TECHNICAL EVALUATION REPORT

MONTE CARLO UNCERTAINTY ANALYSIS OF AEROSOL BEHAVIOR IN THE AP600 REACTOR CONTAINMENT PART 2: FIXED BOUNDARY CONDITIONS AND A KNOWN SOURCE OF NONRADIOACTIVE AEROSOL

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ABSTRACT

A Monte Carlo uncertainty analysis of aerosol behavior in the containment of the AP600 reactor during a hypothetical 3BE accident is described. For this uncertainty analysis, boundary conditions of pressure, temperature, gas composition, steam condensation rates and heat removal rates were treated as certain. Also, the rate of nonradioactive aerosol generation during the period of in-vessel release of radionuclides (1800 to 6480 seconds) was fixed at 56.12728 g/s. Uncertainties in aerosol processes and aerosol properties were considered in the analyses. Uncertainty distributions for the decontamination factors and decontamination coefficients are compared to similar distributions obtained in a previous uncertainty analysis which included uncertainty in the nonradioactive source term. It is found that higher decontamination factors are obtained with the large, known nonradioactive source term. The effective decontamination coefficient during the period 6480 to 13680 seconds is most affected by the nonradioactive source. Most of the aerosol mass removal from the containment atmosphere takes place in this time interval. The median effective decontamination coefficient calculated for this period is quite similar to the time-averaged value of the decontamination coefficient obtained with the NAUAHYGROS computer code. Time-averaged values obtained with the NAUAHYGROS code for later times lie above the 90th percentile of uncertainty distributions calculated for the effective decontamination coefficients. The discrepancies between results of the uncertainty analyses and results obtained with the NAUAHYGROS code at late times affect removal of only the last 10 percent of the aerosol injected into the AP600 containment during the hypothesized accident. It is concluded that the Monte Carlo uncertainty analyses for aerosol behavior and NAUAHYGROS analyses of aerosol behavior will yield best-estimate results in substantial agreement provided that similar boundary conditions and source terms are assumed. Conservative values of the decontamination coefficients that would provide allowances for uncertainties in aerosol properties and processes are about a factor of 10-30% smaller than best-estimate values. These conservative values of the effective decontamination coefficient vary over a range of 0.265 to 0.435 hr^{-1} during the interval from 0 to 86450 seconds after the start of radionuclide release to the AP600 containment atmosphere. Highest values of the effective decontamination coefficient are achieved shortly after completion of in-vessel release of radionuclides to the containment atmosphere when both gravitational settling and diffusiophoresis are important, natural aerosol removal processes. At later times, the effective decontamination coefficient varies toward lower values according to the magnitude of forces driving diffusiophoretic deposition of aerosols.

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I. INTRODUCTION

In a previous report [1], results of a Monte Carlo uncertainty analysis of aerosol behavior in the containment of the AP600 reactor under the conditions of a specific accident (3BE [2]) were reported. Uncertainty distributions for the decontamination factors at selected times (1800, 6400, 13680, 49680, and 86450 seconds) and effective decontamination coefficients produced by natural aerosol processes were developed in this previous work. These uncertainty distributions considered uncertainties in a variety of physical phenomena and uncertainties in the release of nonradioactive aerosol to the containment, but kept fixed essential boundary conditions:

- containment pressure,
- containment atmosphere temperature,
- mole fraction steam in the containment atmosphere,
- rate of steam condensation from the atmosphere, and
- rate of heat removal from the containment atmosphere.

Uncertainty distributions for the effective decontamination coefficients were centered around values significantly less than either the instantaneous or the time-averaged "point" values calculated with the NAUAHYGROS code [2]. A comparison of the point values and the results of the Monte Carlo uncertainty analysis is shown in Figure 1. The solid line in this figure was obtained by linearly interpolating among the instantaneous values calculated with the NAUAHYGROS computer code. Time-averaged values of these instantaneous values are shown as open symbols in Figure 1. Median values of the effective decontamination coefficients found in the Monte Carlo uncertainty analysis are indicated by the X symbol. Bars on these symbols denote the 80 percent confidence intervals. The point values are shown to fall outside the 80 percent confidence intervals obtained in the uncertainty analysis.

It was hypothesized in Reference 1 that the higher values of the decontamination coefficients obtained with the NAUAHYGROS computer code might be the result of a large, assumed source of nonradioactive aerosol during the in-vessel release phase (1800 to 6480 seconds) of the accident. For the NAUAHYGROS code calculations, it was assumed that the nonradioactive aerosol mass would be about 3.62 times the mass of radioactive aerosol. In the Monte Carlo uncertainty analysis, the nonradioactive aerosol mass was taken to be uncertain. It was assumed that this nonradioactive aerosol mass was uniformly distributed over the interval of 0.5 to 2.0 times the mass of radioactive aerosol. There was, then, in all the calculations for the Monte Carlo uncertainty analysis less total aerosol mass than in the NAUAHYGROS calculations. Particles would not be able to grow as much in most of the Monte Carlo uncertainty analysis calculations as in the NAUAHYGROS calculation despite the fact that additional agglomeration mechanisms were included in the Monte Carlo calculations.

The calculations described in this report were undertaken to see if the additional nonradioactive aerosol mass was indeed responsible for the high values of the decontamination coefficients due to natural aerosol processes calculated with the NAUAHYGROS code [2]. The Monte Carlo uncertainty analysis was done exactly as

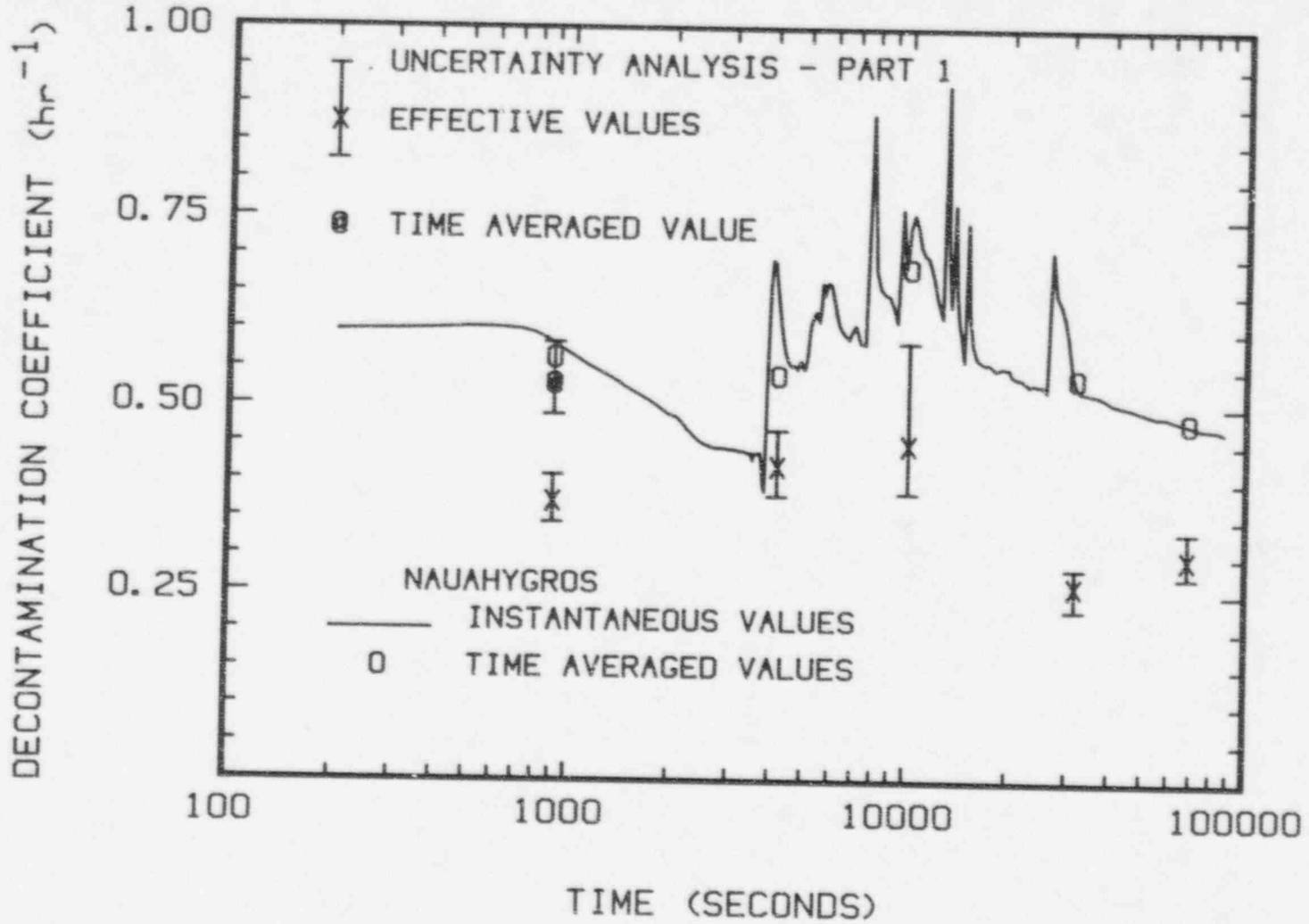

Figure 1. Comparison of Decontamination Coefficients Found in the Monte Carlo Uncertainty Analyses With Fixed Boundary Conditions and Uncertain Source Terms [1] to Results Obtained With the NAUAHYGROS code [2]. The solid line indicates instantaneous values calculated with NAUAHYGROS. Open symbols are the time averages of these instantaneous values. The X symbol and bars indicate the 90 percent confidence intervals for results of the uncertainty analysis.

described in the previous work except the nonradioactive aerosol mass over the interval from 0 to 1800 seconds was taken to be zero and over the interval from 1800 to 6480 seconds was taken to be 56.12728 g/s as it was in the analyses done with the NAUAHYGROS computer code.

