VRI-EPA7.3-FR79-1 OAQPS-78-1,VI-B-13

ANALYSIS OF FGD SYSTEM EFFICIENCY BASED ON EXISTING UTILITY BOILER DATA

NOVEMBER 1979

TECHNICAL REPORT

Prepared for
Office of Air Quality Planning and Standards
Emission Standards and Engineering Division
Environmental Protection Agency

VECTOR RESEARCH, INCORPORATED

Ann Arbor, Michigan

VRI-EPA7.3-FR79-1 OAQPS-78-1, VI-B-13

ANALYSIS OF FGD SYSTEM EFFICIENCY BASED ON EXISTING UTILITY BOILER DATA

R. FARRELL

T. DOYLE

N. ST.CLAIRE

NOVEMBER 1979

TECHNICAL REPORT

Prepared for
Office of Air Quality Planning and Standards
Emission Standards and Engineering Division
Environmental Protection Agency

VECTOR RESEARCH, INCORPORATED

Ann Arbor, Michigan

CONTENTS

1.0 INTRODUCTION AND SUMMARY

The Environmental Protection Agency (EPA) promulgated new standards of performance for electric utility steam generating units, on June 11, 1979. In addition to restricting the levels of pollutants that these units emit into the atmosphere, the standards require a 90 percent reduction in potential SO_2 emissions if they exceed 0.60 lb/million BTUs of heat input. On August 10, 1979, a petition for reconsideration of these standards was submitted to EPA by the Utility Air Regulatory Group (UARG).[1] Part of this petition requested that EPA reconsider the 90 percent removal requirement. This request was based on analyses performed by Entropy Environmentalists, Incorporated, which were documented in Appendix B of the UARG Petition entitled "A Statistical Evaluation of the EPA FGD System Data Base Included in the Subpart DA NSPS Docket". The analysis included a numerical simulation of 1,000 years of flue gas desulfurization (FGD) efficiency to examine the impact of the 90 percent efficiency standard promulgated by EPA.

Vector Research, Incorporated, (VRI) is under contract to EPA to provide statistical and analytical support to the Agency on an as needed basis. On November 1, 1979, VRI was tasked to simulate or otherwise analytically describe FGD system efficiency to permit examination of the questions raised by the Entropy findings. The primary purpose of the task was to determine the levels of system efficiency and variability in

[1]Petition for Reconsideration, Docket Number OAQPS-78-1.

this efficiency that would be necessary to maintain at most one exceedence per year for a thirty-day rolling average on a 90 percent efficiency standard. The VRI simulation was to be based on analysis of data provided by EPA describing the efficiency of 11 flue gas desulfurization units and to additionally describe results over a wide range of facility parameters. The data analysis and simulation results were to be supplied to EPA within two weeks of initiation of the task. The authors were supported in this effort by Dr. Richard Cornell, a VRI associate, and other VRI staff.

This report presents the results of VRI's analysis activities and is organized into four chapters. This introductory chapter provides a description of the task and a summary of major results. The second chapter describes the results obtained concerning the behavior of various thirty-day averages for parametrically described FGD systems. The range of parameters used in generating these results was based in part on the statistical analysis of the data. This analysis is discussed in chapter three. The final chapter then discusses comparisons between VRI's results and those reported by Entropy Environmentalists, Incorporated.

The major conclusions of this analysis were as follows:

(1) The use of thirty-day moving averages of efficiency results in low-variability efficiency measurements at a facility, even when the daily data shows much larger variability. This results in averages which cluster much more closely around the central value of the efficiency measurements than do the daily efficiencies.

(2) Existing facilities show significant correlations in the efficiencies of sulfur removal on successive days. These autocorrelations, as well as the median levels of efficiency

and the fundamental variability of the process, influence the closeness with which thirty-day averages will remain clustered about their mean.

(3) The minimum long run average efficiency levels (described here in terms of the geometric mean) at which a facility must be operated in order that the ratio at which thirty-day rolling averages occur below 90, 89, 88, 87, 86, or 85 percent be held to one per year are shown in exhibit 1-1 for facilities with autocorrelations of 0.7 and various fundamental variability levels, some of which clearly represent good engineering and operating practice and some of which may not. Exhibit 1-2 shows similar data but for a failure rate of one failure per ten years. As the exhibits show, the rate of occurence of 30-day rolling averages below 90 percent would be above one per year for facilities wiht a 92 percent geometric mean efficiency and daily variaility anywhere from 0.20 to 0.60. These facilities would, however, have rates below one per year if the threshold were 89 percent and the daily variability were no greater than 0.26, or if the threshold were 88 percent and the daily variability was no greater than 0.32, or if the threshold were 87 percent and the daily variability was no greater than 0.38, or if the threshold were 86 percent and the daily variability was no greater than 0.43, or if the threshold were 85 percent and the daily variability was no greater than 0.48.

EXHIBIT 1-1: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER YEAR

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.2	91.4	90.6	89.8	89.0	88.2
.21	(.0071)	92.3	91.5	90.7	89.9	89.2	88.4
.22	(.0075)	92.3	91.6	90.8	90.1	89.3	88.5
.23	(.0079)	92.4	91.7	90.9	90.2	89.4	88.7
.24	(.0082)	92.5	91.8	91.1	90.3	89.6	88.8
.25	(.0086)	92.6	91.9	91.2	90.4	89.7	89.0
.26	(.0090)	92.7	92.0	91.3	90.6	89.8	89.1
.27	(.0093)	92.8	92.1	91.4	90.7	90.0	89.3
.28	(.0097)	92.9	92.2	91.5	90.8	90.1	89.4
.29	(.0101)	93.0	92.3	91.6	90.9	90.2	89.5
.30	(.0105)	93.1	92.4	91.7	91.1	90.4	89.7
.31	(.0109)	93.2	92.5	91.9	91.2	90.5	89.8
.32	(.0112)	93.3	92.6	92.0	91.3	90.6	90.0
.33	(.0116)	93.4	92.7	92.1	91.4	90.8	90.1
.34	(.0120)	93.5	92.8	92.2	91.5	90.9	90.2
.35	(.0124)	93.6	92.9	92.3	91.6	91.0	90.4
.36	(.0128)	93.7	93.0	92.4	91.8	91.1	90.5
.37	(.0133)	93.8	93.1	92.5	91.9	91.3	90.6
.38	(.0137)	93.8	93.2	92.6	92.0	91.4	90.8
.39	(.0141)	93.9	93.3	92.7	92.1	91.5	90.9
.40	(.0145)	94.0	93.4	92.8	92.2	91.6	91.0
.41	(.0150)	94.1	93.5	92.9	92.3	91.7	91.2
.42	(.0154)	94.2	93.6	93.0	92.4	91.9	91.3
.43	(.0158)	94.3	93.7	93.1	92.6	92.0	91.4
.44	(.0163)	94.4	93.8	93.2	92.7	92.1	91.5
.45	(.0167)	94.4	93.9	93.3	92.8	92.2	91.7
.46	(.0172)	94.5	94.0	93.4	92.9	92.3	91.8
.47	(.0177)	94.6	94.1	93.5	93.0	92.5	91.9
.48	(.0182)	94.7	94.2	93.6	93.1	92.6	92.0
.49	(.0186)	94.8	94.2	93.7	93.2	92.7	92.2
.50	(.0191)	94.9	94.3	93.8	93.3	92.8	92.3
.51	(.0196)	94.9	94.4	93.9	93.4	92.9	92.4
.52	(.0201)	95.0	94.5	94.0	93.5	93.0	92.5
.53	(.0206)	95.1	94.6	94.1	93.6	93.1	92.6
.54	(.0212)	95.2	94.7	94.2	93.7	93.2	92.7
.55	(.0217)	95.2	94.8	94.3	93.8	93.3	92.9
.56	(.0222)	95.3	94.9	94.4	93.9	93.4	93.0
.57	(.0228)	95.4	94.9	94.5	94.0	93.6	93.1
.58	(.0233)	95.5	95.0	94.6	94.1	93.7	93.2
.59	(.0239)	95.5	95.1	94.7	94.2	93.8	93.3
.60	(.0245)	95.6	95.2	94.7	94.3	93.9	93.4

Facility autocorrelation = 0.7

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 1-2: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TEN YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.6	91.8	91.1	90.3	89.6	88.8
.21	(.0071)	92.7	91.9	91.2	90.5	89.7	89.0
.22	(.0075)	92.8	92.1	91.3	90.6	89.9	89.2
.23	(.0079)	92.9	92.2	91.5	90.8	90.1	89.3
.24	(.0082)	93.0	92.3	91.6	90.9	90.2	89.5
.25	(.0086)	93.1	92.4	91.7	91.0	90.4	89.7
.26	(.0090)	93.2	92.5	91.9	91.2	90.5	89.8
.27	(.0093)	93.3	92.7	92.0	91.3	90.7	90.0
.28	(.0097)	93.4	92.8	92.1	91.5	90.8	90.1
.29	(.0101)	93.5	92.9	92.2	91.6	90.9	90.3
.30	(.0105)	93.6	93.0	92.4	91.7	91.1	90.5
.31	(.0109)	93.7	93.1	92.5	91.9	91.2	90.6
.32	(.0112)	93.8	93.2	92.6	92.0	91.4	90.8
.33	(.0116)	93.9	93.3	92.7	92.1	91.5	90.9
.34	(.0120)	94.0	93.4	92.8	92.2	91.6	91.1
.35	(.0124)	94.1	93.5	93.0	92.4	91.8	91.2
.36	(.0128)	94.2	93.6	93.1	92.5	91.9	91.3
.37	(.0133)	94.3	93.8	93.2	92.6	92.0	91.5
.38	(.0137)	94.4	93.9	93.3	92.7	92.2	91.6
.39	(.0141)	94.5	94.0	93.4	92.9	92.3	91.8
.40	(.0145)	94.6	94.1	93.5	93.0	92.4	91.9
.41	(.0150)	94.7	94.2	93.6	93.1	92.6	92.0
.42	(.0154)	94.8	94.3	93.7	93.2	92.7	92.2
.43	(.0158)	94.9	94.4	93.8	93.3	92.8	92.3
.44	(.0163)	95.0	94.4	93.9	93.4	92.9	92.4
.45	(.0167)	95.0	94.5	94.0	93.5	93.1	92.6
.46	(.0172)	95.1	94.6	94.1	93.7	93.2	92.7
.47	(.0177)	95.2	94.7	94.2	93.8	93.3	92.8
.48	(.0182)	95.3	94.8	94.3	93.9	93.4	92.9
.49	(.0186)	95.4	94.9	94.4	94.0	93.5	93.1
.50	(.0191)	95.5	95.0	94.5	94.1	93.6	93.2
.51	(.0196)	95.5	95.1	94.6	94.2	93.7	93.3
.52	(.0201)	95.6	95.2	94.7	94.3	93.9	93.4
.53	(.0206)	95.7	95.3	94.8	94.4	94.0	93.5
.54	(.0212)	95.8	95.3	94.9	94.5	94.1	93.7
.55	(.0217)	95.8	95.4	95.0	94.6	94.2	93.8
.56	(.0222)	95.9	95.5	95.1	94.7	94.3	93.9
.57	(.0228)	96.0	95.6	95.2	94.8	94.4	94.0
.58	(.0233)	96.1	95.7	95.3	94.9	94.5	94.1
.59	(.0239)	96.1	95.8	95.4	95.0	94.6	94.2
.60	(.0245)	96.2	95.8	95.5	95.1	94.7	94.3

Facility autocorrelation = 0.7

---

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

The rates would be below one occurence per ten years for combinations of thresholds and daily variabilities as follows:

Threshold	Daily Variability
89%	no greater than 0.21
88%	no greater than 0.27
87%	no greater than 0.32
86%	no greater than 0.37
85%	no greater than 0.41

Data for auto correlations other than 0.7 can be found in the body of the report.

(4) There is very little change in these estimates of minimum efficiencies when the assumptions concerning the type of statistical distribution used to represent the efficiency data are varied. Both normal and lognormal distributions provide reasonable fits to the existing daily efficiency data, with the lognormal probably slightly better than the normal. (Because the lognormal distribution appears to fit the data better than the normal, it has been used in generating exhibits 1-1 and 1-2, and in general throughout the analyses.) Both distributional assumptions produce very similar results in terms of the predicted behavior of thirty-day averages taken on a rolling basis.

These conclusions, as well as many other observations, are discussed in more detail in the body of this report.

2.0 PREDICTED BEHAVIOR OF THIRTY DAY AVERAGES OF EFFICIENCY

This chapter describes the main results of this analysis. The principal question of interest is the behavior of thirty-day moving averages of efficiency, and specifically the rate at which such averages would dip below selected thresholds. The behavior of the moving or rolling average was examined for various true (average) efficiencies, variabilities, and time dependencies.

In a setting where penalties could be imposed when such averages fell below a regulatory threshold, EPA would expect to set the threshold level so that facilities designed, constructed, and operated in accordance with good engineering practice would produce very infrequent threshold crossings, while facilities not in accord with good engineering practice would show averages below the threshold on a more frequent basis. That is, the threshold should correspond to some value approximately at the minimum expected to be seen regularly from well-engineered and operated facilities. This analysis is not designed to analyze what levels of performance correspond to good engineering practice, but to show the relation between the operating characteristics of a facility and the rates at which various threshold values of thirty-day averages would be crossed. This information can then be combined by EPA with expert knowledge of the achievable levels of engineering and operating performance in designing regulatory policies.

Although the precise method of computing the thirty-day average might vary somewhat, this analysis has assumed that a daily average efficiency is generated each day from more frequent measurements of emissions, and that these daily averages are then averaged for a period of thirty days. Such thirty-day averages might be computed each day, each week, each month, or at any other frequency, based on the thirty-day period ending with the computation day. The behavior of averages at various computation frequencies will be discussed. We believe that this general scheme contains most policies of interest. In the case of possible changes in the precise methods of computing averages from hourly or more frequent data, the analysis encompasses policies with essentially the same effects as those which might be adopted. All the analyses have assumed that data would be available for each day of operations.

In order to predict the behavior of the averages involved, assumptions must be made about several basic properties of the measurements of scrubbing efficiency at a facility. These assumptions concern the long-run level of scrubbing efficiency achieved, the type and amount of daily variability which will be observed, and any temporal patterns or correlations which might be expected in the observed efficiency.

Before presenting any numerical analyses of the issues, it is necessary to define the various types of measurements which were used in describing and analyzing the process. The level of scrubbing efficiency achieved will be discussed in terms of several different related quantities. For some purposes, it is necessary to consider the measured daily efficiency: this quantity is produced by reducing more frequent measurements of inlet and outlet sulfur concentrations to a daily efficiency figure. These measurements may also be considreed in terms of the equivalent measurements of emissivity, which is 1-efficiency, so that an efficiency of 90 percent corresponds to an emissivity of 10 percent.

Daily efficiency or emissivity measurements (which were the basic data used in the detailed data analyses of actual facilities, as described in chapter 3.0, and which also form a basis in terms of which all these analyses were conducted) are observed to vary when measured repeatedly at a single facility. This variation is stochastic or probabilistic, rather than deterministic, in nature. That is, the exact measurement which will be obtained at some future time is not completely determined from our knowledge of the process, but includes elements of randomness.

Describing the randomness in the daily measurements involves describing the distribution of the daily measurements (that is, the frequencies with which the measurement takes on various values) and the interrelations among the daily measurements for different days. The distribution of the daily measurements is typically described in terms of a measure of the center of the measurements observed (such as the mean, the geometric mean, or the median) a measure of the variability of the measurements about this center (such as the standard deviation or geometric standard deviation), and the particular shape or type of distribution which descirbes the variability (such as the normal or lognormal distribution). The interrelationships between measurements on various days are typically measured in terms of the correlation between measurements on successive days.

