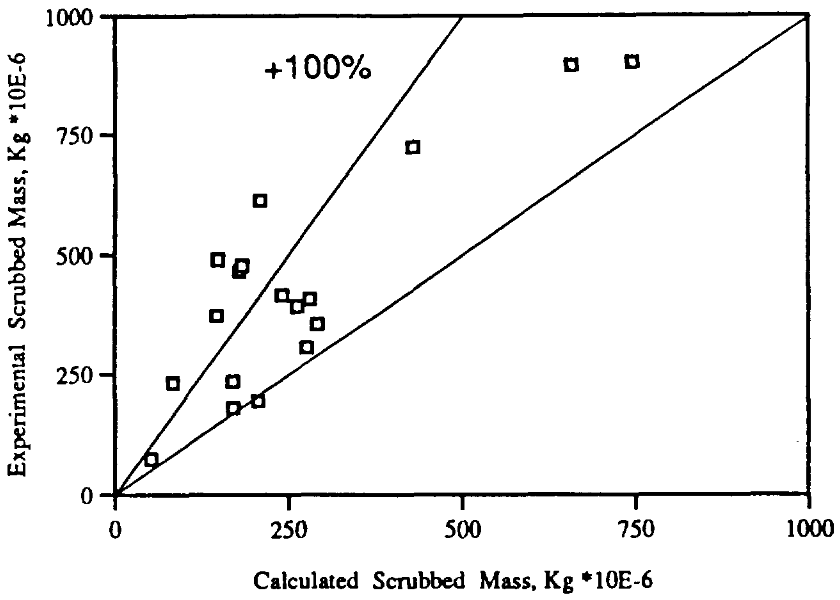

Figure 7: Comparison of Scrubbed Masses for CsI Runs, Ambient Pool Temperature, No Steam

5.2 CsI Scrubbing, Ambient Pool Temperature, With Steam

For runs with steam, the DF's are in good, conservative agreement with the reported data (Figure 8). The agreement is even better if the comparison is based on the scrubbed mass as illustrated in Figure 9.