The elemental releases of radionuclides in the Monte Carlo uncertainty analysis were taken to be the same as those assumed for the analyses with the NAUAHYGROS code. Specific chemical forms of the radionuclides were hypothesized for the NAUAHYGROS calculations. Chemical forms of the radionuclides in the AP600 reactor containment under the conditions of the specific accident were treated as uncertain in the Monte Carlo uncertainty analysis. The additional aerosol mass created because radionuclides react with gaseous species was then varied in the Monte Carlo uncertainty analyses.

Uncertainties due to physical properties of the aerosols and due to uncertainties in aerosol processes were treated in exactly the same way as was described in Reference 1.

II. RESULTS

Results of the calculations are uncertainty distributions for the decontamination factors at 1800, 6480, 13680, 49680, and 86450 seconds and effective decontamination coefficients for the time intervals 0-1800, 1800-6480, 6480-13680, 13680-49680, and 49680-86450 seconds. These uncertainty distributions were calculated as described in Reference 1. The uncertainty distributions are formulated as ranges of values of the decontamination factors or decontamination coefficients that to either the 90 percent or the 50 percent confidence level correspond to quantiles of the uncertainty distribution between 5 and 90 percent at 5 percent steps.

The detailed uncertainty distributions are collected in Appendix A of this report. In the remainder of the discussion of results, only selected values of the distribution are considered:

- the median or 50 percentile values (at 50 percent confidence) which are called the "best estimate values" here,
- the 90 percentile values (at 90 percent confidence) which are called "reasonable upper bound values" here, and
- the 10 percentile values (at 90 percent confidence) which are called "reasonable low bound values" here.

Mean values are also provided here though means of the uncertainty distributions developed here have no particular statistical significance.

The features of the uncertainty distributions for decontamination factors for materials released to the containment during the gap release phase and the in-vessel release phase of the 3BE reactor accident are shown in Table 1. The distributions found for the decontamination factors are essentially the same as those found in the previous work [1] at 1800 and at

Table 1. Features of the Uncertainty Distributions for Decontamination Factors Due to Natural Aerosol Processes

Time (s)	Decontamination Factor			
	Median (50 percentile*)	Upper Bound (90 percentile**)	Lower Bound (10 percentile**)	Mean+
GAP RELEASE				
1800	1.205 to 1.206	1.220 to 1.227	1.184 to 1.185	1.205
6480	2.095 to 2.102	2.209 to 2.267	1.921 to 1.973	2.094
13680	7.038 to 7.353	11.31 to 12.66	4.722 to 5.251	7.905
49680	134.7 to 138.4	222.8 to 265.4	66.04 to 79.87	148.7
86450	2903 to 3090	5524 to 6654	1099 to 1548	3409
IN-VESSEL RELEASE				
6480	1.263 to 1.265	1.286 to 1.297	1.225 to 1.237	1.263
13680	4.228 to 4.411	6.861 to 7.476	2.964 to 3.160	4.759
49680	79.54 to 83.82	133.6 to 156.4	41.67 to 47.76	89.25
86450	1761 to 1878	3236 to 3844	694.9 to 975.4	2032

*At 50 percent confidence.
**At 90 percent confidence.
+The mean has no particular statistical significance.

6480 seconds. Decontamination factors at later times are found to be much larger than was found in the previous uncertainty analysis. The additional aerosol mass from nonradioactive sources accentuates aerosol particle growth and consequently aerosol removal from the containment atmosphere particularly by gravitational settling.

The features of the uncertainty distributions for the effective decontamination coefficients are listed in Table 2. In examining these results, recognize that the formulation adopted here for the effective decontamination coefficient yields distinct values for the materials released during the gap release phase of an accident and for materials released during the in-vessel release phase for the time interval 1800 to 6480 seconds. Also note that the effective decontamination coefficient formulation includes the effect of the aerosol source which contaminates the atmosphere while other processes decontaminate the containment atmosphere. Consequently, the effective decontamination coefficients for gap release material over the time interval 0 to 1800 seconds and for in-vessel release material over the time interval 1800 to 6480 seconds are expected to be lower than instantaneous values of decontamination coefficients calculated in treatments that address the aerosol source and the aerosol removal processes separately.

The median decontamination coefficients calculated here assuming both fixed (not uncertain) boundary conditions and a fixed source of nonradioactive aerosols can be compared to median decontamination coefficients calculated previously assuming the same, fixed boundary conditions and an uncertain source of nonradioactive aerosol:

Time Interval(s)	Median (hr^{-1}) fixed boundary conditions and fixed nonrad source	Median (hr^{-1}) fixed boundary conditions and uncertain nonrad source
0-1800	0.374 ± 0.001	0.372 ± 0.001
1800 - 6480 (gap release)	0.426 ± 0.002	0.420 ± 0.002
1800 - 6480 (in-vessel release)	0.180 ± 0.001	0.178 ± 0.001
6480 - 13680	0.613 ± 0.010	0.449 ± 0.006
13680 - 49680	0.291 ± 0.002	0.260 ± 0.003
49680 - 86450	0.300 ± 0.001	0.298 ± 0.001

The median decontamination coefficients are sensibly identical for the time intervals 0 to 1800, 1800 to 6480, and 49680 to 86450 seconds. The median decontamination coefficients calculated here with a large, fixed source of nonradioactive aerosol are substantially larger for the time interval 6480 to 13680 seconds and somewhat larger for the interval 13680 to 49680 seconds. Again, the additional aerosol mass produced by the large nonradioactive source term during in-vessel release (1800 to 6480 seconds) accentuates particle growth and removal from the containment atmosphere. With time and continued decontamination of the atmosphere once the nonradioactive source has stopped, the effect disappears.

Table 2. Features of the Uncertainty Distributions for the Decontamination Coefficients Due to Natural Aerosol Processes

Time Interval (s)	λ_e, Effective Decontamination Coefficient (hr^{-1})			
	Median (50 percentile*)	Upper Bound (90 percentile**)	Lower Bound (10 percentile**)	Mean+
0-1800	0.373 to 0.375	0.398 to 0.410	0.337 to 0.349	0.373
1800-6480 (gap release)	0.424 to 0.427	0.456 to 0.472	0.374 to 0.389	0.424
1800-6400 (in-vessel release)	0.180 to 0.181	0.193 to 0.200	0.155 to 0.164	0.179
6480-13680	0.603 to 0.623	0.850 to 0.887	0.435 to 0.461	0.639
13680-49680	0.289 to 0.292	0.304 to 0.310	0.264 to 0.272	0.289
49680-86450	0.299 to 0.301	0.324 to 0.336	0.268 to 0.278	0.301

*At 50 percent confidence.
**At 90 percent confidence.
+The mean has no particular statistical significance.

The decontamination coefficients calculated here can be used to estimate the concentrations of various radionuclides in the AP600 reactor containment atmosphere during the 3BE accident. These estimates are shown in Figures 2 through 8. In each of the figures, the best estimate, which is assumed here to be the median or 50 percentile estimate, is shown as a solid line. Reasonable upper and lower bound concentrations are considered here to be indicated by the 90 and 10 percentile estimates which are shown as dashed lines in the figures.

The effective decontamination coefficients calculated here are compared to those calculated with the NAUAHYGROS model [2] in Figure 9. In this figure the decontamination coefficients calculated here are indicated by filled symbols. Bars on the filled symbols indicate the 80 percent confidence interval. The uncertainty distributions of the decontamination coefficients calculated here are compared in Table 3 to time-averaged values obtained from the NAUAHYGROS calculations. Note that the effective decontamination coefficient calculated for the 0 to 1800 second interval is not directly comparable to time-averaged values of the decontamination coefficient calculated with the NAUAHYGROS code. A separate set of Monte Carlo analyses were done to compute time-averaged decontamination coefficients that can be compared directly to values obtained with the NAUAHYGROS code. Results of these calculations for 0 to 1800 seconds are:

$$\lambda \text{ (median)} = 0.530 \pm 0.005 \text{ hr}^{-1}$$

$$\lambda \text{ (upper bound)} = 0.584 \pm 0.010 \text{ hr}^{-1}$$

$$\lambda \text{ (lower bound)} = 0.488 \pm 0.007 \text{ hr}^{-1}$$

$$\lambda \text{ (mean)} = 0.534 \text{ hr}^{-1}$$

These values may be compared to the time-averaged value for the 0 to 1800 second interval obtained with the NAUAHYGROS code, $\lambda = 0.564 \pm 0.007 \text{ hr}^{-1}$. It is evident that the model used for the Monte Carlo uncertainty analysis treats aerosol deposition early in an accident when diffusiophoresis is the dominant deposition process in a manner somewhat similar to the treatment in the NAUAHYGROS code.

During the interval 6480 to 13680 seconds when most of the mass removal takes place, the time-averaged value from the NAUAHYGROS calculation is quite similar to the median of the uncertainty distribution calculated here. The "point" value calculated from results obtained with the NAUAHYGROS code falls in the range characteristic of the 60th percentile of the uncertainty distribution. It is apparent, then, that for large aerosol particles that are removed predominantly by gravitational settling, the NAUAHYGROS computer code and the model used for the uncertainty analysis behave similarly. Most of the aerosol mass injected into the AP600 containment is deposited during the periods for which NAUAHYGROS and the uncertainty analyses yield similar results.

