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OPERATOR AIDS FOR PREDICTION OF SOURCE TERM ATTENUATION

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ABSTRACT:

Simplified expressions for the attenuation of radionuclide releases by sprays and by water pools are devised. These expressions are obtained by correlation of the 10th, 50th and 90th percentiles of uncertainty distributions for the water pool decontamination factor and the spray decontamination coefficient. These uncertainty distributions were obtained by Monte Carlo uncertainty analyses using detailed, mechanistic models of the pools and sprays. Uncertainties considered in the analyses include uncertainties in the phenomena and uncertainties in the initial and boundary conditions dictated by the progression of severe accidents. Final results are graphically displayed in terms of the decontamination factor achieved at selected levels of conservatism versus pool depth and water subcooling or, in the case of sprays, versus time.

I. INTRODUCTION

Under accident conditions, operators of nuclear power plants will be called upon to make quick assessments of the available accident management strategies. Such assessments will include estimates of radionuclide source term attenuations that can be achieved by water pools overlying core debris or by containment sprays. Time pressures on the operators will preclude detailed evaluations using large, mechanistic computer codes. Further, operators are unlikely to have available detailed information on the exact accident scenario or the extent of damage to the plant. Simplified models, or preferably graphical depictions of the potential performance of safety equipment are needed for these operator assessments. The simplified methods must, however, still account for the substantial uncertainty that will exist.

The US Nuclear Regulatory Commission has recently proposed a revised description of the radionuclide releases to reactor containments during severe reactor accidents.[1] In conjunction with the proposed releases to the containment, an effort has been underway to develop revised estimates of the attenuation of the potential radionuclide source term by processes in the reactor containment. To date, simplified models have been developed for source term attenuation by containment sprays[2] and attenuation by water pools overlying core debris interacting with concrete.[3] These simplified models were developed by first constructing very detailed mechanistc models. These mechanistic models were used in detailed uncertainty analyses as described below in Section II. Correlations of the results of uncertainty analyses yield the simplified models used here to prepare operator aids for prediction of source term attenuation. In the future, simplified descriptions of source term attenuation by natural processes and steam suppression pools will be developed following similar procedures.

The simplified expressions for source term attenuation by containment processes explicitly recognize there to be significant uncertainty. Uncertainties considered in the development of these simplified models include uncertainties in phenomena as well as uncertainties in the boundary and initial conditions dictated by the progression of an accident. The uncertainty distributions of the attenuation of the potential accident source term achieved by containment processes can be expressed in terms of quantities the plant operator will know. It is, then, possible to develop simple mathematical expressions for the performance to be expected from the containment processes.

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II. DEVELOPMENT OF THE SIMPLIFIED MODELS

The development of simplified models of containment processes relies on the detailed, mechanistic understanding of these processes that has developed in recent years. The simplification process involves use of mechanistic computer models of the source term attenuation phenomena. Steps in the process are:

A. *identify uncertainties in* the phenomena, material properties, initial conditions and boundary conditions that will affect predictions of source term attenuation;

B. select ranges of values of parameters that are indicative of the identified uncertainties;

C. specify subjective probability distributions for values of the parameters within their uncertainty ranges;

D. construct *uncertainty distributions of* the source term attenuation predicted with the mechanistic models by Monte Carlo sampling of uncertain parameters; and,

E. correlate selected percentiles of the uncertainty distributions against quantities that will be known adequately well even under accident conditions.

Selection of uncertainty ranges for parameters arising in the mechanistic models of containment processes can usually be done by examining experimental data available in the literature or using simple bounding analyses. As a last resort, the ranges can be defined by expert opinion.