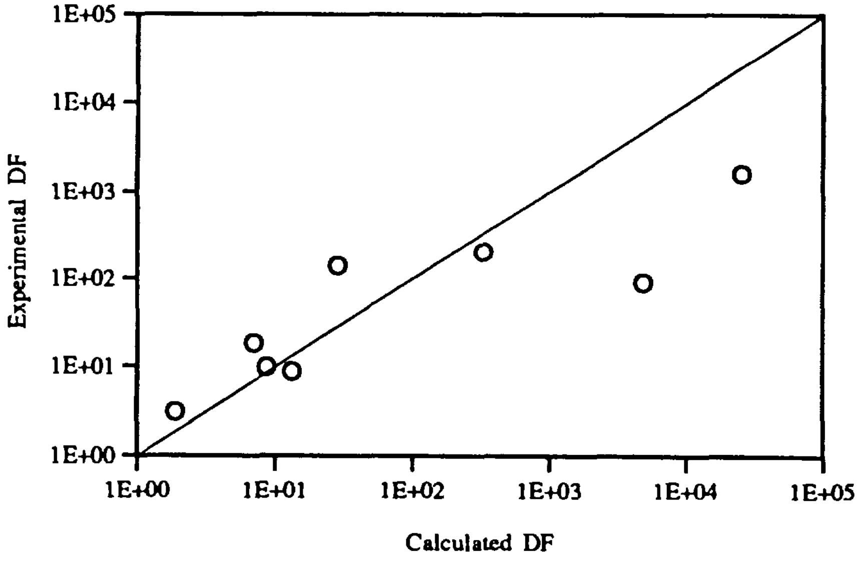

Figure 8: Comparison of DF's for CsI Runs, Ambient Pool Temperature, With Steam

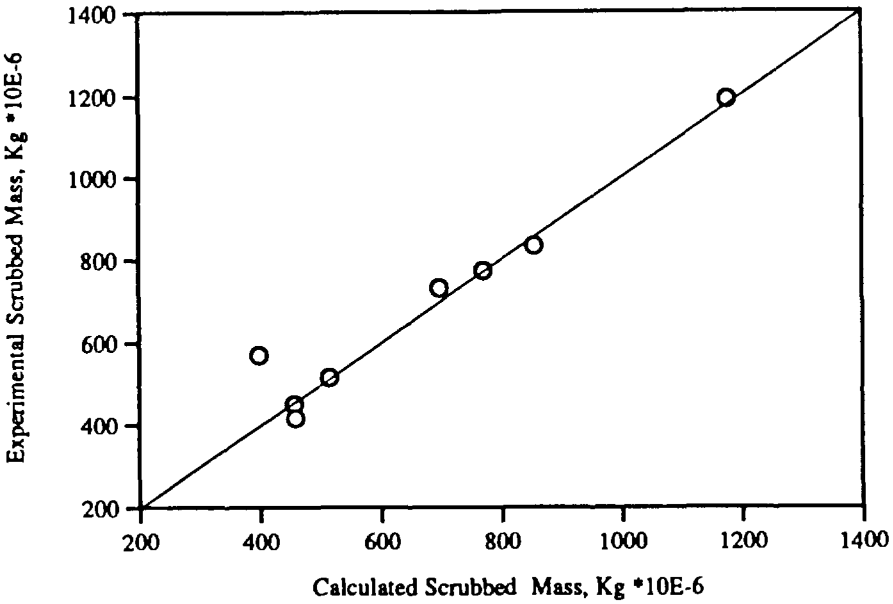

Figure 9: Comparison of Scrubbed Masses for CsI Runs, Ambient Pool Temperature, With Steam

5.3 Sn Scrubbing, Ambient Pool Temperature, with Steam

For the Sn tests, the mean aerosol geometric radius was 0.5 μm, which is five times larger than the corresponding radius of CsI . Accordingly, the DF's are much larger for Sn. The predicted scrubbed mass is in very good agreement with the actual data as shown in Figure 10.

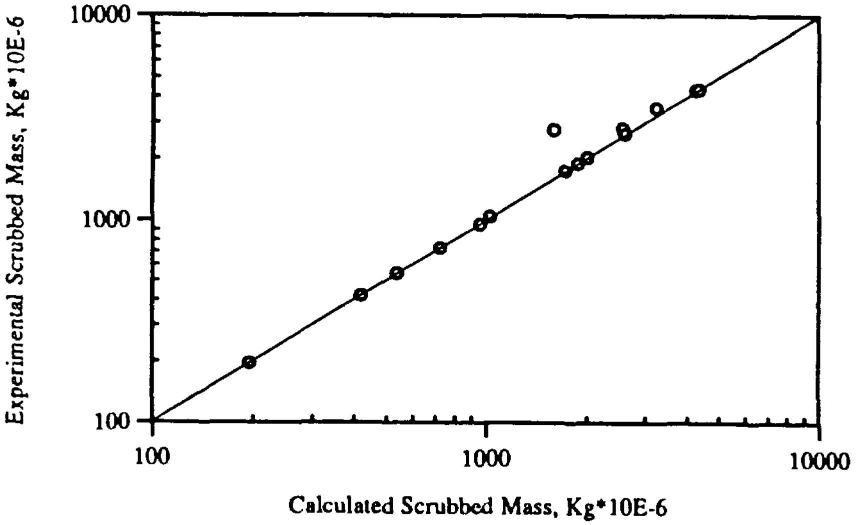

Figure 10: Comparison of Scrubbed Masses for Sn Runs, Ambient Pool Temperature

5.4 CsI Aerosol Scrubbing, Boiling Pool

For saturated pools, BUSCA predicts scrubbed masses which are typically a factor of two lower than the corresponding data as displayed in Figure 11. This could be attributed to condensation above the pool or to turbulence within the boiling pool which would enhance inertial deposition inside the bubble. The aforementioned situations are not presently modelled by BUSCA.