The cause of the high bias of point values of the decontamination factors at times after 13680 seconds has not been identified. Instantaneous values of the decontamination coefficient calculated for late times with the NAUAHYGROS computer code do not seem to follow closely the variations in the driving forces for particle deposition by phoretic

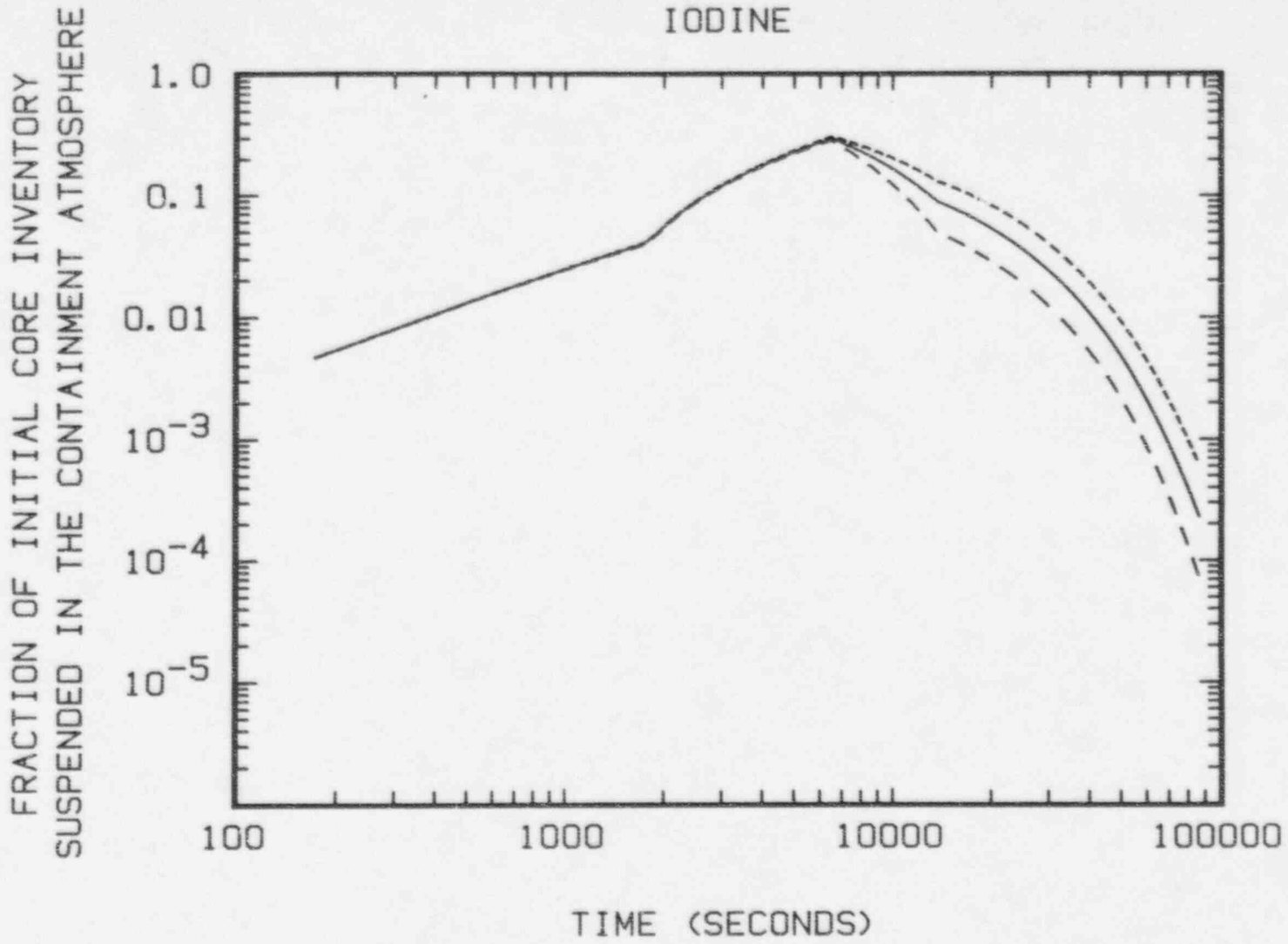

Figure 2. Predicted Iodine Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

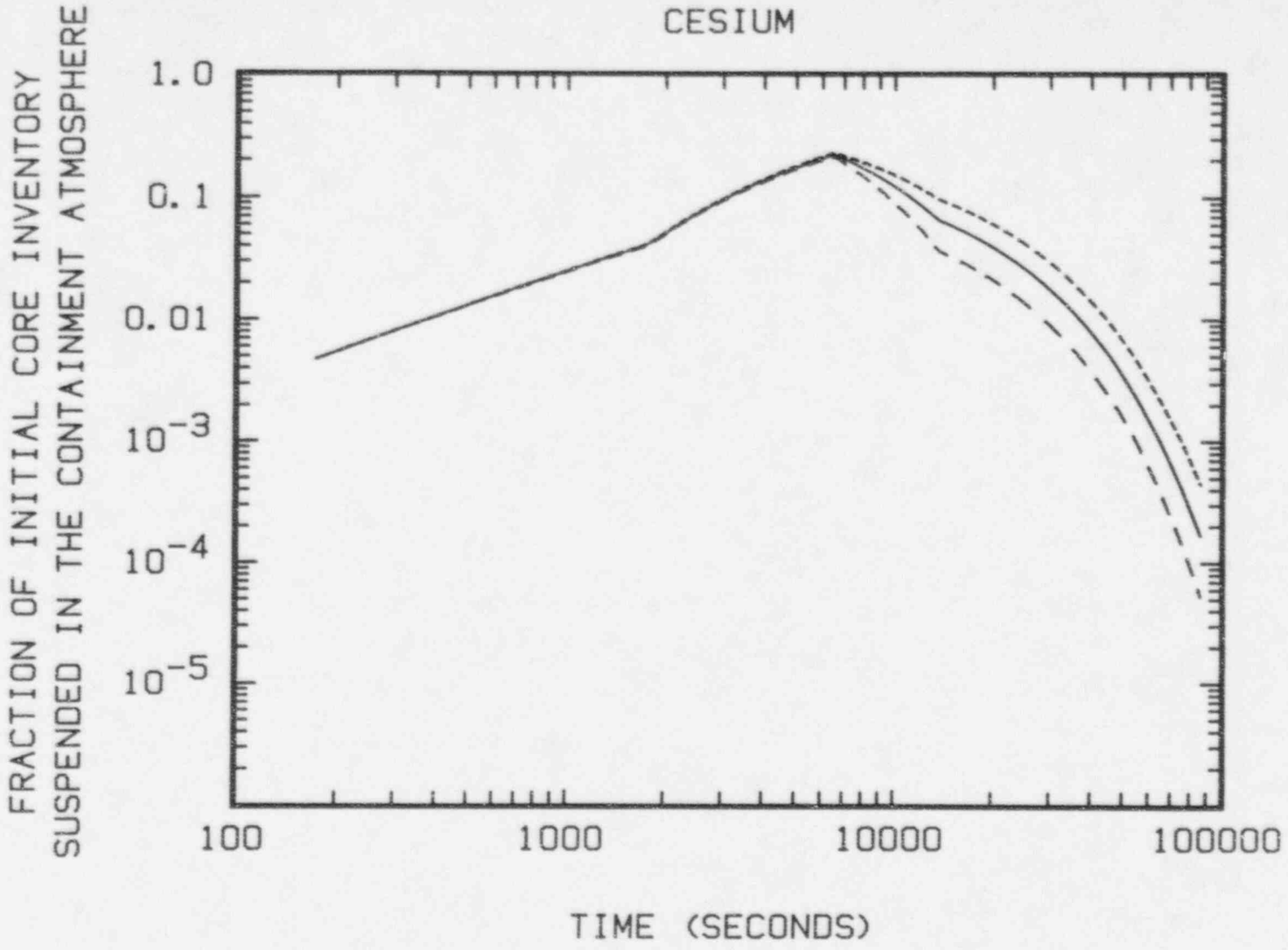

Figure 3. Predicted Cesium Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

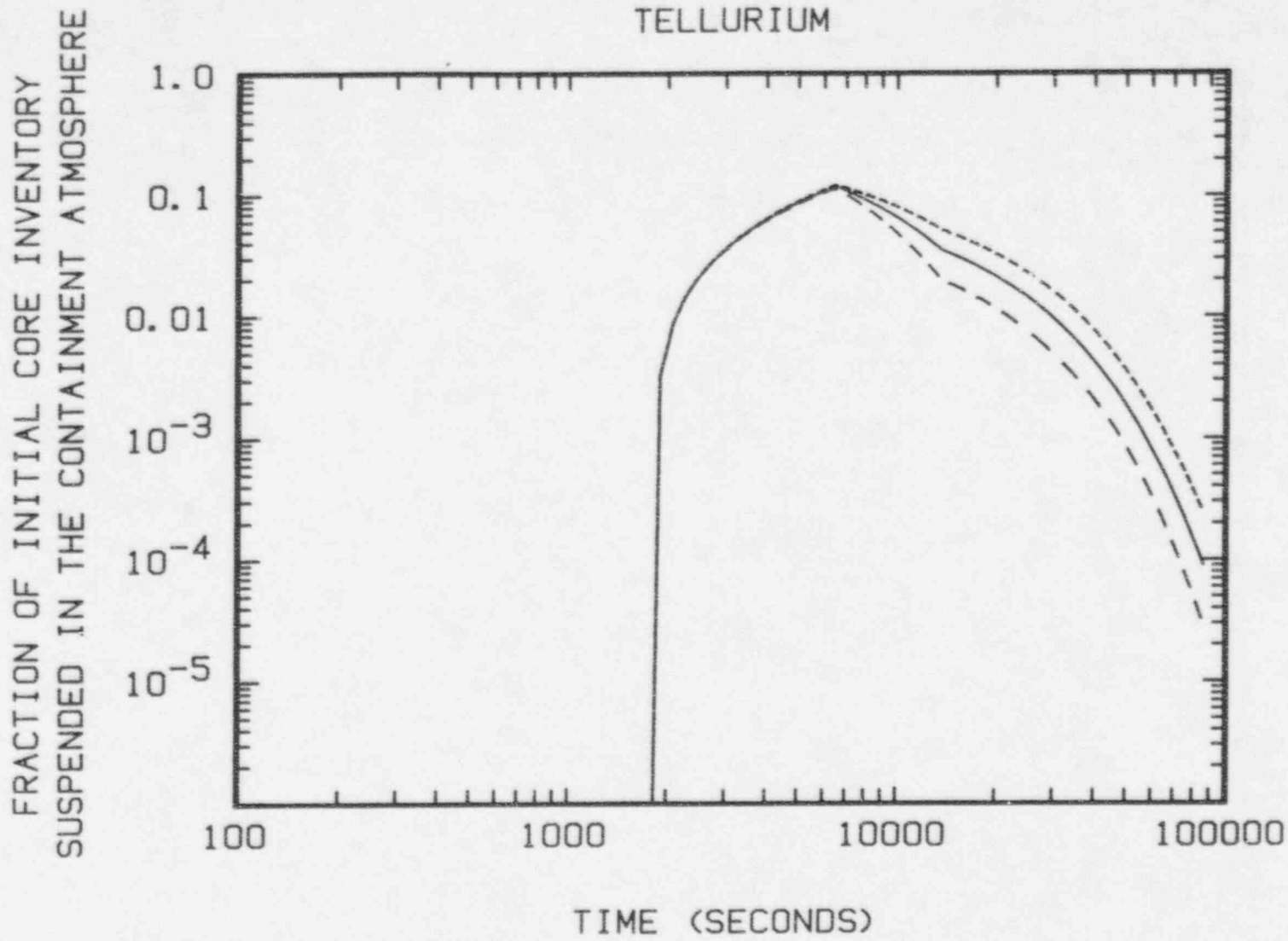

Figure 4. Predicted Tellurium Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