Specification of uncertainty distributions for parametric values within the ranges is a subjective process. For this work, a set of rules have been adopted for the uncertainty distributions. A uniform probability density is specified for a parameter whose meaningful range of values spans less than an order of magnitude. A log-uniform probability density is specified for a parameter whose meaningful range spans more than an order of magnitude. In those few cases where the available information warranted a more peaked probability distribution, a lognormal distribution is specified. All of these distributions have high entropy.[4] Consequently, results of the Monte Carlo uncertainty analyses are not especially sensitive to the shapes of the subjective probability distributions. The Monte Carlo uncertainty analysis consists of repeated evaluations of a source term attenuation process using randomly sampled values of the uncertain parameters. An issue with Monte Carlo sampling is the percent confidence, 100C, that some percent of the uncertainty range, 100 p, has been sampled. The Monte Carlo sampling for this work was continued until the number of samples, n, assured there was a 95 percent confidence and that 95 percent of the range of values had been sampled where C and p are related by:[4]

$$C = 1 - np^{n-1} + (n-1)\,p^n$$

Note that the number of samples necessary to meet this criterion is independent of the number of uncertain parameters being considered.

The accumulated results of the calculations are than used to *construct uncertainty distributions* using distribution-free ordering statistics.[4] That is, predicted performance values are ordered numerically. The probability that the value corresponding to the $\underline{p\text{th}}$ percentile of the underlying uncertainty distribution lies between the $\underline{i\text{th}}$ and $\underline{j\text{th}}$ values in the ordered listing of results is given by:

$$\Pr(Y_i < \xi_p < Y_j) = \Pr(Y_i < \xi_p) - \Pr(Y_j < \xi_p)$$

where

$$\Pr\left(Y_k < \xi_p\right) = \sum_{i=k}^{n} \frac{n!}{i!(n-i)!}\, p^i (1-p)^{n-i}$$

III. RESULTS FOR THE WATER POOL OVERLYING CORE DEBRIS

It is experimentally established that water pools overlying core debris interacting with concrete will sharply attenuate aerosol production even if the water pool does not quench the debris.[5] The attenuation of aerosol emissions comes about because aerosols sediment, inertially impact and diffuse to the walls of bubbles rising through the water pool. In the case of subcooled pools, further attenuation of aerosol emissions comes about by diffusiophoresis.[3] The attenuation of aerosol emissions during the rise of bubbles is described by:

$$\frac{dm}{dx} = -\left[\alpha(\text{sedimentation}) + \alpha(\text{impaction}) + \alpha(\text{diffusion})\right] m$$

where

m = aerosol mass,
$\alpha(i)$ = decontamination coefficients due to sedimentation, impaction and diffusion, and
x = distance through a pool the bubble rises.

Diffusiophoretic decontamination of bubbles was taken to be directly proportional to the change in bubble volume as the bubble equilibrated with the subcooled pool.

The decontamination processes are quite dependent on aerosol particle size and bubble size. For the mechanistic analyses, the above expression was integrated for 20 aerosol size classes spanning the initial aerosol distributions. Results were expressed in terms of the decontamination factor, DF, which is defined as the aerosol mass generated by the melt/concrete interactions divided by the aerosol mass that emerges from the waterpool. Results obtained with the mechanistic model were compared to the decontamination observed in the SWISS-II test.[5] The mechanistic model predicted decontamination factors of 16.8 and 20.1 at times when the observed decontamination factors were 5 to 15 and 19 to 34.

The Monte Carlo analyses of the decontamination factor considered the 18 uncertain parameters listed in Table 1. Further descriptions of these uncertain parameters are to be found in Reference 3. Suffice it here to say that the upper half of the table deals with uncertainties in severe accident progression and the lower half of the table lists uncertainties in aerosol trapping phenomena. Note that the model developed here treats only aerosol particle removal and does not address iodine partitioning from the water pool.

Analyses were done for water pool depths of 30 to 500 cm and pool subcooling of 0 to 70°C. Medians of the uncertainty distributions are considered the best estimates of the decontamination factors. The 10th and 90th percentiles are considered reasonable bounds on the decontamination factors. These percentiles of the distributions were correlated against pool depth, H, and pool subcooling, ΔT:

- Median (50 percentile)

$$\begin{aligned} \ln \mathrm{DF}\,(H,O) &= -0.195036 + 0.17976\,\sqrt{H} \\ &\quad + 4.68319 \times 10^{-9}\ H3 \\ \ln \mathrm{DF}\,(H,\Delta T) &= \ln \mathrm{DF}\,(H,O)\ -0.0843816 \\ &\quad - 0.0704774\,\Delta T \\ &\quad + 8.2346 \times 10^{-5}\,H^{3/2} \\ &\quad + 0.82383\,\sqrt{\Delta T} \\ &\quad + 0.0668\,\sqrt{H\Delta T} \end{aligned}$$