The mean (sometimes called the arithmetic mean) of the measurements is simply the long-run average of the measurements. The geometric mean is the value which would be obtained by taking the antilogarithm of the mean of the logarithms of the measurements. The geometric mean of measurements is always less than the arithmetic mean, no matter how the measurements are distributed. The median of measurements is the value such that 50 percent of the measurements are above it and 50 percent below. The standard deviation of measurements is the root-mean-square average of the deviations of the measurements about their own mean. The geometric standard deviation is the root-mean-square average of the deviations of the logarithms of the measurements about the mean of the logarithms. The correlation (or autocorrelation), of a sequence of measurements varies between -1 and +1. a correlation of +1 indicates perfect correlation -- that is, in our case, successive measurements at a single facility would be identical. A correlation of 0 indicates no dependence between successive measurements. Correlations below 0 indicate that high measurements are followed by low and low by high.

All of these terms may be applied to any sequence of measurements. In the specific problem at hand, they may be applied to daily efficiency measurements, daily emissivity measurements, or thirty-day averages of either. Generally, daily efficiencies are discussed in this analysis in terms of the geometric mean emissivity (or the equivalent efficiency) and the geometric standard deviation of emissivity. This geometric standard deviation may be thought of as a percentage variability in the measurements so that a geometric standard deviation of 0.20 would indicate a daily variation of about 20 percent of the daily mean. These scales of measurement were chosen because they were those which had been used in past studies of the same general topics. The thirty-day averages are typically discussed in terms of the frequencies with which particular levels of emissivity would be exceeded by the thirty-day averages or in terms of their mean and standard deviation (arithmetic, not geometric).

2.1 SCOPE OF ANALYSES

In the specific problem at hand, the evidence supports the use of a model in which observed dependencies in sequences of efficiency measurements are viewed as produced by correlations between immediately successive days. The evidence on this point is discussed in the next chapter. In such a model (an autoregressive model of lag one) the only correlation parameter required to describe the pattern is the basic correlation between the observations on successive days. All other dependencies are then computable from this correlation coefficient. In terms of these parameters, the region of the parameter space examined in this analysis was:

(1) Long-run geometric mean emissivities of six percent to nine percent, with particular attention to the value of eight percent, corresponding to a 92 percent efficiency.[1]

(2) Daily geometric standard deviations of 0.20 to 0.50 and distributions of measurements described by a probability distribution of emissivities similar to the lognormal or normal distribution, probably having more similarity to the lognormal (see chapter 3.0). It must be remembered that these daily variabilities in emissivity lead to much smaller variabilities in the thirty-day-efficiency. For example, a typical facility with daily emissivities of the order of nine percent with a

[1]Although the 92 percent figure is not the geometric mean efficiency but the efficiency corresponding to the geometric mean of emissivity, we will, when appropriate, refer to such values as geometric means without intending to mislead.

50 percent variability would have daily efficiencies of 91 percent, with a daily error of 4.5 percent, and thirty-day average efficiencies of about 91 percent with a variability of only about one percent.

(3) Day-to-day correlations between successive observations of 0.0 to 0.7.

The results of this analysis address three topics:

(1) The average number of times per year that thirty-day average efficiencies, computed daily (360 times per "year"), would be below various thresholds as a function of the facility operating parameters assumed.

(2) The minimum long-run level of efficiency which a facility would have to maintain to limit its average threshold crossings on the same rolling average to one per year, one per two years, one per five years, or one per ten years as a function of the level of variability and correlation of daily observations at the facility. These efficiencies are presented in terms of geometric means, keeping the method of description for all daily data consistent. At these levels, the long-run rate of excessive emissivity measured in terms of thirty-day rolling averages, would be held to the one per year or other rate as given. The actual number of excesses in a specific year would, of course, vary, so that at a rate of one per year, some years would have two, for example, and others zero.

(3) The potential effects of changing the frequency of computation of the averages on the rate at which threshold crossing would occur.

Following the presentation of these results, a very brief section discusses the methods of computation used to generate the estimates.

2.2 ANALYSIS RESULTS

The most basic and fundamental results of this analysis simply describe the mean, standard deviation, and distribution of the thirty-day averages as functions of the elementary process parameters describing the level of efficiency, the variability of the daily observations, and the autocorrelation. Exhibit 2-1 shows the means and standard deviations of the thirty-day rolling averages for a sampling of parameter values in the region examined. Several observations can be made from that data. The most basic is simply that the mean efficiency is different than the efficiency level described by the geometric mean emissivity. This difference simply reflects the differences in meaning between the mean and the geometric mean. The difference would remain even if the data had beem normally distributed: the geometric mean of a normally-distributed datum is not identical to its mean, and the relation between the two values in the parameter region of interest is almost precisely the relation between the same parameters in the lognormal distribution.

A second observation is that the variabilities of the thirty-day averages are much lower than the variabilities of the daily data. This reduction in variability is the basic reason why taking averages of sequences of observations is useful in obtaining consistent estimates of actual performance levels. The third observation which can be made from the exhibit is that both the mean and the standard deviation of the thirty-day averages are clearly influenced by the variability and autocorrelation in the efficiency process, as well as by the level of efficiency.

EXHIBIT 2-1: MEAN AND STANDARD DEVIATION OF 30-DAY AVERAGES

Process Parameters			Thirty-Day Average	
Geom. Mean	Geom. Std. Dev.	Autocor.	Mean	Std. Dev.
.9100	.2000	0.0000	.9082	.0034
.9100	.2000	.3000	.9082	.0045
.9100	.2000	.5000	.9082	.0057
.9100	.2000	.7000	.9082	.0076
.9100	.3000	0.0000	.9059	.0053
.9100	.3000	.3000	.9059	.0070
.9100	.3000	.5000	.9059	.0088
.9100	.3000	.7000	.9059	.0118
.9100	.4000	0.0000	.9025	.0071
.9100	.4000	.3000	.9025	.0098
.9100	.4000	.5000	.9025	.0122
.9100	.4000	.7000	.9025	.0163
.9100	.5000	0.0000	.8980	.0099
.9100	.5000	.3000	.8980	.0130
.9100	.5000	.5000	.8980	.0162
.9100	.5000	.7000	.8980	.0215
.9200	.2000	0.0000	.9184	.0030
.9200	.2000	.3000	.9184	.0040
.9200	.2000	.5000	.9184	.0051
.9200	.2000	.7000	.9184	.0068
.9200	.3000	0.0000	.9163	.0047
.9200	.3000	.3000	.9163	.0063
.9200	.3000	.5000	.9163	.0078
.9200	.3000	.7000	.9163	.0105
.9200	.4000	0.0000	.9133	.0066
.9200	.4000	.3000	.9133	.0087
.9200	.4000	.5000	.9133	.0109
.9200	.4000	.7000	.9133	.0145
.9200	.5000	0.0000	.9093	.0088
.9200	.5000	.3000	.9093	.0116
.9200	.5000	.5000	.9093	.0144
.9200	.5000	.7000	.9093	.0191
.9300	.2000	0.0000	.9286	.0026
.9300	.2000	.3000	.9286	.0035
.9300	.2000	.5000	.9286	.0044
.9300	.2000	.7000	.9286	.0059
.9300	.3000	0.0000	.9268	.0041
.9300	.3000	.3000	.9268	.0055
.9300	.3000	.5000	.9268	.0068
.9300	.3000	.7000	.9268	.0092
.9300	.4000	0.0000	.9242	.0058
.9300	.4000	.3000	.9242	.0076
.9300	.4000	.5000	.9242	.0095
.9300	.4000	.7000	.9242	.0127
.9300	.5000	0.0000	.9207	.0077
.9300	.5000	.3000	.9207	.0101
.9300	.5000	.5000	.9207	.0125
.9300	.5000	.7000	.9207	.0167
.9400	.2000	0.0000	.9388	.0023
.9400	.2000	.3000	.9388	.0030
.9400	.2000	.5000	.9388	.0038
.9400	.2000	.7000	.9388	.0051
.9400	.3000	0.0000	.9372	.0035
.9400	.3000	.3000	.9372	.0047
.9400	.3000	.5000	.9372	.0059
.9400	.3000	.7000	.9372	.0078
.9400	.4000	0.0000	.9350	.0049
.9400	.4000	.3000	.9350	.0065
.9400	.4000	.5000	.9350	.0082
.9400	.4000	.7000	.9350	.0109
.9400	.5000	0.0000	.9320	.0066
.9400	.5000	.3000	.9320	.0087
.9400	.5000	.5000	.9320	.0108
.9400	.5000	.7000	.9320	.0143

Additional analyses not easily presented in tabular form addressed the shape of the distribution of the thirty-day rolling averages. Questions had been raised about whether these averages would be distributed normally. The distribution was found to be very nearly, although not exactly, normal. Although the averages were much more nearly normal than the approximately lognormal daily measurements, all of the analyses took account of the remaining non-normality; no results were based on *normal approximations*.

The data in exhibit 2-1 was presented in terms of facility operating parameters which were simply chosen to sample the region of greatest interest. The actual values of the basic process parameters are available for some experiments at specific facilities. Exhibit 2-2 shows the parameters describing the processes at these facilities. The actual statistical analysis of the data to produce these estimates of the parameters is described in chapter 3.0. Exhibit 2-3 shows the means and standard deviations of thirty-day average efficiency observations which would be expected if a new facility with a 92 percent geometric mean efficiency had the same operating conditions (process variability and autocorrelation) as with each of the individual existing facilities.

As can be seen in these exhibits, there is considerable variation among the results at the individual sites. There cannot be a strictly statistical decision as the degree to which any particular site represents good engineering and operating practices, state-of-the-art systems, well-calibrated and maintained measuring equipment, and otherwise is appropriate for use in extrapolations to future facilities. Any analyses of these issues must be made by engineers rather than statisticians. Accordingly, the remaining analyses of the behavior of the thirty-day

EXHIBIT 2-2: PROCESS PARAMETERS OF ACTUAL FACILITIES

Unit	Geometric Mean	Geometric Standard Deviation	Auto-Correlation
Louisville North	84.4	.295	.6955
Louisville South	83.3	.343	.6949
Pittsburgh I	80.8	.234	.4683
Pittsburgh II	85.4	.212	-.1428
Philadelphia	97.0	.359	.2524
Chicago	89.2	.118	.6983
Shawnee TCA	88.5	.182	.5995
Shawnee Venturi	96.0	.368	.8897
Conesville A	86.0	.447	.7131
Conesville B	92.5	.474	.6255
Lawrence	95.4	.835	.6386

EXHIBIT 2-3: THIRTY-DAY AVERAGE MEAN AND STANDARD DEVIATION FOR 92%-EFFICIENT FACILITIES WITH VARIABILITY AND AUTOCORRELATION OF ACTUAL FACILITIES

		Mean	Standard Deviation
Variability and Autocorrelation from:	Louisville North	91.64%	1.03%
	Louisville South	91.52%	1.22%
	Pittsburgh I	91.78%	0.57%
	Pittsburgh II	91.82%	0.32%
	Philadelphia	91.47%	0.73%
	Chicago	91.94%	0.39%
	Shawnee TCA	91.87%	0.52%
	Shawnee Venturi	91.44%	2.05%
	Conesville A	91.16%	1.66%
	Conesville B	91.05%	1.48%
	Lawrence	88.70%	3.70%

average processes will continue to be presented, as was the initial material in exhibit 2-1, in general parametric terms. The appropriate cases from these parametric results may then be selected by engineers to be used in any further analyses.

In using the parametric results, it may be appropriate to examine the expected behavior of processes with one or more parameters equal to those of specific existing facilities (as was done in generating exhibit 2-3), or to consider the fact that the measurements from existing facilities are from finite, and generally fairly limited, data samples, and to consider the possible errors in estimation which may be present. When this second technique is used, it may be of interest to know that the Shawnee TCA and Pittsburgh II (taken together, assuming that their true long-run levels of variability are identical as the data suggests) have a 95 percent confidence interval on the long-run geometric standard deviation running from 0.16 to 0.23, and that Lousiville North and South taken together have a 95 percent confidence interval from 0.29 to 0.36. (The corresponding 99 percent intervals are from 0.15 to 0.25 for Shawnee TCA and Pittsburgh II and 0.28 to 0.38 for the Louisville facilities.)

Exhibit 2-4 shows the rate (in occurrences per 360-day year) at which 30-day averages of efficiency computed daily would fail to meet a threshold level of 90 percent efficiency for a facility with an actual efficiency level of 92 percent[1] and variability parameters as shown. Each estimated rate is shown with an associated standard error of estimate in parentheses. These estimates are for a facility with a lognormal distribution of emissivity. Facilities with high values of

[1]Corresponding to a geometric mean emissivity of eight percent.

EXHIBIT 2-4: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW - 90% AVERAGES IN A 92% EFFICIENT FACILITY WITH LOGNORMAL OBSERVATIONS

GEOMETRIC DAILY VARIABILITY	PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	0.0	0.002 (.002)	0.189 (.031)	2.514 (.095)
.3	0.320 (.0215)	2.670 (.0865)	9.900 (.332)	25.045 (.7705)
.4	10.233 (.180)	26.3935 (.186)	41.2375 (.3975)	62.4455 (.7365)
.5	52.241 (.2655)	72.1565 (.3950)	87.608 (.5515)	102.496 (.9325)

Lognormal distribution.
Figures in parentheses are standard errors.

either variability (40 percent or greater) or day-to-day correlation (0.7 or greater) would be expected to fail to meet the threshold more than one time per year, with facilities with high values of both variability and correlation failing to meet the threshold for major fractions of their operating days.

Exhibit 2-5 shows a comparison of these results with those which would be expected on similar facilities where the variability of the emissivity was normal[1] rather than lognormal. As can be seen in the exhibit, the pattern of dependency between the plant operating parameters and the rate at which the threshold is not met remains essentially the same. That is, the rate of threshold failures does not depend in any major way on the shape of the statistical distribution of the observations (within the general area of reasonability).

Exhibit 2-6 shows the expected rate at which thirty-day averages below thresholds other than 90 percent would occur for various variability and correlation parameters. Exhibits 2-7 through 2-9 show this same information for geometric mean emissivities other than eight percent (corresponding to more or less efficient facilities). All of these exhibits were derived using the lognormal distribution of emissivity observations; rates of threshold failure for the normal case differ by only small amounts, just as in the 92 percent-efficient cases.

Exhibits 2-10 through 2-13 show the efficiency levels (1.00 - geometric mean emissivities) at which facilities with various variability and correlation parameters would maintain a rate of threshold failure no higher than one per year (with rolling averages computed daily). These

---

[1]Truncated at 0 efficiency.

EXHIBIT 2-5: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW-90% AVERAGES IN A 92% EFFICIENT FACILITY WITH NORMAL OR LOGNORMAL OBSERVATIONS

GEOMETRIC DAILY VARIABILITY		PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	Lognormal:	0.0	0.002 (.002)	0.189 (.031)	2.514 (.095)
	Normal:	0.0	0.009	0.051	1.206
.3	Lognormal:	0.320 (.0215)	2.670 (.0865)	9.900 (.332)	25.045 (.7706)
	Normal:	0.090	1.639	6.678	21.403
.4	Lognormal:	10.233 (.180)	26.3935 (.186)	41.2375 (.3975)	62.4455 (.7365)
	Normal:	7.742	22.777	39.689	64.527
.5	Lognormal:	52.241 (.2555)	72.1565 (.3950)	87.608 (.5515)	102.496 (.9325)
	Normal:	52.061	75.449	92.764	112.50

Lognormal distribution cases above normal cases.

Figures in parentheses are standard errors.