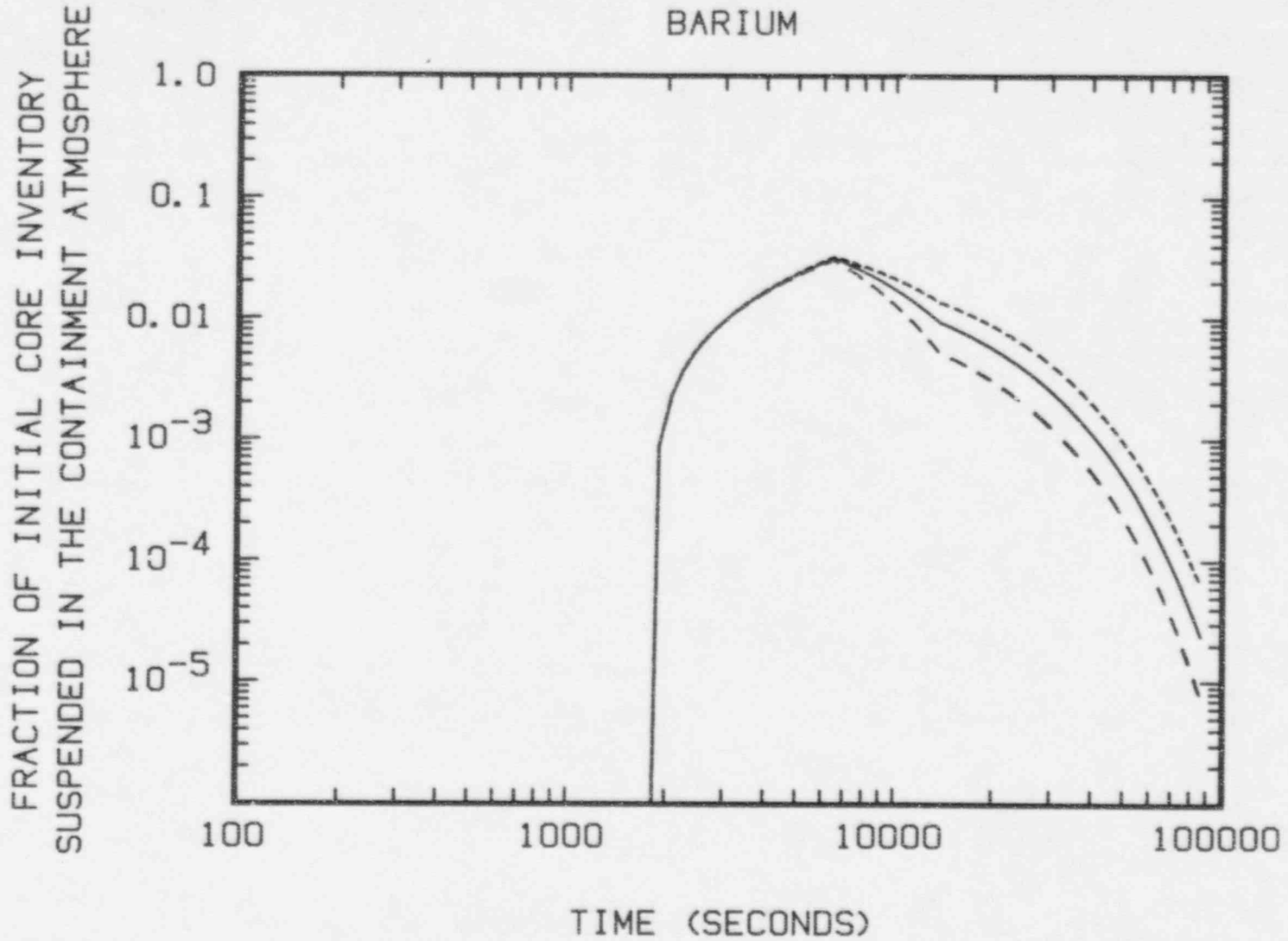

Figure 5. Predicted Barium Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

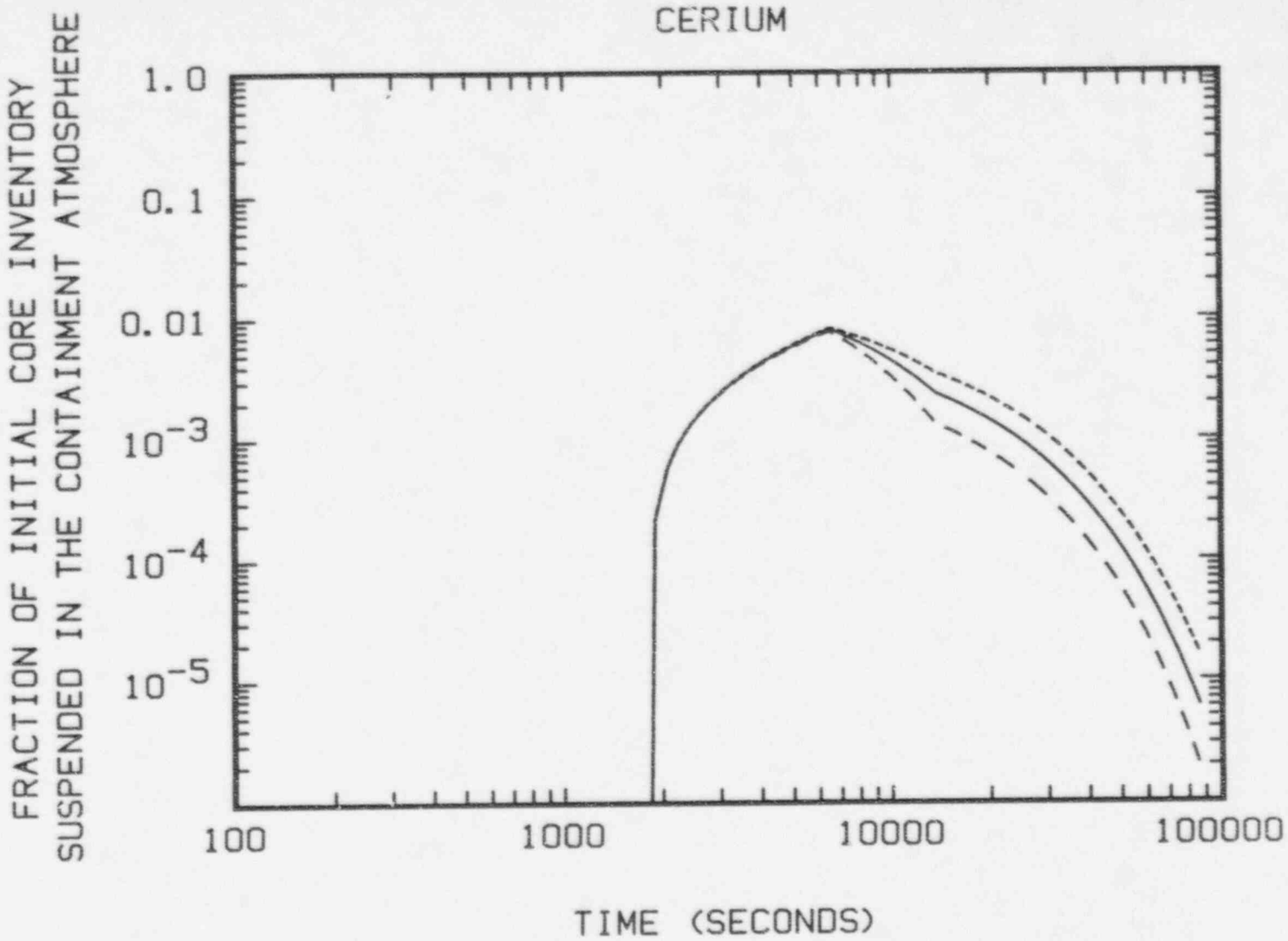

Figure 6. Predicted Cerium Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

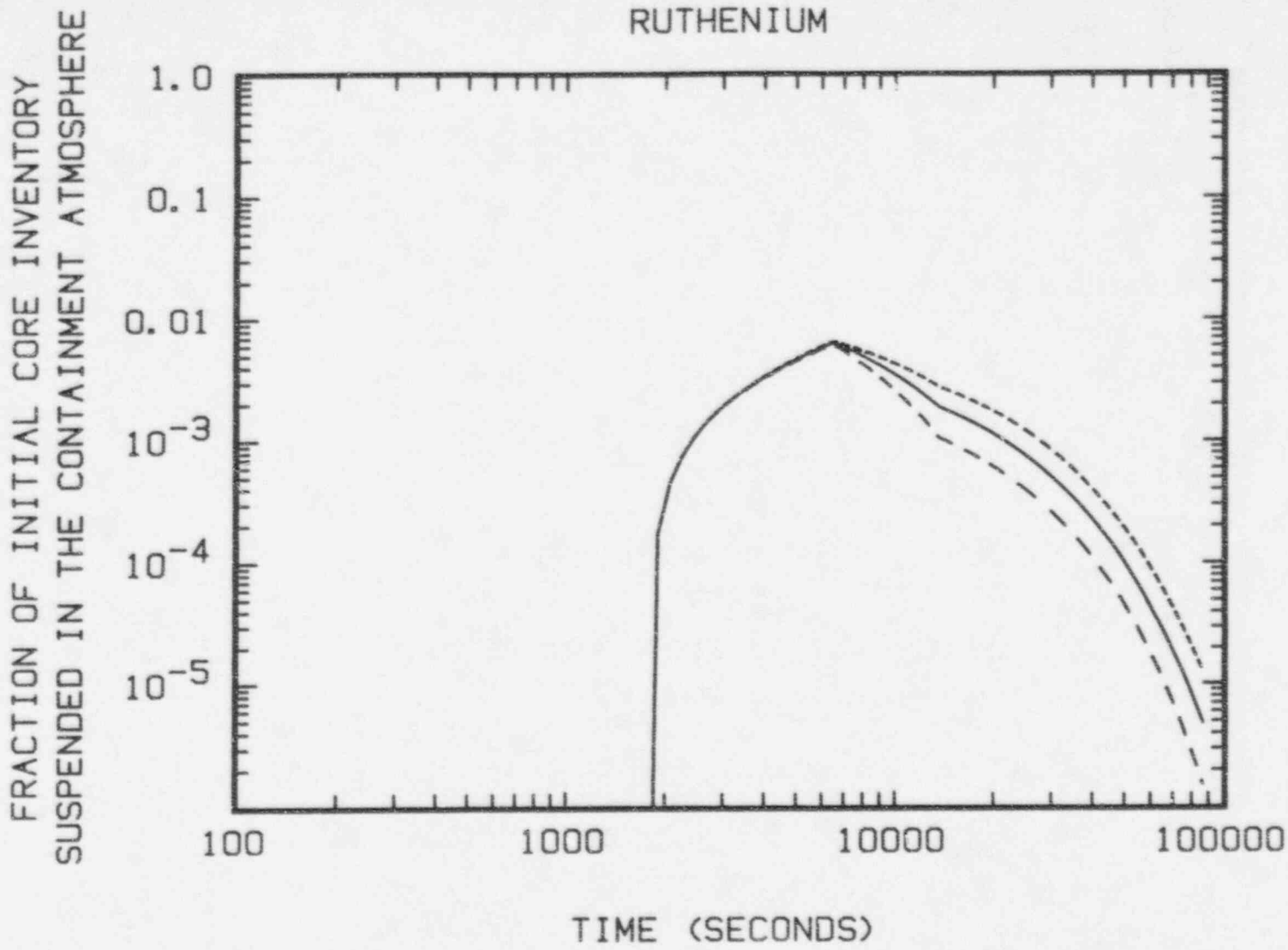

Figure 7. Predicted Ruthenium Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