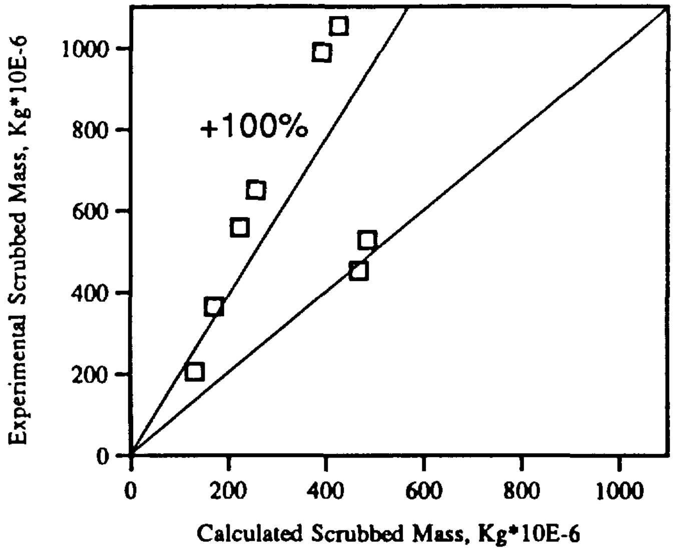

Figure 11: Comparison of Scrubbed Masses for CsI Runs, Boiling Pool, With Steam

6 SIMULATION OF THE TEPCO-TOSHIBA-HITACHI EXPERIMENTS

Pool scrubbing experiments were also performed by a joint team of Tepco, Toshiba, and Hitachi [11], [12]. The tests were conducted in a cylindrical vessel which served as a scrubber tank for LATEX aerosols. The test conditions are summarized in Table 2.

The purpose of the tests was to produce a correlation for the DF as a function of the most significant aerosol and thermal-hydraulic parameters. As a results, the following empirical formula was suggested:

$$DF = DF_s(S, P, T_p, H_s) exp(0.19{d_p}^2) exp((0.88 + 0.52{d_p}^2)H_s)$$

where d_p is the aerosol geometric diameter in μm, and H_s is the pool height in m. The contribution of steam condensation, DF_s, is given by:

Parameter	Standard value	Range
Geometric diameter, μm	0.2, 0.3, 0.5, 1.1	0.2, 0.3, 0.5, 1.1
Orifice diameter, cm	15	1,5,10,15
Steam volume fraction	0.50	0-0.80
Gas flowrate, l/min	47	28-15000
Inlet gas temperature, C	150	20-300
Pool temperature, K	80	20-110
Pool submergence, m	2.7	0-3.8

Table 2: Parameters for the Tepco-Toshiba-Hitachi Experiments

$$DF_s(S,P,T_p,H_s) = \begin{cases} R_s & \text{if } R_s \geq 1 \\ 1 & \text{if } R_s < 1 \end{cases}$$

where:

$$R_s = \frac{1 - W_p}{1 - S}$$

while W_p and S are the inlet and equilibrium vapor volume fractions, respectively.

BUSCA simulations of the Tepco-Toshiba-Hitachi experiments were performed and the results are displayed in Figure 12 and Table 3 . In view of the fact that the experimental DF were determined within a factor of two (+100%, -50%), it can be concluded that the BUSCA predictions are in good, conservative agreement with the data. The agreement is better when steam is present, as was the case with the EPRI experiments.

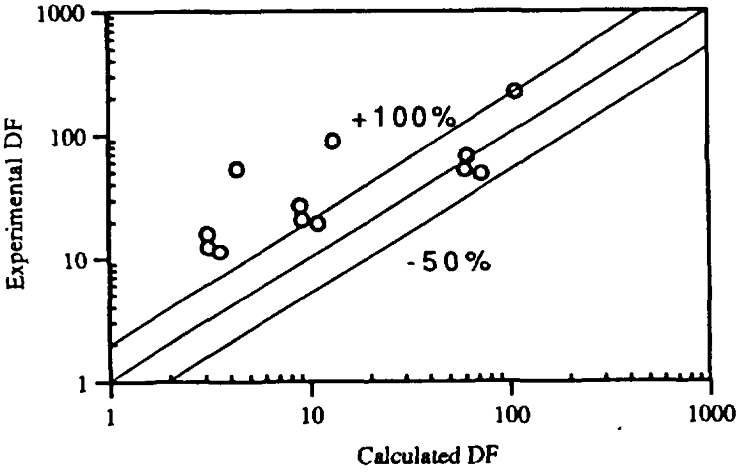

Figure 12: Comparison Between the Tepco-Toshiba-Hitachi Correlation and BUSCA.