EXHIBIT 2-6: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW-THRESHOLD AVERAGES IN A 92% EFFICIENT FACILITY

(with standard errors in parentheses)

GEOMETRIC DAILY VARIABILITY		PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	30-day μ	0.9184	0.9184	0.9184	0.9184
	30-day σ	.0030	.0040	.0051	.0068
	eff<90%	0.0	0.002 (.002)	0.189 (.031)	2.514 (.095)
	" <89%	0.0	0.0	0.0	0.0565 (.017)
	" <88%	0.0	0.0	0.0	0.0
	" <87%	0.0	0.0	0.0	0.0
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.3	30-day μ	0.9163	0.9163	0.9163	0.9163
	30-day σ	.0047	.0063	.0078	.0105
	eff<90%	0.320 (.0215)	2.670 (.0865)	9.900 (.332)	25.045 (.7705)
	" <89%	0.0	0.0285 (.007)	0.690 (.1195)	4.6465 (.319)
	" <88%	0.0	0.0	0.040 (.0145)	0.6595 (.0765)
	" <87%	0.0	0.0	0.0	0.0705 (.023)
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.4	30-day μ	0.9133	0.9133	0.9133	0.9133
	30-day σ	.0066	.0087	.0109	.0145
	eff<90%	10.233 (.180)	26.3935 (.186)	41.2375 (.3975)	62.4455 (.7365)
	" <89%	0.2905 (.0405)	2.9645 (.1565)	8.743 (.1325)	23.1665 (.228)
	" <88%	0.009 (.0085)	0.2175 (.0355)	1.026 (.296)	7.3055 (.118)
	" <87%	0.0	0.0045 (.004)	0.159 (.0575)	2.058 (.108)
	" <86%	0.0	0.0	0.011 (.0055)	0.5675 (.072)
	" <85%	0.0	0.0	0.0	0.1195 (.0325)
.5	30-day μ	0.9093	0.9093	0.9093	0.9093
	30-day σ	.0088	.0116	.0144	.0191
	eff<90%	52.241 (.2655)	72.1565 (.3950)	87.608 (.5515)	102.496 (.9325)
	" <89%	7.6355 (.2150)	20.1945 (.3015)	35.3195 (.6525)	55.534 (.562)
	" <88%	0.6805 (.0835)	4.0905 (.1800)	11.973 (.2725)	27.5385 (.3285)
	" <87%	0.044 (.0225)	0.720 (.0610)	3.570 (.1295)	12.81 (.2015)
	" <86%	0.0	0.1075 (.0360)	1.0565 (.073)	5.71 (.0935)
	" <85%	0.0	0.0135 (.0120)	0.299 (.0555)	2.408 (.0725)

Conditions:

Facility with 8 % geometric mean emissivity (92% efficiency)

Lognormal distribution of observations

EXHIBIT 2-7: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW-THRESHOLD AVERAGES IN A 94% EFFICIENT FACILITY

(with standard errors in parentheses)

GEOMETRIC DAILY VARIABILITY		PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	30-day μ	0.9388	0.9388	0.9388	0.9388
	30-day σ	.0023	.0030	.0038	.0051
	eff<90%	0.0	0.0	0.0	0.0
	" <89%	0.0	0.0	0.0	0.0
	" <88%	0.0	0.0	0.0	0.0
	" <87%	0.0	0.0	0.0	0.0
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.3	30-day μ	0.9372	0.9372	0.9372	0.9372
	30-day σ	.0035	.0047	.0059	.0078
	eff<90%	0.0	0.0	0.0015 (.0015)	0.023 (.0155)
	" <89%	0.0	0.0	0.0	0.0
	" <88%	0.0	0.0	0.0	0.0
	" <87%	0.0	0.0	0.0	0.0
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.4	30-day μ	0.9350	0.9350	0.9350	0.9350
	30-day σ	.0049	.0065	.0082	.0109
	eff<90%	0.0	0.0	0.117 (.0415)	1.5815 (.0695)
	" <89%	0.0	0.0	0.007 (.003)	0.2745 (.0465)
	" <88%	0.0	0.0	0.0	0.083 (.033)
	" <87%	0.0	0.0	0.0	0.0225 (.0125)
	" <86%	0.0	0.0	0.0	0.003 (.003)
	" <85%	0.0	0.0	0.0	0.0
.5	30-day μ	0.9320	0.9320	0.9320	0.9320
	30-day σ	.0066	.0087	.0108	.0143
	eff<90%	0.0065 (.0025)	0.375 (.0885)	2.0455 (.1405)	9.6195 (.253)
	" <89%	0.0	0.0175 (.0055)	0.307 (.047)	3.173 (.1835)
	" <88%	0.0	0.0	0.032 (.012)	1.0375 (.082)
	" <87%	0.0	0.0	0.0045 (.0045)	0.3505 (.0395)
	" <86%	0.0	0.0	0.0005 (.0005)	0.1025 (.0195)
	" <85%	0.0	0.0	0.0	0.026 (.0135)

Conditions:

Facility with 6% geometric mean emissivity (94% efficiency)

Lognormal distribution of observations

EXHIBIT 2-8: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW-THRESHOLD AVERAGES IN A 93% EFFICIENT FACILITY (with standard errors in parentheses)

GEOMETRIC DAILY VARIABILITY		PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	30-day μ	0.9286	0.9286	0.9286	0.9286
	30-day σ	.0026	.0035	.0044	.0059
	eff<90%	0.0	0.0	0.0	0.022 (.0195)
	" <89%	0.0	0.0	0.0	0.0
	" <88%	0.0	0.0	0.0	0.0
	" <87%	0.0	0.0	0.0	0.0
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.3	30-day μ	0.9268	0.9268	0.9268	0.9268
	30-day σ	.0041	.0055	.0068	.0092
	eff<90%	0.0	0.006 (.006)	0.1475 (.030)	2.0385 (.0485)
	" <89%	0.0	0.0	0.0065 (.0065)	0.1465 (.042)
	" <88%	0.0	0.0	0.0	0.0015 (.0015)
	" <87%	0.0	0.0	0.0	0.0
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.4	30-day μ	0.9242	0.9242	0.9242	0.9242
	30-day σ	.0058	.0076	.0095	.0127
	eff<90%	0.0675 (.0155)	0.887 (.203)	4.3635 (.1895)	15.3025 (.418)
	" <89%	0.0	0.0255 (.0075)	0.450 (.045)	4.031 (.197)
	" <88%	0.0	0.0	0.0395 (.0195)	0.842 (.0795)
	" <87%	0.0	0.0	0.015 (.0085)	0.1755 (.035)
	" <86%	0.0	0.0	0.0	0.385 (.011)
	" <85%	0.0	0.0	0.0	0.0045 (.004)
.5	30-day μ	0.9207	0.9207	0.9207	0.9207
	30-day σ	.0077	.0101	.0126	.0167
	eff<90%	2.799 (.175)	10.9885 (.0935)	22.9385 (.635)	41.890 (.932)
	" <89%	0.107 (.022)	1.5165 (.097)	6.2575 (.0925)	18.276 (.611)
	" <88%	0.0045 (.0045)	0.186 (.0195)	1.4525 (.073)	7.522 (.3035)
	" <87%	0.0	0.036 (.0155)	0.299 (.039)	2.764 (.150)
	" <86%	0.0	0.0045 (.0035)	0.0585 (.0165)	1.036 (.0745)
	" <85%	0.0	0.0	0.0	0.385 (.0425)

Conditions:

Facility with 7 % geometric mean emissivity (93% efficiency)

Lognormal distribution of observations

EXHIBIT 2-9: FREQUENCY OF OCCURENCE (OCCASIONS PER YEAR) OF BELOW-THRESHOLD AVERAGES IN A 91% EFFICIENT FACILITY

(with standard errors in parentheses)

GEOMETRIC DAILY VARIABILITY		PROCESS AUTOCORRELATION 0	0.3	0.5	0.7
.2	30-day μ	0.9082	0.9082	0.9082	0.9082
	30-day σ	.0034	.0045	.0057	.0076
	eff<90%	3.696 (0.2160)	14.539 (0.02665)	29.7325 (0.641)	52.027 (0.725)
	" <89%	0.0	0.048 (0.012)	0.6345 (0.042)	4.790 (0.3105
	" <88%	0.0	0.0	0.0	0.1955 [illegible]
	" <87%	0.0	0.0	0.0	0.001
	" <86%	0.0	0.0	0.0	0.0
	" <85%	0.0	0.0	0.0	0.0
.3	30-day μ	0.9059	0.9059	0.9059	0.9059
	30-day σ	.0053	.0070	.0088	.0118
	eff<90%	48.869 (0.604)	71.1785 (1.3085)	88.5115 (0.166)	106.3675 (1.3335
	" <89%	0.982 (0.1015)	6.1075 (0.1885)	16.2275 (0.408)	35.5775 (0.744)
	" <88%	0.004 (0.004)	0.1645 (0.019)	1.529 (0.113)	8.8645 (0.2570
	" <87%	0.0	0.001 (0.001)	0.086 (0.016)	1.611 (0.1135
	" <86%	0.0	0.0	0.003 (0.0025)	0.211 (0.0325
	" <85%	0.0	0.0	0.0	0.0455 (0.016)
.4	30-day μ	0.9025	0.9025	0.9025	0.9025
	30-day σ	.0074	.0098	.0122	.0163
	eff<90%	128.6885 (1.47)	139.3355 (1.36)	143.7005 (1.0485)	148.656 (0.4725
	" <89%	18.807 (0.5955)	39.2805 (0.7885)	55.9655 (1.2265)	76.5555 (0.103)
	" <88%	1.028 (0.0335)	6.584 (0.1465)	16.220 (6.255)	34.416 (0.3195
	" <87%	0.0275 (0.0155)	0.6855 (0.035)	3.5445 (0.245)	14.0615 (0.1825
	" <86%	0.0005 (0.0005)	0.0545 (0.0145)	0.679 (0.785)	5.1245 (0.965)
	" <85%	0.0	0.0035 (0.003)	0.119 (0.027)	1.7045 ([illegible]041)
.5	30-day μ	0.8980	0.8980	0.8980	0.8980
	30-day σ	.0099	.0130	.0162	.0215
	eff<90%	201.053 (1.0585)	191.8035 (1.6735)	186.161 (0.9625)	178.337 (0.9195
	" <89%	72.932 (0.6025)	91.156 (0.9785)	104.3855 (0.3075)	115.7075 (0.911)
	" <88%	15.5555 (0.224)	32.1115 (0.8079)	49.1955 (0.482)	68.561 (0.5375
	" <87%	2.190 (0.147)	9.0455 (0.202)	20.091 (0.2525)	37.7685 (0.394)
	" <86%	0.2365 (0.037)	2.098 (0.041)	7.296 (0.1815)	19.691 (0.2675
	" <85%	0.0165 (0.006)	0.4935 (0.016)	2.4165 (0.068)	10.008 (0.2125

Conditions:

Facility with 9 % geometric mean emissivity (91% efficiency)

Lognormal distribution of observations

EXHIBIT 2-10: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER YEAR

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0054)	91.8	91.0	90.1	89.3	88.5	87.7
.21	(.0057)	91.9	91.1	90.3	89.4	88.6	87.8
.22	(.0060)	92.0	91.2	90.4	89.6	88.7	87.9
.23	(.0063)	92.1	91.3	90.5	89.7	88.9	88.1
.24	(.0065)	92.1	91.4	90.6	89.8	89.0	88.2
.25	(.0068)	92.2	91.4	90.7	89.9	89.1	88.3
.26	(.0071)	92.3	91.5	90.8	90.0	89.2	88.5
.27	(.0074)	92.4	91.6	90.9	90.1	89.4	88.6
.28	(.0077)	92.5	91.7	91.0	90.2	89.5	88.7
.29	(.0080)	92.6	91.8	91.1	90.3	89.6	88.8
.30	(.0083)	92.6	91.9	91.2	90.4	89.7	89.0
.31	(.0087)	92.7	92.0	91.3	90.6	89.8	89.1
.32	(.0090)	92.8	92.1	91.4	90.7	89.9	89.2
.33	(.0093)	92.9	92.2	91.5	90.8	90.1	89.4
.34	(.0096)	93.0	92.3	91.6	90.9	90.2	89.5
.35	(.0099)	93.1	92.4	91.7	91.0	90.3	89.6
.36	(.0103)	93.1	92.5	91.8	91.1	90.4	89.7
.37	(.0106)	93.2	92.6	91.9	91.2	90.5	89.8
.38	(.0109)	93.3	92.6	92.0	91.3	90.6	90.0
.39	(.0113)	93.4	92.7	92.1	91.4	90.8	90.1
.40	(.0116)	93.5	92.8	92.2	91.5	90.9	90.2
.41	(.0119)	93.6	92.9	92.3	91.6	91.0	90.3
.42	(.0123)	93.6	93.0	92.4	91.7	91.1	90.5
.43	(.0127)	93.7	93.1	92.5	91.8	91.2	90.6
.44	(.0130)	93.8	93.2	92.6	91.9	91.3	90.7
.45	(.0134)	93.9	93.3	92.7	92.0	91.4	90.8
.46	(.0138)	94.0	93.4	92.8	92.1	91.5	90.9
.47	(.0141)	94.0	93.4	92.8	92.2	91.7	91.1
.48	(.0145)	94.1	93.5	92.9	92.4	91.8	91.2
.49	(.0149)	94.2	93.6	93.0	92.5	91.9	91.3
.50	(.0153)	94.3	93.7	93.1	92.6	92.0	91.4
.51	(.0157)	94.4	93.8	93.2	92.7	92.1	91.5
.52	(.0161)	94.4	93.9	93.3	92.8	92.2	91.6
.53	(.0165)	94.5	94.0	93.4	92.9	92.3	91.8
.54	(.0169)	94.6	94.0	93.5	93.0	92.4	91.9
.55	(.0174)	94.7	94.1	93.6	93.1	92.5	92.0
.56	(.0178)	94.7	94.2	93.7	93.2	92.6	92.1
.57	(.0182)	94.8	94.3	93.8	93.2	92.7	92.2
.58	(.0187)	94.9	94.4	93.9	93.3	92.8	92.3
.59	(.0192)	95.0	94.5	93.9	93.4	92.9	92.4
.60	(.0196)	95.0	94.5	94.0	93.5	93.0	92.5

Facility autocorrelation = 0.55

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-11: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER YEAR