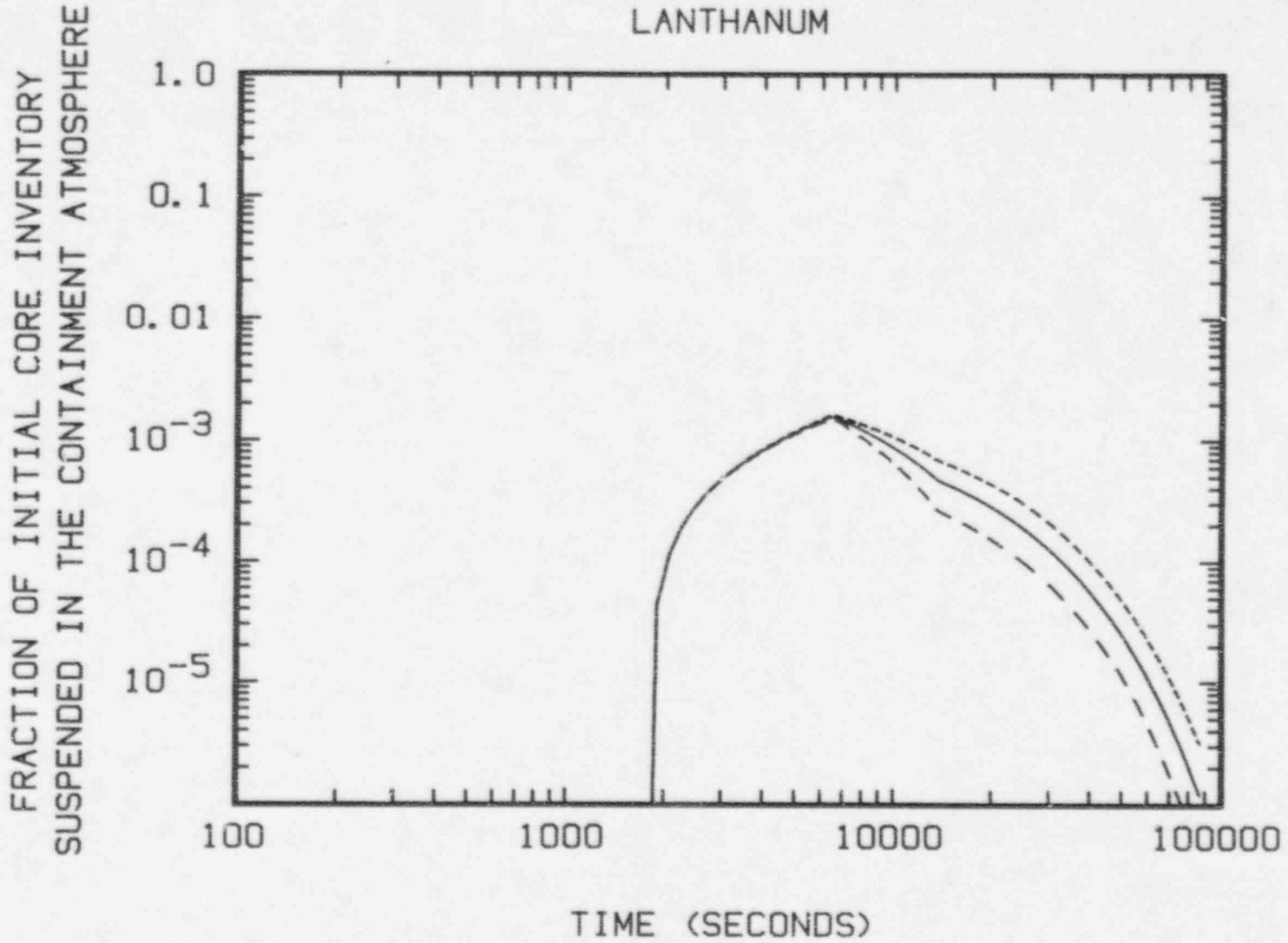

Figure 8. Predicted Lanthanum Concentration in the Containment Atmosphere as a Function of Time for the 3BE Accident at the AP600 Reactor. The solid line is the median estimate. The upper and lower dashed lines are the 90 and 10 percentile estimates.