Particle Diameter, μm	Steam Volume Percent	Experimental DF	BUSCA DF
0.20	0	11.47	3.59
	50	19.25	11.03
	80	48.1	72.50
0.30	0	12.42	3.14
	50	20.8	9.18
	80	52.1	60.1
0.50	0	16.03	3.11
	50	26.9	8.96
	80	67.2	61.9
1.0	0	52.8	4.37
	50	88.9	13.2
	80	222.2	108.0

Table 3: Comparison Between the Tepco-Toshiba-Hitachi Correlation and the BUSCA Predictions

7 CONCLUSION AND RECOMMENDATIONS

This study presented the simulation of pool scrubbing experiments using the code BUSCA. The results are generally in good, conservative agreement with the availabe data, especially for the cases where steam is present in the carrier gas. There are nonetheless areas where additional modeling and experimental data are clearly warranted:

- The code was found to underpredict the data quite systematically when the carrier gas has little or no steam content. It might well be that some of the aerosol removal correlations (e.g. Jet Impaction at the orifice) are too conservative and need to be replaced. Past aerosol experiments have by and large been integral in nature, and thus individual contributions to the removal process could not be detected. To remedy this deficiency and improve the BUSCA models, an extensive aerosol scrubbing program called POSEIDON is underway at PSI [13]. One of the goals of the POSEIDON experiments is to isolate and study some important aerosol removal mechanisms such as Jet Impaction at the orifice or Thermophoresis.

- The code was also found to underpredict the data at boiling pool conditions. As mentioned earlier, this could be due to deposition mechanisms which are not currently modelled in BUSCA, e.g. condensation on the walls above the pool, or a potential removal enhancement caused by turbulence in the boiling pool. The first hypothesis can be experimentally checked in the upcoming POSEIDON experiments by preventing condensation on the walls above the pool. The impact of boiling-induced turbulence could be tackled analytically.

8 NOMENCLATURE

A : total surface area of the bubble
A_d : surface area available for diffusion
$B(r)$: particle mobility function
$C(L/r)$: Cunningham slip correction factor
D_p : particle diffusivity
d_p : particle aerodynamic diameter
g : gravitational acceleration
H_s : pool submergence
K_G : thermal conductivity of bubble gas
K_p : thermal conductivity aerosol particle
k : Boltzmann constant
k_h : heat transfer coefficient
L : molecular mean free path in the bubble gas
M_s : molecular weight of steam
M_i : molecular weight of the i'th noncondensable gas
m_s : mass of steam in the bubble
P : excess pressure above pool surface
R_c : bubble radius of curvature
r : radius of aerosol particle
S : inlet steam volume fraction
T_B : bubble temperature
T_p : pool temperature
t : time
U_B : bubble velocity
V : volume of the bubble
v_{cond} : Diffusiophoretic velocity
v_d : Brownian Diffusion velocity
v_g : Sedimentation velocity
v_{imp} : Centrifugal Impaction velocity
v_{th} : Thermophoretic velocity
W_p : steam volume fraction in the bubble after thermal equilibrium is reached
X_i : mole fraction of the i'th noncondensable gas
X_s : steam mole fraction
χ : mobility shape factor
ρ_G : gas density
ρ_p : particle density
η_G : dynamic viscocity of bubble gas
θ : cylindrical polar coordinate

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October 21, 1994, CNS Session 12
Containment Reliability, Integrity and Risk Assessment

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Structural Integrity Evaluation of the Containment Building for Wolsung-1 Nuclear Power Plant - KOREA
Yongpyo Suh, Seonglo Lee, Jongrim Lee, Daesoo Lee

Categorization of Core-Damage Sequences by Containment Event Tree Analysis for Boiling Water Reactor with Mark-II Containment - JAPAN
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Early Results From An Experimental Program to Determine the Behaviour of Containment Piping Penetration Bellows Subjected to Severe Accident Conditions - UNITED STATES
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