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0058)	91.9	91.1	90.3	89.5	88.6	87.8
.21	(.0061)	92.0	91.2	90.4	89.6	88.8	88.0
.22	(.0064)	92.1	91.3	90.5	89.7	88.9	88.1
.23	(.0067)	92.2	91.4	90.6	89.8	89.0	88.2
.24	(.0070)	92.3	91.5	90.7	89.9	89.2	88.4
.25	(.0073)	92.3	91.6	90.8	90.0	89.3	88.5
.26	(.0076)	92.4	91.7	90.9	90.2	89.4	88.6
.27	(.0080)	92.5	91.8	91.0	90.3	89.5	88.8
.28	(.0083)	92.6	91.9	91.1	90.4	89.7	88.9
.29	(.0086)	92.7	92.0	91.2	90.5	89.8	89.0
.30	(.0089)	92.8	92.1	91.3	90.6	89.9	89.2
.31	(.0093)	92.9	92.2	91.4	90.7	90.0	89.3
.32	(.0096)	93.0	92.3	91.5	90.8	90.1	89.4
.33	(.0099)	93.0	92.3	91.7	91.0	90.3	89.6
.34	(.0103)	93.1	92.4	91.8	91.1	90.4	89.7
.35	(.0106)	93.2	92.5	91.9	91.2	90.5	89.8
.36	(.0110)	93.3	92.6	92.0	91.3	90.6	89.9
.37	(.0113)	93.4	92.7	92.1	91.4	90.7	90.1
.38	(.0117)	93.5	92.8	92.2	91.5	90.9	90.2
.39	(.0121)	93.6	92.9	92.3	91.6	91.0	90.3
.40	(.0124)	93.6	93.0	92.4	91.7	91.1	90.5
.41	(.0128)	93.7	93.1	92.5	91.8	91.2	90.6
.42	(.0132)	93.8	93.2	92.6	91.9	91.3	90.7
.43	(.0135)	93.9	93.3	92.7	92.0	91.4	90.8
.44	(.0139)	94.0	93.4	92.8	92.2	91.5	90.9
.45	(.0143)	94.0	93.4	92.9	92.3	91.7	91.1
.46	(.0147)	94.1	93.5	92.9	92.4	91.8	91.2
.47	(.0151)	94.2	93.6	93.0	92.5	91.9	91.3
.48	(.0155)	94.3	93.7	93.1	92.6	92.0	91.4
.49	(.0159)	94.4	93.8	93.2	92.7	92.1	91.5
.50	(.0164)	94.4	93.9	93.3	92.8	92.2	91.7
.51	(.0168)	94.5	94.0	93.4	92.9	92.3	91.8
.52	(.0172)	94.6	94.1	93.5	93.0	92.4	91.9
.53	(.0177)	94.7	94.1	93.6	93.1	92.5	92.0
.54	(.0181)	94.8	94.2	93.7	93.2	92.7	92.1
.55	(.0186)	94.8	94.3	93.8	93.3	92.8	92.2
.56	(.0190)	94.9	94.4	93.9	93.4	92.9	92.4
.57	(.0195)	95.0	94.5	94.0	93.5	93.0	92.5
.58	(.0200)	95.1	94.6	94.1	93.6	93.1	92.6
.59	(.0205)	95.1	94.6	94.2	93.7	93.2	92.7
.60	(.0210)	95.2	94.7	94.2	93.8	93.3	92.8

Facility autocorrelation = 0.60

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-12: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER YEAR

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0062)	92.0	91.2	90.4	89.6	88.8	88.0
.21	(.0066)	92.1	91.3	90.5	89.7	88.9	88.2
.22	(.0069)	92.2	91.4	90.6	89.9	89.1	88.3
.23	(.0072)	92.3	91.5	90.8	90.0	89.2	88.4
.24	(.0076)	92.4	91.6	90.9	90.1	89.3	88.6
.25	(.0079)	92.5	91.7	91.0	90.2	89.5	88.7
.26	(.0082)	92.6	91.8	91.1	90.3	89.6	88.9
.27	(.0086)	92.7	91.9	91.2	90.5	89.7	89.0
.28	(.0089)	92.8	92.0	91.3	90.6	89.9	89.1
.29	(.0093)	92.8	92.1	91.4	90.7	90.0	89.3
.30	(.0096)	92.9	92.2	91.5	90.8	90.1	89.4
.31	(.0100)	93.0	92.3	91.6	90.9	90.2	89.5
.32	(.0104)	93.1	92.4	91.7	91.1	90.4	89.7
.33	(.0107)	93.2	92.5	91.8	91.2	90.5	89.8
.34	(.0111)	93.3	92.6	92.0	91.3	90.6	89.9
.35	(.0115)	93.4	92.7	92.1	91.4	90.7	90.1
.36	(.0118)	93.5	92.8	92.2	91.5	90.9	90.2
.37	(.0122)	93.6	92.9	92.3	91.6	91.0	90.3
.38	(.0126)	93.6	93.0	92.4	91.7	91.1	90.5
.39	(.0130)	93.7	93.1	92.5	91.8	91.2	90.6
.40	(.0134)	93.8	93.2	92.6	92.0	91.3	90.7
.41	(.0138)	93.9	93.3	92.7	92.1	91.5	90.8
.42	(.0142)	94.0	93.4	92.8	92.2	91.6	91.0
.43	(.0146)	94.1	93.5	92.9	92.3	91.7	91.1
.44	(.0150)	94.1	93.6	93.0	92.4	91.8	91.2
.45	(.0154)	94.2	93.7	93.1	92.5	91.9	91.3
.46	(.0159)	94.3	93.7	93.2	92.6	92.0	91.5
.47	(.0163)	94.4	93.8	93.3	92.7	92.1	91.6
.48	(.0167)	94.5	93.9	93.4	92.8	92.3	91.7
.49	(.0172)	94.6	94.0	93.5	92.9	92.4	91.8
.50	(.0176)	94.6	94.1	93.6	93.0	92.5	91.9
.51	(.0181)	94.7	94.2	93.7	93.1	92.6	92.1
.52	(.0185)	94.8	94.3	93.7	93.2	92.7	92.2
.53	(.0190)	94.9	94.4	93.8	93.3	92.8	92.3
.54	(.0195)	94.9	94.4	93.9	93.4	92.9	92.4
.55	(.0200)	95.0	94.5	94.0	93.5	93.0	92.5
.56	(.0205)	95.1	94.6	94.1	93.6	93.1	92.6
.57	(.0210)	95.2	94.7	94.2	93.7	93.2	92.8
.58	(.0215)	95.2	94.8	94.3	93.8	93.3	92.9
.59	(.0220)	95.3	94.9	94.4	93.9	93.5	93.0
.60	(.0225)	95.4	94.9	94.5	94.0	93.6	93.1

Facility autocorrelation = 0.65

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-13: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER YEAR

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.2	91.4	90.6	89.8	89.0	88.2
.21	(.0071)	92.3	91.5	90.7	89.9	89.2	88.4
.22	(.0075)	92.3	91.6	90.8	90.1	89.3	88.5
.23	(.0079)	92.4	91.7	90.9	90.2	89.4	88.7
.24	(.0082)	92.5	91.8	91.1	90.3	89.6	88.8
.25	(.0086)	92.6	91.9	91.2	90.4	89.7	89.0
.26	(.0090)	92.7	92.0	91.3	90.6	89.8	89.1
.27	(.0093)	92.8	92.1	91.4	90.7	90.0	89.3
.28	(.0097)	92.9	92.2	91.5	90.8	90.1	89.4
.29	(.0101)	93.0	92.3	91.6	90.9	90.2	89.5
.30	(.0105)	93.1	92.4	91.7	91.1	90.4	89.7
.31	(.0109)	93.2	92.5	91.9	91.2	90.5	89.8
.32	(.0112)	93.3	92.6	92.0	91.3	90.6	90.0
.33	(.0116)	93.4	92.7	92.1	91.4	90.8	90.1
.34	(.0120)	93.5	92.8	92.2	91.5	90.9	90.2
.35	(.0124)	93.6	92.9	92.3	91.6	91.0	90.4
.36	(.0128)	93.7	93.0	92.4	91.8	91.1	90.5
.37	(.0133)	93.8	93.1	92.5	91.9	91.3	90.6
.38	(.0137)	93.8	93.2	92.6	92.0	91.4	90.8
.39	(.0141)	93.9	93.3	92.7	92.1	91.5	90.9
.40	(.0145)	94.0	93.4	92.8	92.2	91.6	91.0
.41	(.0150)	94.1	93.5	92.9	92.3	91.7	91.2
.42	(.0154)	94.2	93.6	93.0	92.4	91.9	91.3
.43	(.0158)	94.3	93.7	93.1	92.6	92.0	91.4
.44	(.0163)	94.4	93.8	93.2	92.7	92.1	91.5
.45	(.0167)	94.4	93.9	93.3	92.8	92.2	91.7
.46	(.0172)	94.5	94.0	93.4	92.9	92.3	91.8
.47	(.0177)	94.6	94.1	93.5	93.0	92.5	91.9
.48	(.0182)	94.7	94.2	93.6	93.1	92.6	92.0
.49	(.0186)	94.8	94.2	93.7	93.2	92.7	92.2
.50	(.0191)	94.9	94.3	93.8	93.3	92.8	92.3
.51	(.0196)	94.9	94.4	93.9	93.4	92.9	92.4
.52	(.0201)	95.0	94.5	94.0	93.5	93.0	92.5
.53	(.0206)	95.1	94.6	94.1	93.6	93.1	92.6
.54	(.0212)	95.2	94.7	94.2	93.7	93.2	92.7
.55	(.0217)	95.2	94.8	94.3	93.8	93.3	92.9
.56	(.0222)	95.3	94.9	94.4	93.9	93.4	93.0
.57	(.0228)	95.4	94.9	94.5	94.0	93.6	93.1
.58	(.0233)	95.5	95.0	94.6	94.1	93.7	93.2
.59	(.0239)	95.5	95.1	94.7	94.2	93.8	93.3
.60	(.0245)	95.6	95.2	94.7	94.3	93.9	93.4

Facility autocorrelation = 0.70

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

minimum efficiency critical values are accurate to within at least 0.2 percent (two tenths of one percent). Exhibits 2-14 through 2-25 show similar data for threshold failure rates of one per two years, one per five years, and one per ten years. (Given the randomness of the process, there is no set of operating conditions that can achieve a true zero rate of failure; some failures will occur randomly under any conditions.)

Policies in which averages are computed less frequently than daily, but are still thirty-day averages for the last thirty-days at the time of computation (for example, averages computed weekly or monthly) would, of course, result in fewer threshold failures <u>per year</u> for all facilities, whether or not operated in accordance with good practice, simply because there would be fewer occasions per year on which failures could occur. The effect on the rate of failures per year is, in fact, exactly proportional to the frequency of computation of the average.[1] Thus, if weekly averaging were used, in which a thirty-day average was computed for the thirty-day period ending, for example, on each Friday, the rate of threshold failures <u>per year</u> for any set of operating parameters would simply be one-seventh of that shown in the preceding exhibits. If averages are computed once every thirty days, the rate of failures per year would be one-thirtieth of that in the exhibits, etc. The exhibited critical operating levels at which one failure per year would occur, of course, no longer apply if the frequency of average computation is changed.

---

[1]This fact can be proven completely mathematically for all the processes considered here, whether involving the normal, lognormal, or other distribution. Somewhat in violation of intuition, the proposition remains true <u>no matter what the correlation structure</u> of the daily observations.

EXHIBIT 2-14: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TWO YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0054)	91.9	91.1	90.3	89.5	88.7	87.9
.21	(.0057)	92.0	91.2	90.4	89.6	88.8	88.0
.22	(.0060)	92.1	91.3	90.5	89.7	88.9	88.1
.23	(.0063)	92.2	91.4	90.6	89.8	89.0	88.3
.24	(.0065)	92.3	91.5	90.7	89.9	89.2	88.4
.25	(.0068)	92.4	91.6	90.8	90.1	89.3	88.5
.26	(.0071)	92.4	91.7	90.9	90.2	89.4	88.7
.27	(.0074)	92.5	91.8	91.0	90.3	89.5	88.8
.28	(.0077)	92.6	91.9	91.1	90.4	89.7	88.9
.29	(.0080)	92.7	92.0	91.2	90.5	89.8	89.1
.30	(.0083)	92.8	92.1	91.4	90.6	89.9	89.2
.31	(.0087)	92.9	92.2	91.5	90.7	90.0	89.3
.32	(.0090)	93.0	92.3	91.6	90.9	90.2	89.5
.33	(.0093)	93.1	92.4	91.7	91.0	90.3	89.6
.34	(.0096)	93.1	92.5	91.8	91.1	90.4	89.7
.35	(.0099)	93.2	92.5	91.9	91.2	90.5	89.8
.36	(.0103)	93.3	92.6	92.0	91.3	90.6	90.0
.37	(.0106)	93.4	92.7	92.1	91.4	90.8	90.1
.38	(.0109)	93.5	92.8	92.2	91.5	90.9	90.2
.39	(.0113)	93.6	92.9	92.3	91.6	91.0	90.3
.40	(.0116)	93.6	93.0	92.4	91.7	91.1	90.5
.41	(.0119)	93.7	93.1	92.5	91.8	91.2	90.6
.42	(.0123)	93.8	93.2	92.6	92.0	91.3	90.7
.43	(.0127)	93.9	93.3	92.7	92.1	91.4	90.8
.44	(.0130)	94.0	93.4	92.8	92.2	91.6	91.0
.45	(.0134)	94.1	93.5	92.9	92.3	91.7	91.1
.46	(.0138)	94.1	93.5	93.0	92.4	91.8	91.2
.47	(.0141)	94.2	93.6	93.1	92.5	91.9	91.3
.48	(.0145)	94.3	93.7	93.2	92.6	92.0	91.4
.49	(.0149)	94.4	93.8	93.3	92.7	92.1	91.6
.50	(.0153)	94.5	93.9	93.3	92.8	92.2	91.7
.51	(.0157)	94.5	94.0	93.4	92.9	92.3	91.8
.52	(.0161)	94.6	94.1	93.5	93.0	92.5	91.9
.53	(.0165)	94.7	94.2	93.6	93.1	92.6	92.0
.54	(.0169)	94.8	94.2	93.7	93.2	92.7	92.1
.55	(.0174)	94.8	94.3	93.8	93.3	92.8	92.3
.56	(.0178)	94.9	94.4	93.9	93.4	92.9	92.4
.57	(.0182)	95.0	94.5	94.0	93.5	93.0	92.5
.58	(.0187)	95.1	94.6	94.1	93.6	93.1	92.6
.59	(.0192)	95.1	94.7	94.2	93.7	93.2	92.7
.60	(.0196)	95.2	94.7	94.3	93.8	93.3	92.8

Facility autocorrelation = 0.55

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-15: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TWO YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0058)	92.0	91.2	90.4	89.6	88.8	88.0
.21	(.0061)	92.1	91.3	90.5	89.7	88.9	88.2
.22	(.0064)	92.2	91.4	90.6	89.9	89.1	88.3
.23	(.0067)	92.3	91.5	90.8	90.0	89.2	88.4
.24	(.0070)	92.4	91.6	90.9	90.1	89.3	88.6
.25	(.0073)	92.5	91.7	91.0	90.2	89.5	88.7
.26	(.0076)	92.6	91.8	91.1	90.3	89.6	88.9
.27	(.0080)	92.7	91.9	91.2	90.5	89.7	89.0
.28	(.0083)	92.8	92.0	91.3	90.6	89.9	89.1
.29	(.0086)	92.8	92.1	91.4	90.7	90.0	89.3
.30	(.0089)	92.9	92.2	91.5	90.8	90.1	89.4
.31	(.0093)	93.0	92.3	91.6	90.9	90.2	89.5
.32	(.0096)	93.1	92.4	91.7	91.0	90.4	89.7
.33	(.0099)	93.2	92.5	91.8	91.2	90.5	89.8
.34	(.0103)	93.3	92.6	91.9	91.3	90.6	89.9
.35	(.0106)	93.4	92.7	92.1	91.4	90.7	90.1
.36	(.0110)	93.5	92.8	92.2	91.5	90.9	90.2
.37	(.0113)	93.6	92.9	92.3	91.6	91.0	90.3
.38	(.0117)	93.6	93.0	92.4	91.7	91.1	90.5
.39	(.0121)	93.7	93.1	92.5	91.8	91.2	90.6
.40	(.0124)	93.8	93.2	92.6	92.0	91.3	90.7
.41	(.0128)	93.9	93.3	92.7	92.1	91.4	90.8
.42	(.0132)	94.0	93.4	92.8	92.2	91.6	91.0
.43	(.0135)	94.1	93.5	92.9	92.3	91.7	91.1
.44	(.0139)	94.1	93.6	93.0	92.4	91.8	91.2
.45	(.0143)	94.2	93.6	93.1	92.5	91.9	91.3
.46	(.0147)	94.3	93.7	93.2	92.6	92.0	91.5
.47	(.0151)	94.4	93.8	93.3	92.7	92.1	91.6
.48	(.0155)	94.5	93.9	93.4	92.8	92.3	91.7
.49	(.0159)	94.5	94.0	93.5	92.9	92.4	91.8
.50	(.0164)	94.6	94.1	93.6	93.0	92.5	91.9
.51	(.0168)	94.7	94.2	93.6	93.1	92.6	92.1
.52	(.0172)	94.8	94.3	93.7	93.2	92.7	92.2
.53	(.0177)	94.9	94.3	93.8	93.3	92.8	92.3
.54	(.0181)	94.9	94.4	93.9	93.4	92.9	92.4
.55	(.0186)	95.0	94.5	94.0	93.5	93.0	92.5
.56	(.0190)	95.1	94.6	94.1	93.6	93.1	92.6
.57	(.0195)	95.2	94.7	94.2	93.7	93.2	92.8
.58	(.0200)	95.2	94.8	94.3	93.8	93.3	92.9
.59	(.0205)	95.3	94.9	94.4	93.9	93.4	93.0
.60	(.0210)	95.4	94.9	94.5	94.0	93.6	93.1