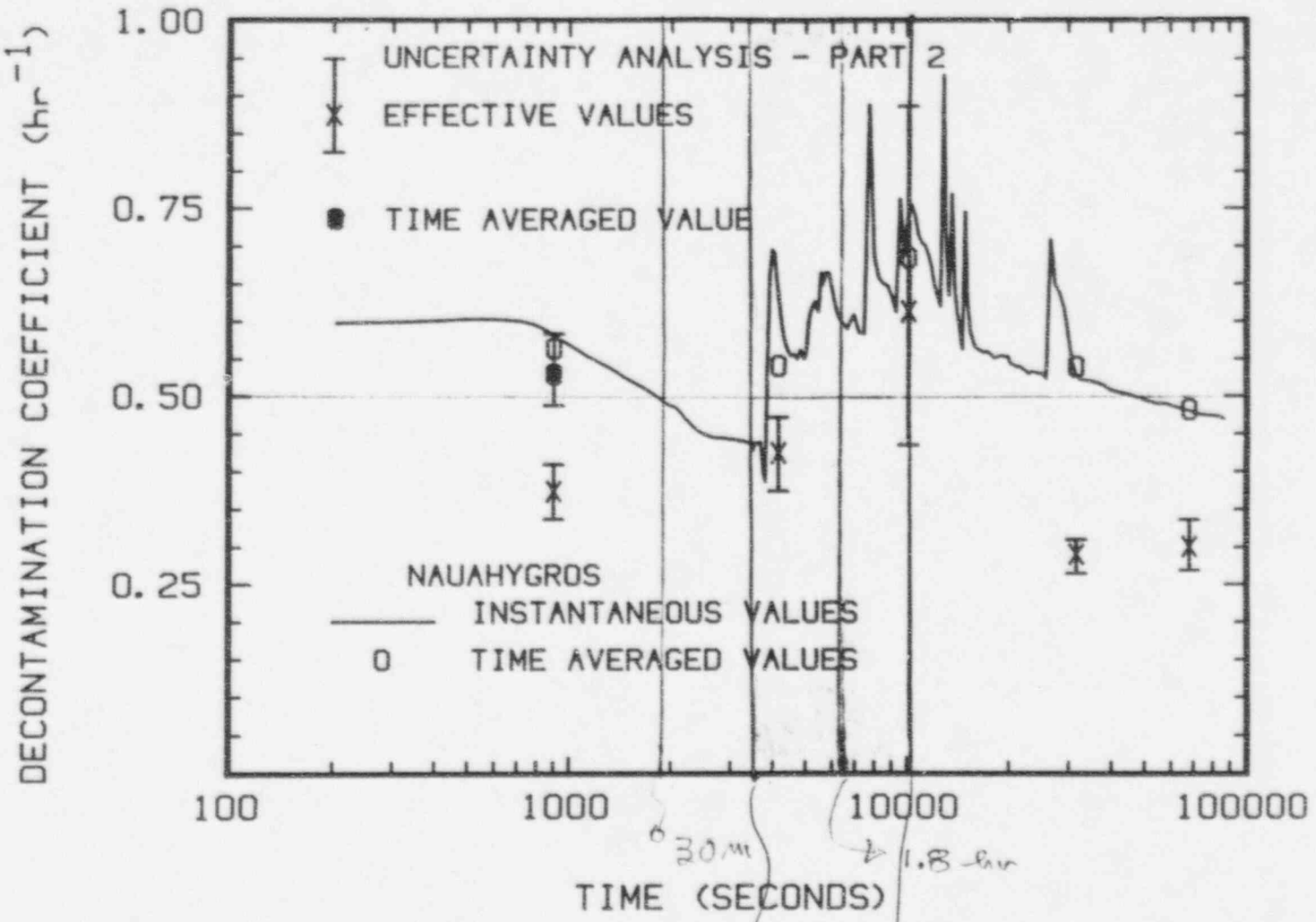

Figure 9. Comparison of Decontamination Coefficients Found in the Monte Carlo Uncertainty Analysis With Fixed Boundary Conditions and Fixed Nonradioactive Aerosol Source Term to Results Obtained With the NAUAHYGROS Code [2]. Results obtained in the calculations described in this report are indicated by filled symbols and bars. Other symbols are defined in Figure 1.

Table 3. Comparison of Uncertainty Distributions for the Decontamination Coefficients to Time-Averaged Values Calculated With the NAUAHYGROS Computer Code

Time Interval (s)	Time Averaged[+] λ_t (hr^{-1})	Upper Bound[(a)] λ_e (hr^{-1})	Median[(b)] λ_e (hr^{-1})	Lower Bound[(a)] λ_e (hr^{-1})
0-1800[*]	0.5645 ± 0.0074	0.404 ± 0.006	0.374 ± 0.001	0.343 ± 0.006
1800-6480	0.5410 ± 0.0091	0.464 ± 0.008	0.426 ± 0.002	0.382 ± 0.008
6480-13680	0.6849 ± 0.0152	0.869 ± 0.019	0.613 ± 0.010	0.448 ± 0.013
13680-49680	0.5392 ± 0.0082	0.307 ± 0.003	0.291 ± 0.002	0.268 ± 0.004
49680-86450	0.4816 ± 0.0032	0.330 ± 0.006	0.300 ± 0.001	0.273 ± 0.005

[*]Source operational during this period so the values of the effective decontamination coefficient, λ_e, are expected to be lower than the time average of instantaneous values, λ_t.

[+]From NAUAHYGROS results [1,2]; uncertainty range is the square root of the variance about the mean.

[(a)]90 percent confidence interval.

[(b)]50 percent confidence interval.

processes. Decontamination coefficients calculated for these late times with the model used for the Monte Carlo uncertainty analysis do vary with these driving forces. It appears, then, that the larger decontamination coefficients calculated with NAUAHYGROS are the results of some differences in the treatments of processes other than diffusiophoresis and thermophoresis. The most likely candidates are differences in the treatments of aerosol particle growth processes at low particle concentrations. The net effect of these differences is that the NAUAHYGROS code predicts somewhat faster removal of the last 10 percent of the aerosol mass injected into the containment than was found in the uncertainty analyses. Still, the uncertainty analyses indicate that about 99 percent of the aerosol has been removed from the atmosphere by 49680 seconds and more than 99.9 percent has been removed by 86450 seconds.

III. CONCLUSIONS

A Monte Carlo uncertainty analysis of aerosol behavior in the containment of the AP600 reactor during a hypothetical 3BE accident has been conducted assuming fixed (not uncertain) boundary conditions and a large, known source of nonradioactive aerosol as well as the radioactive aerosol releases specified in the Revised Severe Accident Source Term [3]. This uncertainty analysis supplements a previous analysis [1] based on similar boundary conditions and radioactive aerosol releases that treated the nonradioactive aerosol source term as uncertain. Both analyses supplement a preliminary analysis [4] that used uncertain, generic light water reactor accident boundary conditions.

Effective decontamination coefficients calculated in these three uncertainty analyses are compared in Table 4. Also shown in this table are the time-averaged decontamination coefficients calculated for the 3BE accident at AP600 with the NAUAHYGROS code. Comparison of the results of the previous analysis [1] and results of the preliminary analysis [4] shows that the unique thermal hydraulic boundary conditions predicted [2] to exist during an AP600 accident enhance aerosol removal from the containment atmosphere by natural processes. The enhanced rates of aerosol removal found in the previous uncertainty analysis [1] are, however, not as large as predicted with the NAUAHYGROS code. Including a large nonradioactive aerosol source term in the uncertainty analysis reported here yields best estimate (median) decontamination coefficients similar to point values calculated with the NAUAHYGROS code except at late times when most of the aerosol has been removed from the containment atmosphere.

These comparisons of results suggest that reasonable agreement on best-estimate decontamination coefficients can be obtained if agreements are reached on:

- boundary conditions (pressure, temperature, gas composition, steam condensation rates and heat removal rates) and
- sources of nonradioactive aerosols to the containment atmosphere.

Further exploration of the treatments of aerosol properties and processes could improve the agreement among calculated values of the decontamination coefficients. Such efforts are,

Table 4. Comparison of Effective Decontamination Coefficients From Various Analyses

Time Interval (seconds)	Median, λ_e (50), and 10 to 90 Percentile Range From: Preliminary Analysis [4]* (hr^{-1})	Previous Analysis [1]** (hr^{-1})	This Work+ (hr^{-1})	Time-Averaged Decontamination Coefficient from NAUAHYGROS (hr^{-1})
0 - 1800	0.034 (0.024 to 0.043)	0.372 (0.336 to 0.413)	0.374 (0.337 to 0.410)	0.564 ± 0.007
1800 - 6480	0.073 (0.054 to 0.102)	0.420 (0.368 to 0.479)	0.425 (0.374 to 0.472)	0.541 ± 0.009
6480 - 13680	0.170 (0.076 to 0.418)	0.449 (0.371 to 0.604)	0.613 (0.435 to 0.887)	0.685 ± 0.015
13680 - 49680	0.091 (0.085 to 0.101)	0.260 (0.225 to 0.290)	0.290 (0.264 to 0.310)	0.539 ± 0.008
49680 - 86450	0.038 (0.027 to 0.052)	0.298 (0.267 to 0.340)	0.300 (0.268 to 0.336)	0.482 ± 0.003

*Uncertain, generic LWR boundary conditions and geometry; uncertain nonradioactive source term.
**AP600 geometry, 3BE boundary conditions, and uncertain nonradioactive source term.
+ AP600 geometry, 3BE boundary conditions, and known nonradioactive source term.

however, less important since most of the aerosol mass is removed during the accident period for which the NAUAHYGROS calculations and the Monte Carlo uncertainty analyses yield similar best-estimate values.

There are uncertainties in aerosol properties and aerosol processes that do affect predictions of decontamination coefficients associated with natural aerosol processes in the AP600 containment atmosphere. Reasonable lower bound values of the decontamination coefficients are about [redacted] as large as the best-estimate values based on the current understanding of aerosol properties and processes in reactor accidents. The discrepancy between lower bound (10 percentile) and best-estimate (50 percentile) values of the effective decontamination coefficients can be narrowed only when there is a better understanding of aerosol processes (for example, collision factors and turbulent processes) and aerosol properties (for example, shape factors, accommodation coefficients, and slip correction factors) during accidents hypothesized to occur in the AP600 reactor.

IV. REFERENCES

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2. Letter from N. J. Liparulo to T. R. Quay, entitled "Information Requested by RAI [redacted] Regarding Input Parameters for the Calculation of Aerosol Removal Coefficients," NTD-NRC-95-4430, DCP/NRC0302 Docket No.: STN-52-003, April 7, 1995.

3. L. Soffer et al., Accident Source Terms for Light-Water Nuclear Power Plants, NUREG-1465 U.S. Nuclear Regulatory Commission, Washington, D.C., 1995.

4. D. A. Powers, K. E. Washington, S. B. Burson, and J. L. Sprung, A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containments, NUREG/CR-6189, SAND94-0407, Sandia National Laboratories, Albuquerque, NM, September 1995.

APPENDIX A. DETAILED UNCERTAINTY DISTRIBUTIONS

The detailed uncertainty distributions for the decontamination factors and the effective decontamination coefficients calculated for this report are listed in Tables A-1 to A-15. Table A-16 is a tabulation of the uncertainty distribution for the time-averaged value of the decontamination coefficient for the period 0 to 1800 seconds. These distributions were developed from the results of the Monte Carlo sampling using nonparametric order statistics. The distributions are presented as the range of values characteristic of specified percentiles of a cumulative distribution. Percentiles are specified at 5 percent intervals from 5 to 95 percent. Ranges of values characteristic of these percentiles must be specified because only a finite number of samples (typically 180) were collected in the Monte Carlo uncertainty analysis. The ranges can be narrowed by further sampling, but they narrow with increasing values of the square root of the number of samples taken. In general, ranges found in this work are narrow enough that they do not complicate the interpretation of the results.