Table 1 Uncertain Parameters in the Calculation of Pool Decontamination Factors

Parameter	Range	Probability Density Function
Ambient Pressure	1 - 9 atms	uniform
Concrete Erosion Rate	3 - 35 cm/hr	log-uniform
Carbon dioxide content of concrete	1 - 36%	log-uniform
Water content of concrete	5 - 8%	uniform
H_2/H_2O Ratio	2 - 10^5	log-uniform
CO/CO_2 quench temperature	1000 - 1300K	uniform
Solute mass	0.05 - 100 g/kg H_2O	log-uniform
Volume fraction suspended solids	0 - 0.1	uniform
Density of suspended solids	1 - 6 g/cm^3	uniform
Uncertainty in water surface tension	± 10%	uniform
Boiling heat flux	0.16 to 1.6 MW/m^2	lognormal mean = 0.5 MW/m^2 std. dev. = 1.645
Mean aerosol particle size	0.25 - 2.5 μm	log-uniform
Geometric standard deviation	1.6 to 3.2	uniform
Aerosol material density	1.5 - 10 g/cm^3	uniform
Coefficient in Davison Schuler Model of initial bubble size	1 - 1.54	uniform
Water/core debris contact angle	20-120°	uniform
Coefficient in the Taylor instability model for bubble size	1.9 - 4	uniform
Efficiency of inertial impaction	0 - 1	uniform

- 10 Percentile

$$\ln DF\,(H,O) = -0.1832417 + 0.0879653\,\sqrt{H} + 8.192503 \times 10^{-5}\,H^{3/2} - 1.2281546 \times 10^{-9}\,H^{3}$$

$$\ln DF\,(H,\Delta T) = \ln DF\,(H,O) + 0.00993606 - 0.0474108\,\Delta T + 0.5696997\,\sqrt{\Delta T} + 0.0433372\,\sqrt{H\Delta T}$$

- 90 Percentile

$$\ln DF\,(H,O) = 0.114994 + 0.29587\,\sqrt{H} + 1.087539 \times 10^{-8}\,H^{3}$$

$$\ln DF\,(H,\Delta T) = \ln DF\,(H,O) + 0.03437166 - 0.233505\,\Delta T + 1.4415216\,\sqrt{\Delta T} + 0.01234607\,\Delta T^{3/2} + 3.92396212 \times 10^{-4}\,H\Delta T + 0.075810892\,\sqrt{H\Delta T} + 1.3850581 \times 10^{-8}\,H^{3}\,\sqrt{\Delta T}$$

These correlation expressions were then used to construct plots of constant DF versus pool depth and subcooling. Results for the medians are shown in Figure 1 as plots of constant DF as functions of the square root of the pool depth in centimeters and the pool subcooling in Kelvins. The widths of the lines in this plot are indicative of the uncertainty in the predictions from the correlations.