Facility autocorrelation = 0.60

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-16: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TWO YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0062)	92.1	91.3	90.6	89.8	89.0	88.2
.21	(.0066)	92.2	91.5	90.7	89.9	89.1	88.4
.22	(.0069)	92.3	91.6	90.8	90.0	89.3	88.5
.23	(.0072)	92.4	91.7	90.9	90.2	89.4	88.6
.24	(.0076)	92.5	91.8	91.0	90.3	89.5	88.8
.25	(.0079)	92.6	91.9	91.2	90.4	89.7	88.9
.26	(.0082)	92.7	92.0	91.3	90.5	89.8	89.1
.27	(.0086)	92.8	92.1	91.4	90.7	89.9	89.2
.28	(.0089)	92.9	92.2	91.5	90.8	90.1	89.4
.29	(.0093)	93.0	92.3	91.6	90.9	90.2	89.5
.30	(.0096)	93.1	92.4	91.7	91.0	90.3	89.6
.31	(.0100)	93.2	92.5	91.8	91.1	90.5	89.8
.32	(.0104)	93.3	92.6	91.9	91.3	90.6	89.9
.33	(.0107)	93.4	92.7	92.0	91.4	90.7	90.1
.34	(.0111)	93.5	92.8	92.2	91.5	90.9	90.2
.35	(.0115)	93.6	92.9	92.3	91.6	91.0	90.3
.36	(.0118)	93.6	93.0	92.4	91.7	91.1	90.5
.37	(.0122)	93.7	93.1	92.5	91.9	91.2	90.6
.38	(.0126)	93.8	93.2	92.6	92.0	91.3	90.7
.39	(.0130)	93.9	93.3	92.7	92.1	91.5	90.9
.40	(.0134)	94.0	93.4	92.8	92.2	91.6	91.0
.41	(.0138)	94.1	93.5	92.9	92.3	91.7	91.1
.42	(.0142)	94.2	93.6	93.0	92.4	91.8	91.2
.43	(.0146)	94.3	93.7	93.1	92.5	92.0	91.4
.44	(.0150)	94.3	93.8	93.2	92.6	92.1	91.5
.45	(.0154)	94.4	93.9	93.3	92.7	92.2	91.6
.46	(.0159)	94.5	94.0	93.4	92.9	92.3	91.8
.47	(.0163)	94.6	94.0	93.5	93.0	92.4	91.9
.48	(.0167)	94.7	94.1	93.6	93.1	92.5	92.0
.49	(.0172)	94.7	94.2	93.7	93.2	92.6	92.1
.50	(.0176)	94.8	94.3	93.8	93.3	92.8	92.2
.51	(.0181)	94.9	94.4	93.9	93.4	92.9	92.4
.52	(.0185)	95.0	94.5	94.0	93.5	93.0	92.5
.53	(.0190)	95.1	94.6	94.1	93.6	93.1	92.6
.54	(.0195)	95.1	94.7	94.2	93.7	93.2	92.7
.55	(.0200)	95.2	94.7	94.3	93.8	93.3	92.8
.56	(.0205)	95.3	94.8	94.4	93.9	93.4	92.9
.57	(.0210)	95.4	94.9	94.4	94.0	93.5	93.1
.58	(.0215)	95.4	95.0	94.5	94.1	93.6	93.2
.59	(.0220)	95.5	95.1	94.6	94.2	93.7	93.3
.60	(.0226)	95.6	95.2	94.7	94.3	93.8	93.4

Facility autocorrelation = 0.65

---

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-17: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TWO YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.3	91.5	90.7	90.0	89.2	88.4
.21	(.0071)	92.4	91.6	90.9	90.1	89.3	88.6
.22	(.0075)	92.5	91.7	91.0	90.2	89.5	88.7
.23	(.0079)	92.6	91.9	91 1	90.4	89.6	88.9
.24	(.0082)	92.7	92.0	91.2	90.5	89.8	89.0
.25	(.0086)	92.8	92.1	91.4	90.6	89.9	89.2
.26	(.0090)	92.9	92.2	91.5	90.8	90.1	89.3
.27	(.0093)	93.0	92.3	91.6	90.9	90.2	89.5
.28	(.0097)	93.1	92.4	91.7	91.0	90.3	89.6
.29	(.0101)	93.2	92.5	91.8	91.1	90.5	89.8
.30	(.0105)	93.3	92.6	91.9	91.3	90.6	89.9
.31	(.0109)	93.4	92.7	92.1	91.4	90.7	90.1
.32	(.0112)	93.5	92.8	92.2	91.5	90.9	90.2
.33	(.0116)	93.6	92.9	92.3	91.6	91.0	90.4
.34	(.0120)	93.7	93.0	92.4	91.8	91.1	90.5
.35	(.0124)	93.8	93.1	92.5	91.9	91.3	90 6
.36	(0128)	93.9	93 2	92.6	92 0	91 4	90.8
.37	(0133)	93.9	93.3	92.7	92.1	91.5	90.9
.38	(.0137)	94.0	93.4	92.8	92.2	91.6	91.0
.39	(.0141)	94.1	93.5	92.9	92.4	91.8	91.2
.40	(.0145)	94.2	93.6	93.1	92.5	91.9	91.3
.41	(.0150)	94.3	93.7	93.2	92.6	92.0	91.4
.42	(.0154)	94.4	93.8	93.3	92.7	92.1	91.6
.43	(.0158)	94.5	93.9	93.4	92.8	92.3	91.7
.44	(.0163)	94.6	94.0	93.5	92.9	92.4	91.8
.45	(.0167)	94.6	94.1	93.6	93.0	92.5	92.0
.46	(.0172)	94.7	94.2	93.7	93.1	92.6	92.1
.47	(.0177)	94.8	94.3	93.8	93.3	92.7	92.2
.48	(.0182)	94.9	94.4	93.9	93.4	92.8	92.3
.49	(.0186)	95.0	94.5	94.0	93.5	93.0	92.5
.50	(.0191)	95.1	94.6	94.1	93.6	93.1	92.6
.51	(.0196)	95.1	94.6	94.2	93.7	93.2	92.7
.52	(.0201)	95.2	94.7	94.3	93.8	93.3	92.8
.53	(.0206)	95.3	94.8	94.3	93.9	93.4	92.9
.54	(.0212)	95.4	94.9	94.4	94.0	93.5	93.1
.55	(.0217)	95.4	95.0	94.5	94.1	93.6	93.2
.56	(.0222)	95.5	95.1	94.6	94.2	93.7	93.3
.57	(.0228)	95.6	95.2	94.7	94.3	93.8	93.4
.58	(.0233)	95.7	95.2	94.8	94.4	93.9	93.5
.59	(.0239)	95.7	95.3	94.9	94.5	94.0	93.6
.60	(.0245)	95.8	95.4	95.0	94.6	94.2	93.7

Facility autocorrelation = 0.70

[1]In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-18: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER FIVE YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0054)	92.0	91.2	90.4	89.7	88.9	88.1
.21	(.0057)	92.1	91.3	90.6	89.8	89.0	88.2
.22	(.0060)	92.2	91.5	90.7	89.9	89.1	88.3
.23	(.0063)	92.3	91.6	90.8	90.0	89.3	88.5
.24	(.0065)	92.4	91.7	90.9	90.1	89.4	88.6
.25	(.0068)	92.5	91.8	91.0	90.3	89.5	88.8
.26	(.0071)	92.6	91.9	91.1	90.4	89.6	88.9
.27	(.0074)	92.7	92.0	91.2	90.5	89.8	89.0
.28	(.0077)	92.8	92.1	91.4	90.6	89.9	89.2
.29	(.0080)	92.9	92.2	91.5	90.7	90.0	89.3
.30	(.0083)	93.0	92.3	91.6	90.9	90.2	89.5
.31	(.0087)	93.1	92.4	91.7	91.0	90.3	89.6
.32	(.0090)	93.2	92.5	91.8	91.1	90.4	89.7
.33	(.0093)	93.2	92.6	91.9	91.2	90.5	89.9
.34	(.0096)	93.3	92.7	92.0	91.3	90.7	90.0
.35	(.0099)	93.4	92.8	92.1	91.4	90.8	90.1
.36	(.0103)	93.5	92.9	92.2	91.6	90.9	90.3
.37	(.0106)	93.6	93.0	92.3	91.7	91.0	90.4
.38	(.0109)	93.7	93.0	92.4	91.8	91.2	90.5
.39	(.0113)	93.8	93.1	92.5	91.9	91.3	90.7
.40	(.0116)	93.9	93.2	92.6	92.0	91.4	90.8
.41	(.0119)	93.9	93.3	92.7	92.1	91.5	90.9
.42	(.0123)	94.0	93.4	92.8	92.2	91.6	91.0
.43	(.0127)	94.1	93.5	92.9	92.3	91.7	91.2
.44	(.0130)	94.2	93.6	93.0	92.4	91.9	91.3
.45	(.0134)	94.3	93.7	93.1	92.6	92.0	91.4
.46	(.0138)	94.4	93.8	93.2	92.7	92.1	91.5
.47	(.0141)	94.4	93.9	93.3	92.8	92.2	91.7
.48	(.0145)	94.5	94.0	93.4	92.9	92.3	91.8
.49	(.0149)	94.6	94.1	93.5	93.0	92.4	91.9
.50	(.0153)	94.7	94.1	93.6	93.1	92.5	92.0
.51	(.0157)	94.8	94.2	93.7	93.2	92.7	92.1
.52	(.0161)	94.8	94.3	93.8	93.3	92.8	92.3
.53	(.0165)	94.9	94.4	93.9	93.4	92.9	92.4
.54	(.0169)	95.0	94.5	94.0	93.5	93.0	92.5
.55	(.0174)	95.1	94.6	94.1	93.6	93.1	92.6
.56	(.0178)	95.1	94.7	94.2	93.7	93.2	92.7
.57	(.0182)	95.2	94.7	94.3	93.8	93.3	92.8
.58	(.0187)	95.3	94.8	94.4	93.9	93.4	92.9
.59	(.0192)	95.4	94.9	94.4	94.0	93.5	93.1
.60	(.0196)	95.4	95.0	94.5	94.1	93.6	93.2

Facility autocorrelation = 0.55

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-19: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER FIVE YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0058)	92.2	91.4	90.6	89.8	89.0	88.2
.21	(.0061)	92.3	91.5	90.7	89.9	89.2	88.4
.22	(.0064)	92.4	91.6	90.8	90.1	89.3	88.5
.23	(.0067)	92.5	91.7	90.9	90.2	89.4	88.7
.24	(.0070)	92.6	91.8	91.1	90.3	89.6	88.8
.25	(.0073)	92.6	91.9	91.2	90.4	89.7	89.0
.26	(.0076)	92.7	92.0	91.3	90.6	89.8	89.1
.27	(.0080)	92.8	92.1	91.4	90.7	90.0	89.3
.28	(.0083)	92.9	92.2	91.5	90.8	90.1	89.4
.29	(.0086)	93.0	92.3	91.6	90.9	90.2	89.5
.30	(.0089)	93.1	92.4	91.8	91.1	90.4	89.7
.31	(.0093)	93.2	92.5	91.9	91.2	90.5	89.8
.32	(.0096)	93.3	92.6	92.0	91.3	90.6	90.0
.33	(.0099)	93.4	92.7	92.1	91.4	90.8	90.1
.34	(.0103)	93.5	92.8	92.2	91.5	90.9	90.2
.35	(.0106)	93.6	92.9	92.3	91.7	91.0	90.4
.36	(.0110)	93.7	93.0	92.4	91.8	91.1	90.5
.37	(.0113)	93.8	93.1	92.5	91.9	91.3	90.6
.38	(.0117)	93.9	93.2	92.6	92.0	91.4	90.8
.39	(.0121)	93.9	93.3	92.7	92.1	91.5	90.9
.40	(.0124)	94.0	93.4	92.8	92.2	91.6	91.0
.41	(.0128)	94.1	93.5	92.9	92.3	91.8	91.2
.42	(.0132)	94.2	93.6	93.0	92.5	91.9	91.3
.43	(.0135)	94.3	93.7	93.1	92.6	92.0	91.4
.44	(.0139)	94.4	93.8	93.2	92.7	92.1	91.5
.45	(.0143)	94.4	93.9	93.3	92.8	92.2	91.7
.46	(.0147)	94.5	94.0	93.4	92.9	92.3	91.8
.47	(.0151)	94.6	94.1	93.5	93.0	92.5	91.9
.48	(.0155)	94.7	94.2	93.6	93.1	92.6	92.0
.49	(.0159)	94.8	94.3	93.7	93.2	92.7	92.2
.50	(.0164)	94.9	94.3	93.8	93.3	92.8	92.3
.51	(.0168)	94.9	94.4	93.9	93.4	92.9	92.4
.52	(.0172)	95.0	94.5	94.0	93.5	93.0	92.5
.53	(.0177)	95.1	94.6	94.1	93.6	93.1	92.6
.54	(.0181)	95.2	94.7	94.2	93.7	93.2	92.8
.55	(.0186)	95.2	94.8	94.3	93.8	93.3	92.9
.56	(.0190)	95.3	94.9	94.4	93.9	93.5	93.0
.57	(.0195)	95.4	94.9	94.5	94.0	93.6	93.1
.58	(.0200)	95.5	95.0	94.6	94.1	93.7	93.2
.59	(.0205)	95.6	95.1	94.7	94.2	93.8	93.3
.60	(.0210)	95.6	95.2	94.8	94.3	93.9	93.4