The ranges are tabulated at two confidence levels—90 percent and 50 percent. At the 90 percent confidence level there is a 90 percent confidence that the true value of the uncertain parameter indicative of the specified percentile of the cumulative distribution lies within the quoted range and a 10 percent probability that it is at either a higher or lower value. The narrower ranges at the 50 percent confidence level can be similarly interpreted.

Mean values of the sample sets are also listed in the tables. These mean values do not have any particular statistical significance for the uncertainty distributions found in this work. It is usually found that the mean is quite near the median (50 percentile) of a distribution.

Table A-1. Uncertainty Distribution for the Gap Release Decontamination Factor at 1800 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	1.181 to 1.185	1.181 to 1.183
10	1.184 to 1.191	1.187 to 1.189
15	1.188 to 1.194	1.190 to 1.192
20	1.192 to 1.197	1.192 to 1.195
25	1.194 to 1.199	1.196 to 1.198
30	1.197 to 1.201	1.198 to 1.199
35	1.199 to 1.203	1.199 to 1.201
40	1.200 to 1.205	1.201 to 1.203
45	1.202 to 1.206	1.203 to 1.205
50	1.204 to 1.207	1.205 to 1.206
55	1.205 to 1.208	1.206 to 1.207
60	1.207 to 1.209	1.207 to 1.208
65	1.207 to 1.212	1.208 to 1.210
70	1.209 to 1.215	1.210 to 1.213
75	1.211 to 1.216	1.213 to 1.215
80	1.215 to 1.219	1.215 to 1.218
85	1.217 to 1.224	1.218 to 1.220
90	1.220 to 1.227	1.223 to 1.226
95	1.226 to 1.230	1.228 to 1.229
	Mean = 1.205	

Table A-2. Uncertainty Distribution for the Gap Release Decontamination Factor at 6480 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	1.904 to 1.939	1.908 to 1.918
10	1.921 to 1.973	1.941 to 1.959
15	1.955 to 2.007	1.969 to 1.990
20	1.982 to 2.023	2.003 to 2.015
25	2.001 to 2.046	2.018 to 2.034
30	2.022 to 2.062	2.037 to 2.056
35	2.042 to 2.073	2.056 to 2.063
40	2.059 to 2.087	2.063 to 2.077
45	2.065 to 2.099	2.077 to 2.096
50	2.083 to 2.106	2.095 to 2.102
55	2.096 to 2.114	2.102 to 2.108
60	2.103 to 2.128	2.108 to 2.117
65	2.112 to 2.144	2.117 to 2.137
70	2.123 to 2.165	2.138 to 2.150
75	2.142 to 2.180	2.152 to 2.171
80	2.164 to 2.203	2.174 to 2.189
85	2.181 to 2.236	2.192 to 2.210
90	2.209 to 2.267	2.229 to 2.260
95	2.262 to 2.292	2.268 to 2.285
	Mean = 2.094	

Table A-3. Uncertainty Distribution for the Gap Release Decontamination Factor at 13680 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	4.423 to 4.840	4.606 to 4.712
10	4.722 to 5.251	4.871 to 5.085
15	5.041 to 5.474	5.223 to 5.360
20	5.312 to 5.794	5.418 to 5.596
25	5.490 to 6.072	5.629 to 5.988
30	5.786 to 6.315	5.997 to 6.131
35	6.068 to 6.625	6.139 to 6.352
40	6.208 to 6.816	6.357 to 6.669
45	6.450 to 7.252	6.670 to 7.040
50	6.715 to 7.736	7.038 to 7.353
55	7.117 to 8.072	7.352 to 7.770
60	7.512 to 8.870	7.772 to 8.303
65	7.822 to 9.543	8.331 to 8.940
70	8.514 to 9.893	8.969 to 9.648
75	9.281 to 10.44	9.677 to 10.00
80	9.802 to 10.09	10.02 to 10.70
85	10.48 to 11.89	10.96 to 11.50
90	11.31 to 12.66	11.86 to 12.19
95	12.29 to 13.39	12.72 to 13.15
	Mean = 7.905	

Table A-4. Uncertainty Distribution for the Gap Release Decontamination Factor at 49680 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	57.90 to 68.73	61.72 to 65.92
10	66.04 to 79.87	69.19 to 74.68
15	73.95 to 87.59	79.58 to 82.04
20	80.57 to 98.53	84.67 to 90.20
25	89.00 to 106.7	93.30 to 101.0
30	97.36 to 111.0	102.1 to 108.2
35	106.5 to 120.2	108.4 to 112.4
40	109.1 to 129.2	112.6 to 122.6
45	115.1 to 137.5	122.6 to 134.7
50	125.0 to 144.7	134.7 to 138.4
55	136.1 to 153.8	138.4 to 147.6
60	141.4 to 172.8	147.6 to 158.7
65	149.3 to 185.4	159.5 to 176.5
70	163.6 to 194.0	176.6 to 188.4
75	181.5 to 206.8	189.7 to 197.2
80	193.8 to 221.1	200.6 to 217.3
85	209.8 to 233.8	219.6 to 227.4
90	222.8 to 265.4	233.3 to 241.9
95	248.7 to 306.8	266.9 to 291.8
	Mean = 148.7	

Table A-5. Uncertainty Distribution for the Gap Release Decontamination Factor at 86450 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	928.6 to 1132	1007 to 1090
10	1099 to 1548	1185 to 1378
15	1354 to 1803	1441 to 1671
20	1642 to 1969	1696 to 1864
25	1810 to 2199	1882 to 2036
30	1951 to 2413	2051 to 2266
35	2101 to 2586	2275 to 2513
40	2344 to 2848	2524 to 2665
45	2555 to 3024	2668 to 2903
50	2705 to 3233	2903 to 3090
55	2934 to 3426	3090 to 3258
60	3155 to 3614	3259 to 3490
65	3312 to 4082	3494 to 3661
70	3524 to 4526	3667 to 4245
75	3811 to 4753	4269 to 4622
80	4487 to 5431	4693 to 5108
85	4758 to 5892	5278 to 5596
90	5524 to 6654	5779 to 6169
95	6379 to 9303	6801 to 7608
	Mean = 3409	

Table A-6. Uncertainty Distribution for the In-Vessel Release Decontamination Factor at 6480 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	1.220 to 1.227	1.221 to 1.224
10	1.225 to 1.237	1.227 to 1.235
15	1.232 to 1.245	1.237 to 1.242
20	1.239 to 1.248	1.244 to 1.246
25	1.245 to 1.253	1.246 to 1.250
30	1.248 to 1.257	1.250 to 1.255
35	1.252 to 1.259	1.255 to 1.257
40	1.256 to 1.262	1.258 to 1.260
45	1.258 to 1.265	1.260 to 1.263
50	1.261 to 1.267	1.263 to 1.265
55	1.264 to 1.269	1.265 to 1.268
60	1.266 to 1.272	1.268 to 1.269
65	1.268 to 1.273	1.269 to 1.272
70	1.270 to 1.278	1.273 to 1.275
75	1.273 to 1.282	1.276 to 1.280
80	1.278 to 1.285	1.281 to 1.283
85	1.282 to 1.292	1.284 to 1.287
90	1.286 to 1.297	1.289 to 1.296
95	1.296 to 1.302	1.298 to 1.302
	Mean = 1.263	

Table A-7. Uncertainty Distribution for the In-Vessel Release Decontamination Factor at 13680 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	2.821 to 2.996	2.899 to 2.954
10	2.964 to 3.160	3.005 to 3.119
15	3.104 to 3.356	3.142 to 3.267
20	3.200 to 3.458	3.312 to 3.415
25	3.358 to 3.616	3.420 to 3.504
30	3.446 to 3.782	3.525 to 3.680
35	3.573 to 3.987	3.688 to 3.819
40	3.719 to 4.133	3.824 to 4.032
45	3.900 to 4.351	4.034 to 4.229
50	4.070 to 4.606	4.228 to 4.411
55	4.260 to 4.899	4.411 to 4.672
60	4.457 to 5.290	4.675 to 5.000
65	4.743 to 5.539	5.010 to 5.416
70	5.214 to 6.008	5.433 to 5.655
75	5.523 to 6.233	5.759 to 6.088
80	5.929 to 6.783	6.166 to 6.487
85	6.285 to 7.261	6.582 to 6.926
90	6.861 to 7.476	7.192 to 7.376
95	7.408 to 7.949	7.518 to 7.789
	Mean = 4.759	

Table A-8. Uncertainty Distribution for the In-Vessel Release Decontamination Factor at 49680 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	36.50 to 42.76	38.57 to 41.48
10	41.67 to 47.76	43.39 to 45.95
15	45.72 to 53.75	47.50 to 50.19
20	48.38 to 59.38	52.10 to 55.56
25	53.85 to 63.96	55.73 to 60.97
30	58.38 to 67.01	61.18 to 64.67
35	63.04 to 72.02	64.79 to 68.03
40	66.09 to 77.35	68.25 to 73.39
45	70.61 to 82.78	73.43 to 79.58
50	74.64 to 87.96	79.54 to 83.82
55	81.04 to 93.23	83.78 to 88.46
60	86.34 to 105.3	88.48 to 97.79
65	89.05 to 112.0	97.88 to 105.7
70	99.49 to 117.8	106.2 to 113.6
75	108.9 to 125.1	114.1 to 119.8
80	116.6 to 130.9	120.9 to 128.3
85	125.6 to 140.6	129.7 to 134.0
90	133.6 to 156.4	138.5 to 146.1
95	149.3 to 175.8	157.1 to 168.5
	Mean = 89.25	