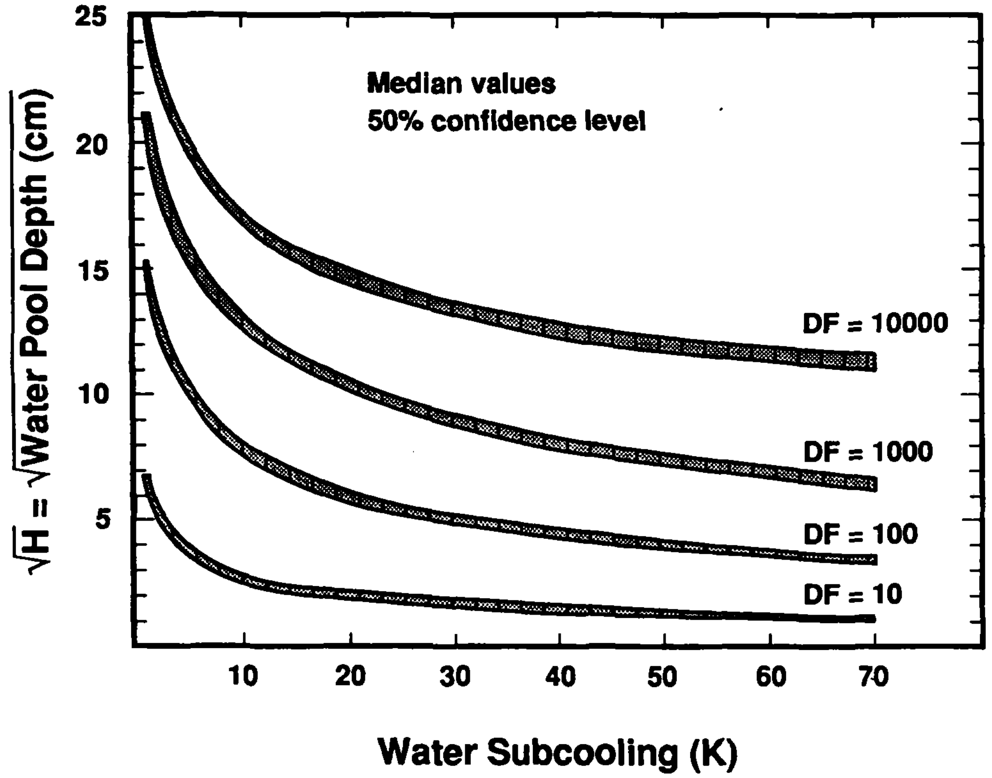

Figure 1 Water subcooling and Depth Needed to Achieve Specified Decontamination of Gases Produced by Core Debris Interactions with Concrete.

IV. RESULTS FOR AEROSOL REMOVAL BY SPRAYS

Spray droplets will remove aerosol particles from the containment atmosphere. Removal occurs by impaction, interception and diffusion. Late in a reactor accident, when structures in the containment have become quite warm, diffusiophoresis caused by steam condensing on droplets may augment these removal mechanisms, but the effect is small and has been neglected in this work. The aerosol removal is quite dependent on both the aerosol particle size and the droplet size. For this work, realistic distributions of spray droplet sizes were considered. Uncertainty in the initial spray droplet sizes due to solutes such as borate was recognized in the analysis.[6] The evolution of the droplet size distribution during free fall through the containment atmosphere was also considered.[2]

The rate of aerosol removal can be calculated from the differential equation:[1]

$$\frac{dm}{dt} = \left[\frac{\lambda\,(DF,Q,H)}{1+\alpha} \right] m$$

where m = mass concentration of aerosol in the containment atmosphere

α = volume of the containment not contacted by the spray divided by the volume of the containment that is contacted by the spray

λ = decontamination coefficient

The spray decontamination coefficient is a function of the water flux to the containment atmosphere, Q, and the fall distance of water droplets. Because spray droplets preferentially remove both very large and very small particles, but are inefficient at removing aerosol particles in the size range of 0.1 to 0.3 μm, the decontamination coefficient is also a function of the extent of decontamination, DF.

Sprays may be operated for arbitrary lengths of time in a reactor accident. Analyses then focused on the uncertainty distributions in the spray decontamination coefficient rather than on the overall decontamination factor. Uncertain quantities considered in the analyses are listed in Table 2. Details concerning these uncertain quantities are presented in Reference 2. Note that the list includes parameters to select between competing models of individual phenomena.

The median (50th percentile), 10th and 90th percentiles of the distributions were correlated against water flux, Q, fall distance, H, and decontamination factor, DF:

$$\ln \lambda\,(DF,Q,H) \quad = \quad \ln (\lambda_o E)$$

Expressions for λ_o and E depend on the user selected level of confidence:

For the median of the uncertainty distribution, which was considered by the author to be a best estimate, λ_o and E are given by:

$$\begin{aligned}\ln \lambda_o \quad &= \quad 6.8371 + 1.0074 \ln Q - 4.1731 \times 10^{-3}\, Q^2 H \\ &\quad - 1.2478\, Q - 2.4045 \times 10^{-5}\, H \\ &\quad + 9.006 \times 10^{-8}\, Q H^2\end{aligned}$$

$$\begin{aligned}E \quad &= \quad (0.1815 - 0.02655 \ln Q)\left(1 - \left(\frac{1.1}{DF}\right)^{0.5843}\right) \\ &\quad + \left(\frac{1.1}{DF}\right)^{0.5843}\end{aligned}$$

Reasonable lower bounds for λ_o and E are given by the 10 percentile values:

$$\begin{aligned}\ln \lambda_o \quad &= \quad 5.5750 + 0.94362 \ln Q - 7.327 \times 10^{-7}\, Q H^2 \\ &\quad - 6.9821 \times 10^{-3}\, Q^2 H \; + \; 3.555 \times 10^{-6}\, Q^2 H^2\end{aligned}$$

$$\begin{aligned}E \quad &= \quad (0.1108 - 0.00463 \ln Q)\left(1 - \left(\frac{1.1}{DF}\right)^{0.8945}\right) \\ &\quad + \left(\frac{1.1}{DF}\right)^{0.8945}\end{aligned}$$

Reasonable upper bounds are given by the 90 percentile values:

$$\ln \lambda_o \quad = \quad 7.10927 - 8.0868 \times 10^{-4}\, Q^2 H + 0.92549 \ln Q$$

$$\begin{aligned}E \quad &= \quad (0.3751 - 0.0149 \ln Q)\left(1 - \left(\frac{1.1}{DF}\right)^{0.5843}\right) \\ &\quad + \left(\frac{1.1}{DF}\right)^{0.2786}\end{aligned}$$

The differential equation for spray decontamination shown above was then integrated to produce plots of the time required to achieve specified levels of decontamination as a function of water flux. Such a plot using the median values of the decontamination coefficient is shown in Figure 2. Note that for a specific plant, the water flux axis could be changed to water flow or pump speed.

Table 2 Uncertain Parameters in the Calculations of Spray Decontamination Coefficients

Parameter	Range	Probability Density Function
Spray droplet size distribution	0 - 1	uniform
Pressure	1.1 - 9.0 atms	uniform
Partial pressure of steam in atmosphere	0.1 - 7.9 atms	uniform
Mean aerosol particle size	1.5 - 5.5 μm	uniform
Geometric standard deviation	1.6 - 3.7	uniform
Dynamic shape factor of aerosol	1 - 4	lognormal mean = 1.35 std. dev. = 3.04
Uncertainty in water surface tension	± 10%	uniform
Uncertainty in water density	0 - 0.05 g/cm^3	uniform
Uncertainty in gas viscosity	± 4%	uniform
Uncertainty in droplets shape model[b]	0 - 1	uniform
Uncertainty in droplet terminal velocity model[b]	0 - 1	uniform
Uncertainty in the model of flow regime for impaction and interception[b]	0 - 1	uniform
Uncertainty in the model of droplet coalescence efficiency[b]	0 - 1	uniform

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[b] Parameters associated with model uncertainties were used as switches to select or to interpolate between competing models.

V. CONCLUSIONS

Uncertainty analyses of detailed, mechanistic models of source term attenuation by sprays and water pools have been conducted using Monte Carlo methods. Selected percentiles in the uncertainty distributions have been correlated against quantities that will be known to operators during severe accidents. These simplified models have been used to create graphs that can be quickly used to estimate the potential effectiveness of sprays and water pools in accident management.

VI. NOMENCLATURE

C = Confidence that some particular fraction of the uncertainty range has been sampled

DF = decontamination factor

E = expression for the variation in the spray decontamination coefficient as decontamination progresses

H = pool depth or spray droplet fall distance (cm)

i = index

k = index

m = aerosol mass in the gas phase

n = number of Monte Carlo samples taken to meet the sampling criterion

p = sampled fraction of the uncertainty distribution

Pr( ) = probability that the expression within parentheses is true,

Q = spray water flux to the containment atmosphere ($\mathrm{cm^3\ H_2O/cm^{2\text{-}s}}$)