Facility autocorrelation = 0.60

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-20: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER FIVE YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0062)	92.3	91.5	90.8	90.0	89.2	88.4
.21	(.0066)	92.4	91.6	90.9	90.1	89.4	88.6
.22	(.0069)	92.5	91.8	91.0	90.3	89.5	88.8
.23	(.0072)	92.6	91.9	91.1	90.4	89.6	88.9
.24	(.0076)	92.7	92.0	91.2	90.5	89.8	89.1
.25	(.0079)	92.8	92.1	91.4	90.6	89.9	89.2
.26	(.0082)	92.9	92.2	91.5	90.8	90.1	89.4
.27	(.0086)	93.0	92.3	91.6	90.9	90.2	89.5
.28	(.0089)	93.1	92.4	91.7	91.0	90.3	89.7
.29	(.0093)	93.2	92.5	91.8	91.2	90.5	89.8
.30	(.0096)	93.3	92.6	92.0	91.3	90.6	89.9
.31	(.0100)	93.4	92.7	92.1	91.4	90.8	90.1
.32	(.0104)	93.5	92.8	92.2	91.5	90.9	90.2
.33	(.0107)	93.6	92.9	92.3	91.7	91.0	90.4
.34	(.0111)	93.7	93.0	92.4	91.8	91.1	90.5
.35	(.0115)	93.8	93.1	92.5	91.9	91.3	90.7
.36	(.0118)	93.9	93.2	92.6	92.0	91.4	90.8
.37	(.0122)	94.0	93.3	92.7	92.1	91.5	90.9
.38	(.0126)	94.0	93.4	92.9	92.3	91.7	91.1
.39	(.0130)	94.1	93.5	93.0	92.4	91.8	91.2
.40	(.0134)	94.2	93.6	93.1	92.5	91.9	91.3
.41	(.0138)	94.3	93.7	93.2	92.6	92.0	91.5
.42	(.0142)	94.4	93.8	93.3	92.7	92.2	91.6
.43	(.0146)	94.5	93.9	93.4	92.8	92.3	91.7
.44	(.0150)	94.6	94.0	93.5	92.9	92.4	91.8
.45	(.0154)	94.7	94.1	93.6	93.0	92.5	92.0
.46	(.0159)	94.7	94.2	93.7	93.2	92.6	92.1
.47	(.0163)	94.8	94.3	93.8	93.3	92.7	92.2
.48	(.0167)	94.9	94.4	93.9	93.4	92.9	92.4
.49	(.0172)	95.0	94.5	94.0	93.5	93.0	92.5
.50	(.0176)	95.1	94.6	94.1	93.6	93.1	92.6
.51	(.0181)	95.1	94.7	94.2	93.7	93.2	92.7
.52	(.0185)	95.2	94.7	94.3	93.8	93.3	92.8
.53	(.0190)	95.3	94.8	94.4	93.9	93.4	93.0
.54	(.0195)	95.4	94.9	94.5	94.0	93.5	93.1
.55	(.0200)	95.5	95.0	94.5	94.1	93.6	93.2
.56	(.0205)	95.5	95.1	94.6	94.2	93.7	93.3
.57	(.0210)	95.6	95.2	94.7	94.3	93.9	93.4
.58	(.0215)	95.7	95.3	94.8	94.4	94.0	93.5
.59	(.0220)	95.8	95.3	94.9	94.5	94.1	93.6
.60	(.0225)	95.8	95.4	95.0	94.6	94.2	93.7

Facility autocorrelation = 0.65

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-21: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER FIVE YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.4	91.7	90.9	90.2	89.4	88.7
.21	(.0071)	92.6	91.8	91.1	90.3	89.6	88.8
.22	(.0075)	92.7	91.9	91.2	90.5	89.7	89.0
.23	(.0079)	92.8	92.1	91.3	90.6	89.9	89.2
.24	(.0082)	92.9	92.2	91.5	90.7	90.0	89.3
.25	(.0086)	93.0	92.3	91.6	90.9	90.2	89.5
.26	(.0090)	93.1	92.4	91.7	91.0	90.3	89.6
.27	(.0093)	93.2	92.5	91.8	91.2	90.5	89.8
.28	(.0097)	93.3	92.6	92.0	91.3	90.6	89.9
.29	(.0101)	93.4	92.7	92.1	91.4	90.8	90.1
.30	(.0105)	93.5	92.8	92.2	91.5	90.9	90.2
.31	(.0109)	93.6	93.0	92.3	91.7	91.0	90.4
.32	(.0112)	93.7	93.1	92.4	91.8	91.2	90.5
.33	(.0116)	93.8	93.2	92.6	91.9	91.3	90.7
.34	(.0120)	93.9	93.3	92.7	92.1	91.4	90.8
.35	(.0124)	94.0	93.4	92.8	92.2	91.6	91.0
.36	(.0128)	94.1	93.5	92.9	92.3	91.7	91.1
.37	(.0133)	94.2	93.6	93.0	92.4	91.8	91.3
.38	(.0137)	94.3	93.7	93.1	92.5	92.0	91.4
.39	(.0141)	94.4	93.8	93.2	92.7	92.1	91.5
.40	(.0145)	94.4	93.9	93.3	92.8	92.2	91.7
.41	(.0150)	94.5	94.0	93.4	92.9	92.3	91.8
.42	(.0154)	94.6	94.1	93.5	93.0	92.5	91.9
.43	(.0158)	94.7	94.2	93.7	93.1	92.6	92.1
.44	(.0163)	94.8	94.3	93.8	93.2	92.7	92.2
.45	(.0167)	94.9	94.4	93.9	93.3	92.8	92.3
.46	(.0172)	95.0	94.5	94.0	93.5	93.0	92.5
.47	(.0177)	95.1	94.6	94.1	93.6	93.1	92.6
.48	(.0182)	95.1	94.6	94.2	93.7	93.2	92.7
.49	(.0186)	95.2	94.7	94.3	93.8	93.3	92.8
.50	(.0191)	95.3	94.8	94.4	93.9	93.4	92.9
.51	(.0196)	95.4	94.9	94.5	94.0	93.5	93.1
.52	(.0201)	95.5	95.0	94.5	94.1	93.6	93.2
.53	(.0206)	95.5	95.1	94.6	94.2	93.8	93.3
.54	(.0212)	95.6	95.2	94.7	94.3	93.9	93.4
.55	(.0217)	95.7	95.3	94.8	94.4	94.0	93.5
.56	(.0222)	95.8	95.3	94.9	94.5	94.1	93.7
.57	(.0228)	95.8	95.4	95.0	94.6	94.2	93.8
.58	(.0233)	95.9	95.5	95.1	94.7	94.3	93.9
.59	(.0239)	96.0	95.6	95.2	94.8	94.4	94.0
.60	(.0245)	96.1	95.7	95.3	94.9	94.5	94.1

Facility autocorrelation = 0.70

---

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-22: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TEN YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0054)	92.1	91.3	90.6	89.8	89.0	88.2
.21	(.0057)	92.2	91.5	90.7	89.9	89.1	88.3
.22	(.0060)	92.3	91.6	90.8	90.0	89.3	88.5
.23	(.0063)	92.4	91.7	90.9	90.2	89.4	88.6
.24	(.0065)	92.5	91.8	91.0	90.3	89.5	88.8
.25	(.0068)	92.6	91.9	91.1	90.4	89.7	88.9
.26	(.0071)	92.7	92.0	91.3	90.5	89.8	89.1
.27	(.0074)	92.8	92.1	91.4	90.7	89.9	89.2
.28	(.0077)	92.9	92.2	91.5	90.8	90.1	89.4
.29	(.0080)	93.0	92.3	91.6	90.9	90.2	89.5
.30	(.0083)	93.1	92.4	91.7	91.0	90.3	89.6
.31	(.0087)	93.2	92.5	91.8	91.1	90.5	89.8
.32	(.0090)	93.3	92.6	91.9	91.3	90.6	89.9
.33	(.0093)	93.4	92.7	92.0	91.4	90.7	90.1
.34	(.0096)	93.5	92.8	92.2	91.5	90.8	90.2
.35	(.0099)	93.5	92.9	92.3	91.6	91.0	90.3
.36	(.0103)	93.6	93.0	92.4	91.7	91.1	90.5
.37	(.0106)	93.7	93.1	92.5	91.8	91.2	90.6
.38	(.0109)	93.8	93.2	92.6	92.0	91.3	90.7
.39	(.0113)	93.9	93.3	92.7	92.1	91.5	90.9
.40	(.0116)	94.0	93.4	92.8	92.2	91.6	91.0
.41	(.0119)	94.1	93.5	92.9	92.3	91.7	91.1
.42	(.0123)	94.2	93.6	93.0	92.4	91.8	91.2
.43	(.0127)	94.2	93.7	93.1	92.5	91.9	91.4
.44	(.0130)	94.3	93.8	93.2	92.6	92.1	91.5
.45	(.0134)	94.4	93.9	93.3	92.7	92.2	91.6
.46	(.0138)	94.5	93.9	93.4	92.8	92.3	91.7
.47	(.0141)	94.6	94.0	93.5	93.0	92.4	91.9
.48	(.0145)	94.7	94.1	93.6	93.1	92.5	92.0
.49	(.0149)	94.7	94.2	93.7	93.2	92.6	92.1
.50	(.0153)	94.8	94.3	93.8	93.3	92.7	92.2
.51	(.0157)	94.9	94.4	93.9	93.4	92.9	92.3
.52	(.0161)	95.0	94.5	94.0	93.5	93.0	92.5
.53	(.0165)	95.1	94.6	94.1	93.6	93.1	92.6
.54	(.0169)	95.1	94.6	94.2	93.7	93.2	92.7
.55	(.0174)	95.2	94.7	94.3	93.8	93.3	92.8
.56	(.0178)	95.3	94.8	94.3	93.9	93.4	92.9
.57	(.0182)	95.4	94.9	94.4	94.0	93.5	93.0
.58	(.0187)	95.4	95.0	94.5	94.1	93.6	93.2
.59	(.0192)	95.5	95.1	94.6	94.2	93.7	93.3
.60	(.0196)	95.6	95.1	94.7	94.3	93.8	93.4

Facility autocorrelation = 0.55

---

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-23: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TEN YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0058)	92.3	91.5	90.7	89.9	89.2	88.4
.21	(.0061)	92.4	91.6	90.8	90.1	89.3	88.5
.22	(.0064)	92.5	91.7	91.0	90.2	89.4	88.7
.23	(.0067)	92.6	91.8	91.1	90.3	89.6	88.8
.24	(.0070)	92.7	91.9	91.2	90.5	89.7	89.0
.25	(.0073)	92.8	92.0	91.3	90.6	89.9	89.1
.26	(.0076)	92.9	92.1	91.4	90.7	90.0	89.3
.27	(.0080)	93.0	92.3	91.6	90.8	90.1	89.4
.28	(.0083)	93.1	92.4	91.7	91.0	90.3	89.6
.29	(.0086)	93.2	92.5	91.8	91.1	90.4	89.7
.30	(.0089)	93.3	92.6	91.9	91.2	90.6	89.9
.31	(.0093)	93.3	92.7	92.0	91.3	90.7	90.0
.32	(.0096)	93.4	92.8	92.1	91.5	90.8	90.2
.33	(.0099)	93.5	92.9	92.2	91.6	90.9	90.3
.34	(.0103)	93.6	93.0	92.4	91.7	91.1	90.4
.35	(.0106)	93.7	93.1	92.5	91.8	91.2	90.6
.36	(.0110)	93.8	93.2	92.6	92.0	91.3	90.7
.37	(.0113)	93.9	93.3	92.7	92.1	91.5	90.8
.38	(.0117)	94.0	93.4	92.8	92.2	91.6	91.0
.39	(.0121)	94.1	93.5	92.9	92.3	91.7	91.1
.40	(.0124)	94.2	93.6	93.0	92.4	91.8	91.2
.41	(.0128)	94.3	93.7	93.1	92.5	92.0	91.4
.42	(.0132)	94.3	93.8	93.2	92.6	92.1	91.5
.43	(.0135)	94.4	93.9	93.3	92.8	92.2	91.6
.44	(.0139)	94.5	94.0	93.4	92.9	92.3	91.8
.45	(.0143)	94.6	94.1	93.5	93.0	92.4	91.9
.46	(.0147)	94.7	94.1	93.6	93.1	92.5	92.0
.47	(.0151)	94.8	94.2	93.7	93.2	92.7	92.1
.48	(.0155)	94.8	94.3	93.8	93.3	92.8	92.3
.49	(.0159)	94.9	94.4	93.9	93.4	92.9	92.4
.50	(.0164)	95.0	94.5	94.0	93.5	93.0	92.5
.51	(.0168)	95.1	94.6	94.1	93.6	93.1	92.6
.52	(.0172)	95.2	94.7	94.2	93.7	93.2	92.7
.53	(.0177)	95.2	94.8	94.3	93.8	93.3	92.9
.54	(.0181)	95.3	94.9	94.4	93.9	93.5	93.0
.55	(.0186)	95.4	94.9	94.5	94.0	93.6	93.1
.56	(.0190)	95.5	95.0	94.5	94.1	93.7	93.2
.57	(.0195)	95.6	95.1	94.7	94.2	93.8	93.3
.58	(.0200)	95.6	95.2	94.8	94.3	93.9	93.4
.59	(.0205)	95.7	95.3	94.8	94.4	94.0	93.6
.60	(.0210)	95.8	95.4	94.9	94.5	94.1	93.7

Facility autocorrelation = 0.60

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-24: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TEN YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0062)	92.4	91.6	90.9	90.1	89.4	88.6
.21	(.0066)	92.5	91.8	91.0	90.3	89.5	88.8
.22	(.0069)	92.6	91.9	91.1	90.4	89.7	88.9
.23	(.0072)	92.7	92.0	91.3	90.5	89.8	89.1
.24	(.0076)	92.8	92.1	91.4	90.7	89.9	89.2
.25	(.0079)	92.9	92.2	91.5	90.8	90.1	89.4
.26	(.0082)	93.0	92.3	91.6	90.9	90.2	89.5
.27	(.0086)	93.1	92.4	91.8	91.1	90.4	89.7
.28	(.0089)	93.2	92.6	91.9	91.2	90.5	89.8
.29	(.0093)	93.3	92.7	92.0	91.3	90.7	90.0
.30	(.0096)	93.4	92.8	92.1	91.5	90.8	90.1
.31	(.0100)	93.5	92.9	92.2	91.6	90.9	90.3
.32	(.0104)	93.6	93.0	92.3	91.7	91.1	90.4
.33	(.0107)	93.7	93.1	92.5	91.8	91.2	90.6
.34	(.0111)	93.8	93.2	92.6	92.0	91.3	90.7
.35	(.0115)	93.9	93.3	92.7	92.1	91.5	90.9
.36	(.0118)	94.0	93.4	92.8	92.2	91.6	91.0
.37	(.0122)	94.1	93.5	92.9	92.3	91.7	91.1
.38	(.0126)	94.2	93.6	93.0	92.4	91.9	91.3
.39	(.0130)	94.3	93.7	93.1	92.6	92.0	91.4
.40	(.0134)	94.4	93.8	93.2	92.7	92.1	91.5
.41	(.0138)	94.5	93.9	93.3	92.8	92.2	91.7
.42	(.0142)	94.5	94.0	93.5	92.9	92.4	91.8
.43	(.0146)	94.6	94.1	93.6	93.0	92.5	91.9
.44	(.0150)	94.7	94.2	93.7	93.1	92.6	92.1
.45	(.0154)	94.8	94.3	93.8	93.2	92.7	92.2
.46	(.0159)	94.9	94.4	93.9	93.4	92.8	92.3
.47	(.0163)	95.0	94.5	94.0	93.5	93.0	92.5
.48	(.0167)	95.1	94.6	94.1	93.6	93.1	92.6
.49	(.0172)	95.1	94.6	94.2	93.7	93.2	92.7
.50	(.0176)	95.2	94.7	94.3	93.8	93.3	92.8
.51	(.0181)	95.3	94.8	94.4	93.9	93.4	92.9
.52	(.0185)	95.4	94.9	94.5	94.0	93.5	93.1
.53	(.0190)	95.5	95.0	94.5	94.1	93.6	93.2
.54	(.0195)	95.5	95.1	94.6	94.2	93.7	93.3
.55	(.0200)	95.6	95.2	94.7	94.3	93.9	93.4
.56	(.0205)	95.7	95.3	94.8	94.4	94.0	93.5
.57	(.0210)	95.8	95.3	94.9	94.5	94.1	93.6
.58	(.0215)	95.8	95.4	95.0	94.6	94.2	93.8
.59	(.0220)	95.9	95.5	95.1	94.7	94.3	93.9
.60	(.0226)	96.0	95.6	95.2	94.8	94.4	94.0