Table A-9. Uncertainty Distribution for the In-Vessel Release Decontamination Factor at 86450 Seconds

Percentile	Values of the Decontamination Factor Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	585.6 to 719.9	640.4 to 685.1
10	594.9 to 975.4	747.5 to 862.6
15	835.8 to 1102	891.5 to 1019
20	1000 to 1198	1029 to 1150
25	1107 to 1349	1154 to 1232
30	1176 to 1456	1244 to 1386
35	1278 to 1584	1390 to 1526
40	1424 to 1722	1528 to 1620
45	1547 to 1859	1620 to 1761
50	1649 to 1926	1761 to 1878
55	1800 to 2019	1878 to 1964
60	1891 to 2140	1965 to 2041
65	1993 to 2379	2049 to 2175
70	2097 to 2679	2183 to 2517
75	2333 to 2862	2555 to 2773
80	2675 to 3175	2813 to 3069
85	2865 to 3421	3133 to 3305
90	3236 to 3844	3373 to 3634
95	3786 to 5332	3924 to 4396
	Mean = 2032	

Table A-10. Uncertainty Distribution for the Effective Decontamination Coefficient During the Interval 0 to 1800 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.332 to 0.340	0.333 to 0.335
10	0.337 to 0.349	0.342 to 0.346
15	0.345 to 0.354	0.348 to 0.352
20	0.350 to 0.359	0.352 to 0.356
25	0.355 to 0.363	0.357 to 0.362
30	0.359 to 0.366	0.362 to 0.363
35	0.362 to 0.369	0.364 to 0.367
40	0.364 to 0.372	0.367 to 0.370
45	0.367 to 0.374	0.370 to 0.373
50	0.371 to 0.376	0.373 to 0.375
55	0.373 to 0.378	0.375 to 0.377
60	0.376 to 0.380	0.377 to 0.378
65	0.377 to 0.384	0.378 to 0.381
70	0.379 to 0.389	0.381 to 0.386
75	0.383 to 0.392	0.386 to 0.390
80	0.389 to 0.396	0.390 to 0.394
85	0.392 to 0.404	0.394 to 0.399
90	0.398 to 0.410	0.402 to 0.407
95	0.408 to 0.414	0.410 to 0.412
	Mean = 0.373 hr^{-1}	

Table A-11. Uncertainty Distribution for the Effective Decontamination Coefficient for Gap Release Material During the Interval 1800 to 6480 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.367 to 0.378	0.368 to 0.373
10	0.374 to 0.389	0.379 to 0.385
15	0.383 to 0.399	0.388 to 0.395
20	0.390 to 0.405	0.398 to 0.402
25	0.399 to 0.411	0.403 to 0.406
30	0.404 to 0.416	0.407 to 0.414
35	0.409 to 0.419	0.414 to 0.417
40	0.415 to 0.423	0.417 to 0.420
45	0.418 to 0.426	0.420 to 0.424
50	0.421 to 0.429	0.424 to 0.427
55	0.425 to 0.431	0.427 to 0.430
60	0.427 to 0.435	0.430 to 0.432
65	0.431 to 0.439	0.432 to 0.436
70	0.434 to 0.445	0.436 to 0.441
75	0.438 to 0.449	0.442 to 0.447
80	0.444 to 0.455	0.447 to 0.452
85	0.449 to 0.464	0.452 to 0.457
90	0.456 to 0.472	0.462 to 0.470
95	0.470 to 0.479	0.472 to 0.477
	Mean = 0.424 hr^{-1}	

Table A-12. Uncertainty Distribution for the Effective Decontamination Coefficient of In-Vessel Release Material During the Interval 1800 to 6480 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.153 to 0.157	0.153 to 0.155
10	0.155 to 0.164	0.157 to 0.162
15	0.160 to 0.168	0.164 to 0.166
20	0.164 to 0.170	0.168 to 0.169
25	0.168 to 0.174	0.169 to 0.172
30	0.170 to 0.176	0.172 to 0.175
35	0.172 to 0.177	0.175 to 0.176
40	0.175 to 0.179	0.176 to 0.178
45	0.176 to 0.181	0.178 to 0.180
50	0.178 to 0.182	0.180 to 0.181
55	0.180 to 0.183	0.181 to 0.182
60	0.181 to 0.185	0.182 to 0.183
65	0.183 to 0.186	0.183 to 0.185
70	0.184 to 0.189	0.186 to 0.187
75	0.186 to 0.191	0.188 to 0.190
80	0.188 to 0.193	0.190 to 0.192
85	0.191 to 0.197	0.192 to 0.194
90	0.193 to 0.200	0.195 to 0.199
95	0.200 to 0.203	0.200 to 0.203
	Mean = 0.179 hr^{-1}	

Table A-13. Uncertainty Distribution for the Effective Decontamination Coefficient During the Interval 6480 to 13680 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.417 to 0.441	0.424 to 0.434
10	0.435 to 0.461	0.443 to 0.454
15	0.453 to 0.487	0.459 to 0.477
20	0.468 to 0.506	0.482 to 0.491
25	0.487 to 0.525	0.493 to 0.513
30	0.503 to 0.545	0.514 to 0.533
35	0.518 to 0.576	0.534 to 0.549
40	0.541 to 0.594	0.549 to 0.584
45	0.566 to 0.615	0.585 to 0.603
50	0.585 to 0.644	0.603 to 0.623
55	0.609 to 0.678	0.623 to 0.653
60	0.628 to 0.717	0.653 to 0.692
65	0.662 to 0.738	0.693 to 0.726
70	0.703 to 0.779	0.726 to 0.746
75	0.734 to 0.800	0.752 to 0.788
80	0.771 to 0.837	0.790 to 0.819
85	0.804 to 0.868	0.828 to 0.858
90	0.850 to 0.887	0.865 to 0.876
95	0.880 to 0.913	0.890 to 0.906
	Mean = 0.639 hr^{-1}	

Table A-14. Uncertainty Distribution for the Effective Decontamination Coefficient During the Interval 13680 to 49680 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.257 to 0.266	0.260 to 0.264
10	0.264 to 0.272	0.266 to 0.269
15	0.268 to 0.276	0.272 to 0.274
20	0.273 to 0.281	0.275 to 0.279
25	0.277 to 0.283	0.279 to 0.282
30	0.281 to 0.286	0.282 to 0.284
35	0.282 to 0.288	0.285 to 0.286
40	0.285 to 0.289	0.286 to 0.288
45	0.287 to 0.291	0.288 to 0.289
50	0.288 to 0.293	0.289 to 0.292
55	0.290 to 0.294	0.292 to 0.293
60	0.292 to 0.296	0.293 to 0.295
65	0.294 to 0.298	0.295 to 0.296
70	0.295 to 0.298	0.296 to 0.298
75	0.297 to 0.300	0.298 to 0.299
80	0.298 to 0.303	0.299 to 0.302
85	0.300 to 0.306	0.303 to 0.305
90	0.304 to 0.310	0.306 to 0.308
95	0.309 to 0.315	0.311 to 0.312
	Mean = 0.289 hr^{-1}	

Table A-15. Uncertainty Distribution for the Effective Decontamination Coefficient During the Interval 49680 to 86450 Seconds

Percentile	Values of the Effective Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.262 to 0.270	0.264 to 0.266
10	0.268 to 0.278	0.270 to 0.276
15	0.273 to 0.283	0.278 to 0.280
20	0.279 to 0.287	0.281 to 0.284
25	0.283 to 0.291	0.285 to 0.288
30	0.286 to 0.294	0.289 to 0.291
35	0.290 to 0.297	0.292 to 0.296
40	0.292 to 0.299	0.295 to 0.297
45	0.296 to 0.301	0.297 to 0.299
50	0.298 to 0.303	0.299 to 0.301
55	0.300 to 0.305	0.301 to 0.303
60	0.302 to 0.308	0.303 to 0.306
65	0.304 to 0.312	0.306 to 0.309
70	0.306 to 0.314	0.309 to 0.312
75	0.310 to 0.318	0.313 to 0.315
80	0.314 to 0.321	0.316 to 0.319
85	0.319 to 0.329	0.320 to 0.325
90	0.324 to 0.336	0.328 to 0.334
95	0.334 to 0.340	0.336 to 0.338
	Mean = 0.301 hr^{-1}	

Table A-16. Uncertainty Distribution for Time-Averaged Decontamination Coefficient for the Period 0 to 1800 Seconds

Percentile	Values of the Time-Averaged Decontamination Coefficient (hr^{-1}) Characteristic of the Indicated Percentile at a Confidence Level, C, of	
	C = 90%	C = 50%
5	0.4614 to 0.4823	0.4717 to 0.4799
10	0.4751 to 0.5012	0.4803 to 0.4971
15	0.4844 to 0.5078	0.4983 to 0.5050
20	0.5003 to 0.5138	0.5048 to 0.5093
25	0.5051 to 0.5187	0.5088 to 0.5164
30	0.5093 to 0.5230	0.5139 to 0.5188
35	0.5143 to 0.5261	0.5185 to 0.5234
40	0.5186 to 0.5292	0.5218 to 0.5262
45	0.5221 to 0.5339	0.5257 to 0.5292
50	0.5257 to 0.5359	0.5271 to 0.5339
55	0.5272 to 0.5386	0.5335 to 0.5360
60	0.5337 to 0.5474	0.5350 to 0.5387
65	0.5351 to 0.5544	0.5383 to 0.5484
70	0.5384 to 0.5602	0.5429 to 0.5556
75	0.5467 to 0.5715	0.5543 to 0.5603
80	0.5560 to 0.5765	0.5602 to 0.5726
85	0.5613 to 0.5879	0.5725 to 0.5809
90	0.5744 to 0.5948	0.5816 to 0.5917
95	0.5899 to 0.6071	0.5935 to 0.6012
	Mean = 0.5342 hr^{-1}	