ΔT = Subcooling of the water pool (k)

x = bubble rise distance (cm)

Y_k = kth ordered result of the Monte Carlo uncertainty analysis

α = Volume of the containment not sprayed divided by the sprayed containment volume

α(diffusion) = coefficient for aerosol removal from bubbles by diffusion

α(impaction) = coefficient for aerosol removal from bubbles by inertial impaction

α(sedimentation) = coefficient for aerosol removal from bubbles by sedimentation

λ = spray decontamination coefficient

λ_o = spray decontamination coefficient when DF = 1.1

ξ_p = boundary of the pth quantile in the uncertainty distribution

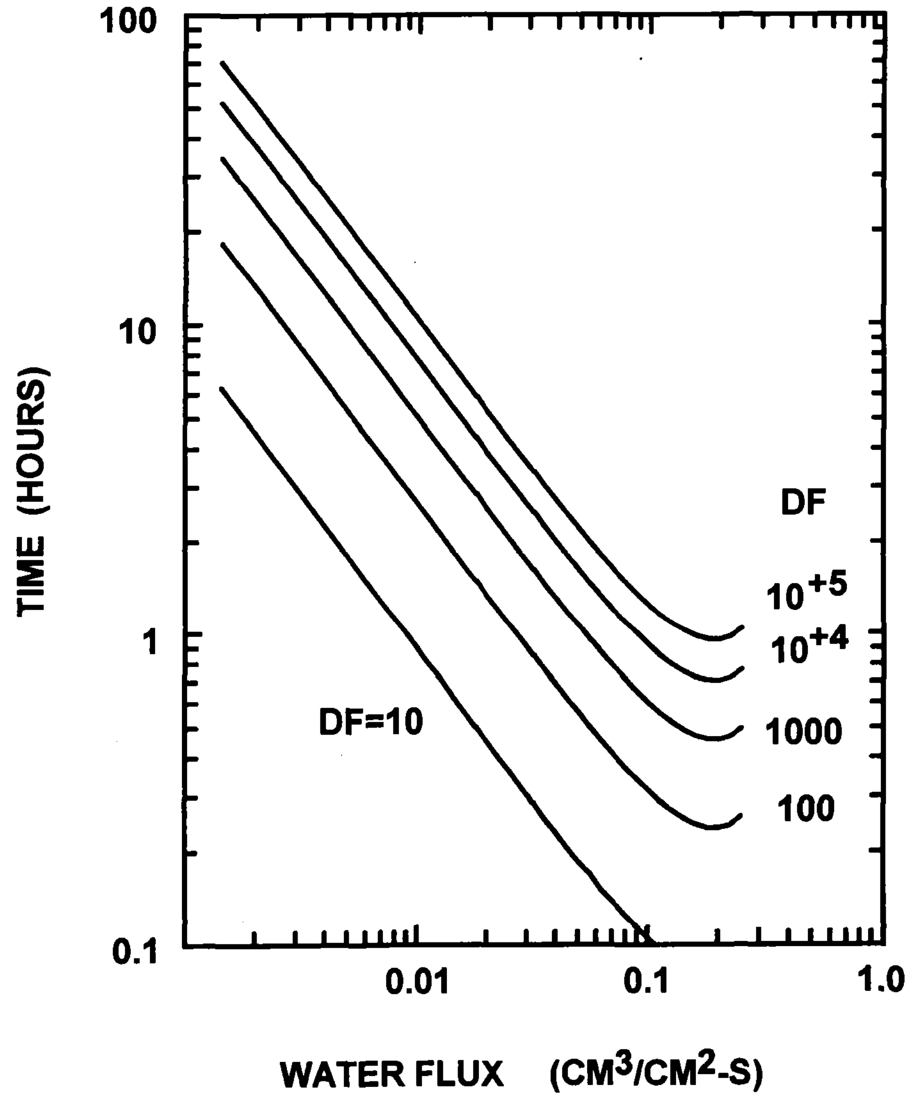

Figure 2 Median (Best Estimate) of Time Required for Sprays Operating at Various Flow Rates to Achieve Specified Levels of Atmosphere Decontamination.

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