Facility autocorrelation = 0.65

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

EXHIBIT 2-25: MINIMUM GEOMETRIC MEAN EFFICIENCIES REQUIRED TO MAINTAIN NO MORE THAN ONE FAILURE PER TEN YEARS

Daily Std. Dev. (in log)	Std. Dev. of 30-Day Average[1]	Minimum Efficiency For Threshold Shown					
		<90%	<89%	<88%	<87%	<86%	<85%
.20	(.0068)	92.6	91.8	91.1	90.3	89.6	88.8
.21	(.0071)	92.7	91.9	91.2	90.5	89.7	89.0
.22	(.0075)	92.8	92.1	91.3	90.6	89.9	89.2
.23	(.0079)	92.9	92.2	91.5	90.8	90.1	89.3
.24	(.0082)	93.0	92.3	91.6	90.9	90.2	89.5
.25	(.0086)	93.1	92.4	91.7	91.0	90.4	89.7
.26	(.0090)	93.2	92.5	91.9	91.2	90.5	89.8
.27	(.0093)	93.3	92.7	92.0	91.3	90.7	90.0
.28	(.0097)	93.4	92.8	92.1	91.5	90.8	90.1
.29	(.0101)	93.5	92.9	92.2	91.6	90.9	90.3
.30	(.0105)	93.6	93.0	92.4	91.7	91.1	90.5
.31	(.0109)	93.7	93.1	92.5	91.9	91.2	90.6
.32	(.0112)	93.8	93.2	92.6	92.0	91.4	90.8
.33	(.0116)	93.9	93.3	92.7	92.1	91.5	90.9
.34	(.0120)	94.0	93.4	92.8	92.2	91.6	91.1
.35	(.0124)	94.1	93.5	93.0	92.4	91.8	91.2
.36	(.0128)	94.2	93.6	93.1	92.5	91.9	91.3
.37	(.0133)	94.3	93.8	93.2	92.6	92.0	91.5
.38	(.0137)	94.4	93.9	93.3	92.7	92.2	91.6
.39	(.0141)	94.5	94.0	93.4	92.9	92.3	91.8
.40	(.0145)	94.6	94.1	93.5	93.0	92.4	91.9
.41	(.0150)	94.7	94.2	93.6	93.1	92.6	92.0
.42	(.0154)	94.8	94.3	93.7	93.2	92.7	92.2
.43	(.0158)	94.9	94.4	93.8	93.3	92.8	92.3
.44	(.0163)	95.0	94.4	93.9	93.4	92.9	92.4
.45	(.0167)	95.0	94.5	94.0	93.5	93.1	92.6
.46	(.0172)	95.1	94.6	94.1	93.7	93.2	92.7
.47	(.0177)	95.2	94.7	94.2	93.8	93.3	92.8
.48	(.0182)	95.3	94.8	94.3	93.9	93.4	92.9
.49	(.0186)	95.4	94.9	94.4	94.0	93.5	93.1
.50	(.0191)	95.5	95.0	94.5	94.1	93.6	93.2
.51	(.0196)	95.5	95.1	94.6	94.2	93.7	93.3
.52	(.0201)	95.6	95.2	94.7	94.3	93.9	93.4
.53	(.0206)	95.7	95.3	94.8	94.4	94.0	93.5
.54	(.0212)	95.8	95.3	94.9	94.5	94.1	93.7
.55	(.0217)	95.8	95.4	95.0	94.6	94.2	93.8
.56	(.0222)	95.9	95.5	95.1	94.7	94.3	93.9
.57	(.0228)	96.0	95.6	95.2	94.8	94.4	94.0
.58	(.0233)	96.1	95.7	95.3	94.9	94.5	94.1
.59	(.0239)	96.1	95.8	95.4	95.0	94.6	94.2
.60	(.0245)	96.2	95.8	95.5	95.1	94.7	94.3

Facility autocorrelation = 0.70

---

[1] In computing the 30-day average variability, a geometric mean emission level of 92% was assumed.

2.3 METHODOLOGY

Monte-Carlo simulation techniques were used to generate the data in for the lognormal-distribution processes in exhibits 2-4 through 2-9. The IBM Scientific Subroutine Package uniform random number generator RANDU was used to generate the basic pseudo-random number stream for the analyses. Box and Muller's technique was used for generating pseudo-random normal random deviates (with an accuracy in the resultant distribution of at least six digits).[1] Lognormal deviates were generated by the exponential function from these normal deviates. All the estimates were generated using non-overlapping random-number streams of 720,000 days (2,000 years). The standard errors of the estimates were estimated by treating the 2,000 years as four replicated experiments of 500 years each. The computations were performed to 32 and 64 bit accuracy on a Hewlett-Packard Series 1000 Model F computer, and the runs consumed about 40 CPU hours of computation. The simulation was checked by comparing statistics for which exact results were known from theory, and all cases agreed to three or more digit accuracies (with sample periods of 8,000,000 days in this testing).

The normal-distribution estimates were generated by exact solution of the mathematical system, to accuracy of five or more decimals. Completely exact solutions of the lognormal case were not available, which led to the use of Monte-Carlo simulation. The critical values given in exhibits 2-10 through 2-25 could not be found with the required accuracy by simulation in the two-week term of this analysis, because

---

[1]This technique is significantly more accurate in its results than those usually used in good statistical practice. It was used because of the requirement to estimate very small probabilities.

such a determination by simulating all points necessary to search for the critical values would have required approximately 2000 hours of computer time. Accordingly, mathematical methods were used to compute these values to within 0.2 percent. These methods, although derived from standard techniques, were developed specifically for this analysis. The techniques involve first using series approximations to the lognormal distribution function and to its thirtieth convolution with itself, so as to obtain accurate estimates of the third and fourth moments and cumulants of the statistical distribution of the thirty-day averages. (The first and second moments are known exactly in closed form.) These estimates are then used in Edgeworth and Cornish-Fisher series expansions of the distribution of the thirty-day averages, from which expected rates of threshold failures and critical values can be completed. It was found that only one non-normal term of the Edgeworth expansion was required to achieve the desired accuracy. These methods were compared with the simulation techniques to verify their accuracy (and the accuracy of the computer implementations used.) All results were within 0.1 percent of the correct values as determined by simulation, indicating that the expansions are somewhat more accurate in the region of interest than the guaranteed bound of 0.2 percent we obtained analytically. The exact expression used to compute the critical minimum-efficiency values reported above is given in exhibit 2-26.

EXHIBIT 2-26: FORMULA FOR ESTIMATING THE GEOMETRIC MEAN EFFICIENCY AT WHICH A LOGNORMAL PROCESS WILL ACHIEVE A RATE OF ROLLING-AVERAGE THRESHOLD FAILURES BELOW ONE PER YEAR[1]

$$1 - \frac{1 - Z}{\left(2.773 + 1.115 \frac{\sigma\left[60 + 4f(r^2) + 2f(r) + 4\sum_{1}^{29}(30-i)(i-1)r^i + 8\sum_{1}^{29}(30-i)\frac{r^{i+1}(1-r^{i-1})}{1-r}\right]}{18000\,[.0333 + .00222\, f(r)]^{3/2}}\right) X + e^{\sigma^2/2}}$$

with

$f(r) = r/(1-r) - y(1-r^{30})/(1-r)^2$ and similarly for $f(r^2)$

$r = (e^{\rho\sigma^2} - 1)/(e^{\sigma^2} - 1)$

$w = e^{\sigma^2/2}$

and

$x = [\, e^{\sigma^2}(e^{\sigma^2} - 1)(.0333 + .00222\, f(r))\,]^{1/2}$

where

σ and ρ are the parameters describing the variability and autocorrelation of the lognormal process and Z is the threshold at which the rate of failures is to be $\leq$ 1/year.

---

[1]Other critical rates involve changes in the constants 2.773 and 1.115.

3.0 DESCRIPTIVE STATISTICS ON FGD SYSTEM EFFICIENCY DATA

Basic descriptive statistics were required in construction of the model simulating the variable efficiency of steam generating units. The appropriate model structure and statistical distribution characteristics were determined from an examination of observations reported from eleven operating units. In addition, operating system parameters were varied over ranges determined partly on the basis of parameter estimates made from the data. This chapter consists of four sections describing the observations and statistical analyses of them.

Section 3.1 defines the variable analyzed and describes the data base used. A lognormal description of the analysis variable was used by EPA and Entropy in previous analysis of this data. Section 3.2 discusses the appropriateness of such a description. As was shown in the analysis reported in chapter 2.0, the issue of distributional form has little influence on the principal results. In section 3.3 the means, standard deviations, and autocorrelation factors are presented for each of the eleven units. Differences in these parameters among the eleven units are also noted. Additionally, the appropriateness of a first-order autogressive model is discussed. Section 3.4 discusses possible confounding of results caused by variation in the sulfur content of untreated emissions.

3.1 DATA SET

Data on the efficiency factor from eleven electric utility steam generating units were provided to VRI by the EPA. The data which was received in printed tabular form was believed to be that previously analyzed by EPA and Entropy. The eleven units, the number of observations from each and the time period in which the observations were made are described in exhibit 3-1. Each observation represents a twenty-four hour average of FGD system efficiency calculated from the unput and output emission levels at each unit. (Efficiency was defined as the percentage of SO_2 removed from the gas flow through the scrubbing process.)

As shown in exhibit 3-1, the amount and time frame of the data differed significantly from one unit to the next. The limited number of observations from the Philadelphia and Pittsburgh II units make the data from these two facilities of limited use. The twenty-four data points from Conesville A and the twenty-one from Conesville B represent the only measurements taken over a six-month period. Further, the data set for any individual unit was generally characterized by intermittant data voids. This scattering of data points limits the degree of certainty with which any inferences concerning the correlation structure of the process should be reviewed.

3.2 LOGNORMAL TRANSFORMATION

3.2.1 THE UNTRANSFORMED VARIABLE

An analysis of the distribution of the efficiency values for each of the units indicated that at least four were clearly negatively skewed (see exhibit 3-2). Skewness, the third moment about the mean, measures the degree to which a distribution is unbalanced or "off-center". A negative skewness factor indicates a distribution with a long left-hand tail. A variable with a normal distribution is balanced and has a skewness of zero. Two of the units with significant skewness were also

EXHIBIT 3-1: ANALYSIS DATA BASE DESCRIPTION

Steam Generating Unit	Number of Observations	Time Period During Which Observations Were Made	
Louisville North	66	July 21, 1977 - Dec. 23, 1977	(156 days)
Louisville South	89	July 21, 1977 - Dec. 23, 1977	(156 days)
Pittsburgh I	20	Sept. 14, 1977 - Nov. 9, 1977	(57 days)
Pittsburgh II	11	Nov. 10, 1977 - Dec. 6, 1977	(27 days)
Philadelphia	8	Sept. 18, 1977 - Oct. 9, 1977	(22 days)
Chicago	52	Aug. 9, 1977 - Nov. 23, 1977 July 30, 1978 - Sept. 8, 1978	(107 days) (41 days)
Shawnee TCA	42	Dec. 7, 1978 - Jan. 25, 1979	(49 days)
Shawnee Venturi	31	Dec. 7, 1978 - Jan. 29, 1979	(51 days)
Conesville A	24	June 15, 1978 - Dec. 13, 1978	(183 days)
Conesville B	21	June 15, 1978 - Dec. 13, 1978	(183 days)
Lawrence	30	Jan. 16, 1979 - Feb. 21, 1979	(37 days)

EXHIBIT 3-2: SKEWNESS[1] AND KURTOSIS[2] FACTORS AND SIGNIFICANCE[3]

Unit	UNTRANSFORMED VARIABLE (Efficiency)				TRANSFORMED VARIABLE Log (1 - efficiency)			
	Skewness	Significant at .05	Kurtosis	Significant at .05	Skewness	Significant at .05	Kurtosis	Significant at .05
Louisville North	-.507	Yes	-.167	No	-.241	No	.006	No
Louisville South	-.480	No	-.409	No	-.302	No	-.118	No
Pittsburgh I	-.467	No	.062	No	-.206	No	.120	No
Pittsburgh II	-1.085	No	.357	No	.725	No	-.271	No
Philadelphia	-.765	No	.266	No	-.132	No	-.142	No
Chicago	-.972	Yes	3.707	Yes	.210	No	2.173	Yes
Shawnee TCA	-.629	Yes	-.015	No	.219	No	-.452	No
Shawnee Ventur	-.539	No	-.399	No	-.099	No	-.821	No
Conesville A	-.284	No	.005	No	-.574	No	-.660	No
Conesville B	-.351	No	-.574	No	-.654	No	.115	No
Lawrence	-1.333	Yes	1.140	Yes	-.022	No	-.854	No

[1]Skewness measures the degree to which the distribution is "off-center". A negative skew indicates a long left-hand tail. This factor is zero for a normal distribution.

[2]Kurtosis measures the degree of peakedness in the distribution. A positive value indicates a high peak and a negative value indicates a flatter peak. This factor is zero for normal distribution.

[3]"Significant at .05" indicates 95 percent certainty that the distribution is different from a normal distribution in this characteristic.

found to have a significantly non-zero kurtosis. Kurtosis, a function of the fourth moment about the mean, is often considered to measure the degree of peakedness in the distribution. A positive value indicates a higher peak (and longer tails) than in the normal distribution and a negative value indicates a flatter peak. A variable with a normal distribution has a kurtosis of zero.

Since the negative skewness was a significant and consistant feature of the efficiency variable, the $\log_e$ transformation performed by both EPA and Entropy in previous analyses of the data might be expected to produce a variable with a more normal distribution.

3.2.2 THE TRANSFORMED VARIABLE

The transformation variable used is log (1-efficiency). For most of the units, the transformation improved the normality of the distribution significantly. This improvement can be seen in the skewness and kurtosis values for the untransformed and transformed variable, displayed in exhibit 3-2. The significance column of the display indicates the certainty with which the sample statistic implies an actual departure from the normal distribution.

Exhibit 3-3 presents the arithmetic medians, means, and standard deviations predicted for the observations under the lognormal assumption. Comparison of these predicted values with the actual sample statistics provides an intuitive feel for the goodness of fit of the lognormal distribution. The lognormal assumption results in accurate predictions except in the estimates of standard deviations at the Conesville and Lawrence units.

EXHIBIT 3-3: COMPARISON OF ARITHMETIC VALUES PREDICTED BY THE LOGNORMAL DISTRIBUTION ASSUMPTION WITH ESTIMATES FROM THE OBSERVATIONS

	Arithmetic Values Predicted By Lognormal Assumptions			Observed Estimates From Untransformed Variable		
Unit	Median	Mean	Standard Deviation	Median	Mean	Standard Deviation
Louisville North	84.4	83.8	4.9	84.6	83.8	4.7
Louisville South	83.3	82.2	6.2	83.3	82.3	5.9
Pittsburgh I	80.8	80.2	4.5	81.2	80.3	4.6
Pittsburgh II	85.4	85.0	3.2	86.1	85.1	3.4
Philadelphia	97.0	96.8	1.2	96.7	96.8	1.2
Chicago	89.2	89.1	1.3	88.9	89.1	1.3
Shawnee TCA	88.5	88.3	2.2	88.5	88.3	2.2
Shawnee Venturi	96.0	95.8	1.6	95.7	95.8	1.5
Conesville A	86.0	84.5	7.3	84.1	84.7	6.1
Conesville B	92.5	91.6	4.2	91.9	91.7	3.5
Lawrence	95.4	93.4	6.6	95.3	93.6	5.3

[1]For lognormal distributions: (the quantity (1-efficiency) is lognormally distributed).

Median $= e^{\mu}$

Mean $= e^{\mu} e^{\sigma^2/2}$

Standard Deviation $= e^{\mu} e^{\sigma^2/2} (e^{\sigma^2} - 1)^{1/2}$

μ = mean of logarithmic variable.

σ = Standard deviation of logarithmic variable.

In spite of the apparent better agreement between the lognormal distribution and that data, Kolmogorov-Smirnov tests comparing both normal and lognormal distributions with the data indicated that either assumption could be accepted.

Overall, then, the lognormal distribution presents a slightly better characterization of the efficiency data than the normal. However, from the available data, it is evident that the lognormal description is not an ideal fit for all cases, and that the distribution is also very nearly normal in many of the cases.

3.3 ESTIMATED PARAMETERS AND COMPARABILITY AMONG UNITS

3.3.1 MEANS AND STANDARD DEVIATIONS

Exhibit 3-4 presents the medians, means, and standard deviations of the transformed variable, log (1-efficiency). The differences in the means and standard deviations among the eleven units can readily be seen from examination of the exhibit. Statistical tests[1] were performed on the differences in means and variances for each pair of units. (The variance is the square of the standard deviation.) The results of these tests are presented in exhibits 3-5 and 3-6. The level of significance indicates the probability of the observed difference occurring by chance if, in reality, there was no difference between the two means (or variances). For example, the significance of the difference in variances between the Louisville South and Pittsburgh I units is .0305. This means that if there were really no difference in the variances at these units,

---

[1]T-tests were performed on the means and F-tests on the variances.

EXHIBIT 3-4: ESTIMATED PARAMETERS OF TRANSFORMED VARIABLE

UNIT	MEDIAN	MEAN (μ)	STANDARD DEVIATION (σ)
Louisville North	-1.8836	-1.8608	.295
Louisville South	-1.7910	-1.7868	.343
Pittsburgh I	-1.6885	-1.6492	.234
Pittsburgh II	-1.9729	-1.9223	.212
Philadelphia	-3.5143	-3.4927	.359
Chicago	-2.2047	-2.2217	.118
Shawnee TCA	-2.1840	-2.1608	.182
Shawnee Venturi	-3.1353	-3.2270	.368
Conesville A	-1.8798	-1.9626	.447
Conesville B	-2.5170	-2.5884	.474
Lawrence	-3.0791	-3.0714	.835

EXHIBIT 3-5: STATISTICAL SIGNIFICANCE OF DIFFERENCES IN VARIABILITIES AT DIFFERENT FACILITIES

SIGNIFICANCES OF DIFFERENCES IN SITES

Unit/Unit	Louisville North	Louisville South	Pittsburgh I	Pittsburgh II	Philadelphia	Chicago	Shawnee TCA	Shawnee Ventur	Conesville A	Conesville B	Lawrence
Louisville North											
Louisville South	.1037										
Pittsburgh I	.1288	.0305									
Pittsburgh II	.1277	.0492	.3882								
Philadelphia	.1905	.3721	.0652	.0645							
Chicago	.0000	.0000	.0000	.0026	.0000						
Shawnee TCA	.0000	.0000	.0091	.2335	.0025	.0017					
Shawnee Venturi	.0000	.2964	.0209	.0347	.5157	.0000	.0000				
Convesville A	.2145	.0405	.0028	.0092	.2845	.0000	.0000	.1574			
Convesville B	.0000	.0207	.0016	.0062	.2306	.0000	.0000	.1025	.3908		
Lawrence	.0000	.0000	.0000	.0000	.0136	.0000	.0000	.0000	.0015	.0054	

[1] Significance refers to the probability that the observed difference could have occurred by chance even if there were no real difference in the factors compared. A significance of .05 or less is usually considered to be of statistical importance.

EXHIBIT 3-6: STATISTICAL SIGNIFICANCE OF DIFFERENCES IN GEOMETRIC MEAN EMISSIONS AT FACILITIES

SIGNIFICANCES OF DIFFERENCES IN SITES

Unit/Unit	Louisville North	Louisville South	Pittsburgh I	Pittsburgh II	Philadelphia	Chicago	Shawnee ICA	Shawnee Ventur	Conesville A	Conesville D	Lawrence
Louisville North		.2249	.0276	.6148	.0000	.0000	.0001	.0000	.2554	.0000	.0000
Louisville South			.1389	.2507	.0000	.0000	.0000	.0000	.0421	.0000	.0000
Pittsburgh I				.0530	.0000	.0000	.0000	.0000	.0060	.0000	.0000
Pittsburgh II					.0000	.0166	.0612	.0000	.7600	.0000	.0000
Philadelphia						.0000	.0000	.0747	.0000	.0000	.0050
Chicago							.4342	.0000	.0054	.0002	.0000
Shawnee ICA								.0000	.0395	.0000	.0000
Shawnee Venturi									.0000	.0000	.1061
Convesville A										.0000	.0000
Convesville B											.0000
Lawrence											

[1] Significance refers to the probability that the observed difference could have occurred by chance even if there were no real difference in the factors compared. A significance of .05 or less is usually considered to be of statistical importance.

3.05 percent of random samples drawn from these units would produce a difference in sample variance of the observed magnitude. A significance level of .05 or lower is usually considered to be clear evidence of a difference.

The variances at the Chicago and Shawnee TCA units were significantly lower than the variances at almost all of the other units. EPA officials noted that both of these units are well run and a low variability in efficiency was expected. The Pittsburgh II unit was described as being similar to the Shawnee TCA units, but because of the limited number of observations the results are of less interest. The significantly high variance at the Lawrence unit is believed by EPA officials to be the result of an unusually low sulfur content of the coal.

Because of the highly significant differences in the variances among the units examined and the inaccurate estimation of variance at the Conesville and Lawrence units, it is not appropriate to combine these variances for analysis.

3.3.2 AUTOCORRELATION

The lag-one autocorrelation estimates for each of the eleven units are presented in exhibit 3-7, along with the number of observations from which the estimates were drawn and the significance of the factor. (The observations included were those for which there was also an observation on the preceding or succeeding day.) The level of significance is dependent on the number of observations, hence the autocorrelation factor of 0.6255 at the Conesville B unit is not significant because it is based on only seven observations while the autocorrelation factor of 0.5995 at

EXHIBIT 3-7: FIRST-ORDER AUTOCORRELATION FACTORS ON THE VARIABLE LOG (1 - EFFICIENCY)

UNIT	N	Autocorrelation[1]	Significant at .05 level
Louisville North	49	.6955	yes
Louisville South	72	.6949	yes
Pittsburgh I	11	.4683	no
Pittsburgh II	7	-.1428	no
Philadelphia	5	.2524	no
Chicago	37	.6983	yes
Shawnee TCA	37	.5995	yes
Shawnee Venturi	25	.8897	yes
Conesville A	13	.7131	yes
Conesville B	7	.6255	no
Lawrence	27	.6386	yes

[1] The autocorrelation was determined by comparing day 't' with day 't-1'; the data was not collapsed and missing data was not filled in, so that only the observation days which were preceded or followed by another observation day were included.

Shawnee TCA is significant. It seems almost certain that first-order autocorrelation does, in fact, exist at most or all units. Entropy used an estimate of 0.7 in their simulation model. This appears to be an appropriate value if the model is dealing with a unit similar to one of the Louisville units. However, for units more similar to the Shawnee TCA unit, 0.6 would be a more reasonable estimate. Differences in operational procedures at the units are an unknown but probably relevant factor.

3.3.3 AUTOREGRESSIVE MODEL

The possibility of autocorrelation factors associated with lags of two or more was also examined. A first-order autogressive model is one in which the variable in time "t" is a function of the same variable in time "t-1". A second-order autogressive model was compared with a first-order autogressive model. A comparison of the residual led to the conclusion that the first-order autogressive model is appropriate. A further examination of partial correlations up to a lag of ten led to the conclusion that the first-order autogressive model is appropriate.

3.4 POSSIBLE CONFOUNDING FACTORS

It is recognized that many other factors may be related to the efficiency variable. It was suspected that the efficiency factor at a given unit might be related to the level of sulfur in the raw emissions. Data was available for all but the Lawrence unit on the pounds per million BTUs of sulfur in the gas before processing. The Pittsburgh I and Conesville scrubbers processed gas with a significantly higher average sulfur content than the other units (see exhibit 3-8). No

EXHIBIT 3-8: COMPARISON OF MEAN SULFUR CONTENT OF INPUT EMISSIONS AND MEAN EFFICIENCY

UNIT	MEAN SULFUR CONTENT OF INPUT EMISSIONS (lb/MMBTU)	MEAN OF EFFICIENCY (Arithmetic Equivalent of Transformed Variable)
Louisville North	5.653	83.8
Louisville South	5.687	82.2
Pittsburgh I	6.647	80.2
Pittsburgh II	5.462	85.0
Philadelphia	5.049	96.8
Chicago	5.643	89.1
Shawnee TCA	5.555	88.3
Shawnee Venturi	5.660	95.8
Conesville A	7.793	84.5
Conesville B	7.359	91.6
Lawrence	NA	93.4

relationship appeared to exist, however, between mean efficiency at a unit and the mean level of sulfur before scrubbing.

Within individual units, statistically significant correlations between efficiency and sulfur content were found at two units, the Chicago unit and the Shawnee TCA unit. At the Shawnee TCA unit, the relationship was the expected negative one (-.45) with increasing sulfur content leading to decreasing efficiency. At the Chicago unit, however, a positive correlation (.47) was found, with increasing sulfur content leading to increasing efficiency.

On the basis of the evidence, then, one must conclude that there is no predictable relation between the actual levels of sulfur emissions before scrubbing and the efficiency of the scrubbing operation, and that the analyses reported here are not contaminated by any confounding effect of this nature.

Many additional factors are of probable relevance in determining the efficiency levels of scrubbers. Operating procedures can be altered to compensate for high or low sulfur content as well as high or low electricity demands. The location and type of measuring device used can affect efficiency readings. The age, type, and condition of the scrubber equipment may also affect efficiency. The present data set does not offer any evidence of the types or magnitudes of any effects from these or other sources.

4.0 COMPARISON WITH ENTROPY RESULTS

This chapter summarizes the degree to which the findings in the preceding chapters appear to agree with the results developed by Entropy Environmentalists, Incorporated. It is organized into two sections which parallel the material presented in chapters 2.0 and 3.0. In the first section the number of exceedences predicted by Entropy are compared to those predicted by VRI, with a potential explanation of the observed differences. The second section compares the VRI and Entropy descriptions of the statistical structure characterizing the efficiency of eleven flue gas desulfurization (FGD) units at eight electric utility sites. The disparities between the Entropy and VRI estimates of process parameter values are examined, and rationales for these differences are discussed.

4.1 PREDICTED EXCEEDENCES

Although the details of Entropy's 1,000 year simulation were not available, VRI believes the material presented in chapter 2.0 nearly replicates the Entropy approach. Some differences between the VRI and Entropy simulated data are attributable to the inherent random nature of the simulation process itself and the slight improvement in confidence levels of VRI's figures produced as a consequence of the doubling of the number of simulated years (2,000 instead of 1,000). Where VRI used parameters comparable to those reported by Entropy, reasonably similar numbers of exceedences were predicted.

Although these results show generally the same pattern of effects, there are differences greater than can be explained by chance effects.

In view of the great care taken in this analysis, including special rechecking of the disparate results, we suspect that the Entropy results are probably less accurate where differences exist, possibly due to the use of less accurate random number generation and transformation techniques. In this connection, it is worth noting that VRI's estimates were generated using methods considerably more precise than usually found in good statistical practice. This extra precision was required in view of the requirements to make accurate estimates of extremely small probabilities.

Despite these minor differences, VRI's results substantiate Entropy's conclusion that the number of exceedences per year is extremely sensitive to the median (or mean) FGD system efficiency and the variability in this efficiency. VRI-simulated values nearly replicate Entropy's findings that the degree of autocorrelation can affect the number of exceedences although with less impact than variation in the mean and variance. VRI's analyses also provide information not provided by Entropy such as the data in exhibits 2-10 through 2-15; in these areas, no comparisons are possible.

4.2 PROCESS STRUCTURE

Analysis of the 24-hour FGD efficiency data indicate that the measured values of efficiency are not symetrically distributed about their mean, generally weakening any normal distribution hypothesis. VRI's analysis agrees with the Entropy and EPA findings that the quantity (1-efficiency) has a distribution which can be reasonably approximated by a lognormal distribution. There are many other candidate distributions which might equally well be used to describe the observed distribution of efficiency values. As shown in chapter 2.0, adoption of other distributions would not significantly influence the analysis results, but instead might confuse major differences between the Entropy and VRI results with insignificant discrepancies. Consequently, the above analysis used primarily the lognormal distribution hypothesis proposed by EPA and concurred with by Entropy.

Entropy further found that the FGD efficiency data had significant first-order autocorrelation. VRI's results upheld this finding even though VRI's estimate of autocorrelation was based on consecutive calendar days rather than the method suggested by Entropy's statistical consultant which collapsed serial data into a string of days for which data were available. In addition, VRI's negative finding on the presence of higher order autocorrelation helped to validate the Entropy implicit assumption that first-order (one day) lags were sufficient to describe process time dependencies.

VRI used a data base which appeared to be approximately, but not exactly, the same as that employed in the Entropy analysis. Specific differences between the data provided are evidenced: (1) by disparities in the numbers of observations at particular sites; and (2) by differences in numerical estimates. Disparities in the numbers of observations occurred for two of the utilities reported, i.e.:

	Number of Observations	
Site	VRI	Entropy
Chicago	52	35
Shawnee TCA	42	37

Entropy does not report the number of observations from the Lawrence unit, so comparisons cannot be made. VRI-estimated parameter values for σ and μ generally differ from Entropy's estimates by no more than two percent except for the following sites.

Site	Logarithmic Parameter Values					
	μ_{VRI}	σ_E	μ_{VRI}	σ_E	μ_{VRI}	σ_E
Chicago	-2.222	-2.206	.118	.106	.698	.86
Shawnee TCA	-2.161	-2.168	.182	.186	.600	.65
Lawrence	-3.071	-3.437	.835	.676	.639	N/A

As noted above, VRI and Entropy were not using identical data bases for the Chicago and Shawnee TCA sites. It is expected that the differences at the Lawrence site may also be the result of a different data base. Finally, the Entropy data base combined observations from the Louisville north and south units into a single site (Cane Run) while they were treated separately in VRI's analysis. Entropy notes that averaging the results of these two units reduces the overall variability of the combined sites. This effect is illustrated by the difference between the two VRI logarithmic estimates of for Louisville (0.295 and 0.343) and the single average Louisville estimate reported by Entropy (0.289).

4.3 DIFFERENCES AMONG SITES

VRI and Entropy agree in finding that the evidence from existing utility boiler units shows statistically significant differences in the levels of variability at different sites. VRI has assumed that at least some of its variability represents differences in engineering design and operating practices, including some designs and/or operating practices which may not represent the future state of the art for boiler units. VRI therefore did not combine all the data together to estimate future site variability. Entropy, in its analysis of these differences, did combine the data to generate forecasting intervals, discussed in terms of levels of correctness. In this analysis, Entropy assumed that future sites would have levels of variability distributed as broadly as the variabilities observed at existing sites. Thus, Entropy assumed that the data from each of the existing sites constitutes a sample representating appropriate state of the art design and operating practices which would be used in future facilites. Without this assumption, there is no justification for using forecasting intervals based on the complete range of variabilities.

Rather than adopt this strong assumption, VRI has chosen to present the bulk of its results in parametric form covering the range of variabilities, leaving engineering analysis (combined with the data from chapters 2.0 and 3.0) to identify the levels of variability which should actually be expected at future sites. EPA personnel suggested that Shawnee TCA and Pittsburgh II might be the best representatives of future practices. Statistical analysis of these two sites suggests that they had a common variability. Accordingly, a confidence interval for the variability at these sites was presented in chapter 2.0. A confidence interval is also presented there for the Louisville units.