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To the Graduate School:

This thesis entitled "Incorporating Uncertainties into Risk Assessment with an Application to the Exploratory Studies Facilities at Yucca Mountain" by Paul M. Fathauer is presented to the Graduate School of Clemson University. I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Systems Engineering.

Robert A. Field
Thesis Advisor

We have reviewed this thesis
and recommend its acceptance:

Thomas J. Oldcamp
Timothy A. Debel

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MASTER

Accepted for the Graduate School:

A. Dewayne Brooks

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INCORPORATING UNCERTAINTIES INTO RISK
ASSESSMENT WITH AN APPLICATION TO THE
EXPLORATORY STUDIES FACILITIES AT
YUCCA MOUNTAIN

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Environmental Systems Engineering

by
Paul M. Fathauer
August 1995

ABSTRACT

A methodology that incorporates variability and reducible sources of uncertainty into the probabilistic and consequence components of risk was developed. The method was applied to the north tunnel of the Exploratory Studies Facility at Yucca Mountain in Nevada. In this assessment, variability and reducible sources of uncertainty were characterized and propagated through the risk assessment models using a Monte Carlo based software package. The results were then manipulated into risk curves at the 5% and 95% confidence levels for both the variability and overall uncertainty analyses, thus distinguishing between variability and reducible sources of uncertainty. In the Yucca Mountain application, the designation of the north tunnel as an item important to public safety, as defined by 10 CFR 60, was determined. Specifically, the annual frequency of a rock fall breaching a waste package causing an off-site dose of 500 mrem (5×10^{-3} Sv) was calculated. The annual frequency, taking variability into account, ranged from 1.9×10^{-9} per year at the 5% confidence level to 2.5×10^{-9} per year at the 95% confidence level. The frequency range after including all uncertainty was 9.5×10^{-10} to 1.8×10^{-8} per year. The maximum observable frequency, at the 100% confidence level, was 4.9×10^{-8} per year. This is below the 10^{-6} per year frequency criteria of 10 CFR 60. Therefore, based on this work, the north tunnel does not fall under the items important to public safety designation for the event studied.

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CHAPTER 1

INTRODUCTION

Risk

Risk can be considered a two component concept involving the chance occurrence of an adverse event and the resulting consequence (Morgan, 1981b; Covello and Merkhofer, 1993). For instance, when investing in the stock market, there is a chance that high inflation will lead to devaluation of an investment. Skydiving is risky because there is a chance that the chute will not open. The fact that risk inherently involves a chance event separates a risk from a hazard. The term hazard refers to an undesirable consequence without regard to the likelihood of it occurring. Thus, one of the hazards of a thunderstorm is being struck by lightening.

Environmental Risk

For everyday risks such as riding in a car or an airplane, examples of adverse events abound; however, their context as used in reference to environmental risk needs to be clarified. In the environmental arena, an adverse event occurs when three conditions are met (Covello and Merkhofer, 1993). First, a contaminant must be present that, if released, might harm a receptor such as a human, a fragile ecosystem, etc. Next, pathways must exist through which the receptor is exposed to the contaminant. Finally, mechanisms

must exist through which exposure to the contaminant results in an adverse health or environmental consequence.

Environmental Risk Assessment

In the early 1970's, increased public concern about the effects of technology on the environment led to the emergence of many new laws and regulations (Morgan, 1981a). From these social and political changes, environmental risk assessment evolved¹. Regulatory agencies, in an attempt to mitigate controversy in regulatory policies, developed the risk assessment procedures to incorporate risk into the decision making process (National Research Council, 1983). It continues to be used as an objective input to risk managers in aiding decision making (Morgan, 1981b). Risk managers combine the output of risk assessment with other technical, political, economic and social factors in determining the effectiveness of a new technology, cleanup strategy, or a manufacturing plant (EPA, 1984; Freudenburg, 1988).

Uncertainties in Environmental Risk Assessment

In its most general form, the risk assessment procedure requires the use of mathematical models to characterize the chemical/physical/biological processes that occur following an adverse event. These models, in turn, contain parameters that must be specified. In a deterministic risk assessment, each parameter is assigned a single value. From

¹ For simplicity, the term risk assessment will be used in place of environmental risk assessment in the remainder of this thesis.

this, a single resulting consequence is calculated. Unfortunately, a single-valued, deterministic risk assessment does not adequately characterize risk. There are two reasons for this.

The first stems from the generic concept that risk consists of an adverse event and a resulting consequence. In the environmental context, many risk assessments are performed under the assumption that the adverse events occurs. In reality, the occurrence of the adverse event is often probabilistic. The importance of incorporating the probabilistic nature of adverse events is illustrated in safety assessments of nuclear power plants (Rasmussen et al., 1975). The consequences of a reactor core melt, which results in a large release of radioactivity, would provide little insight in characterizing the risk without incorporating the probability of the event. Therefore, probabilistic risk assessment (PRA) was developed to quantify both components of risk.

The second reason that a single-valued risk characterization is inadequate is because risk assessments are inherently uncertain. The uncertainties can be placed in two general categories, variability and reducible uncertainty. Variability refers to natural variations in time, space and/or among receptors of the parameters that are used in risk assessment models. Reducible uncertainty is due to lack of knowledge about a parameter or, more generally, about a given chemical/physical/biological process. Because of variability, risk assessment parameters are more appropriately characterized by distributions than by single parameters. When these parameter distributions are propagated through the risk assessment procedure, the result is also a distribution. However, there is additional,

reducible uncertainty in the specification of the parameter distributions due to factors such as limited measurements, measurement error, etc. Reducible uncertainties also arise from the use of models and simplifying assumptions. There can also be reducible uncertainties in event probabilities, especially when dealing with rare events such as earthquakes or tornadoes or with sequences of failures in engineered systems. These uncertainties add another dimension to risk characterization as summarized in Table 1.1. That is, risk can be characterized by quantifying the variability in both the adverse event and consequence components of risk. Furthermore, uncertainty in the assessment of risk can be characterized through quantification of the reducible uncertainty in both risk components.

Presented in Table 1.2 is a matrix representing current risk assessment methods. It is now recognized that a deterministic risk assessment is not sufficient in characterizing risk because of the degree of certainty it implies. The incorporation of variability in risk assessment has increased in recent years; however, incorporation of reducible uncertainty is uncommon. The nuclear power industry has increased incorporation of variability and sometimes reducible uncertainty in PRA. However, uncertainty analysis in PRA has not seen widespread use outside the nuclear power arena. Thus, the principal objectives of this thesis were to present a framework for incorporating variability and reducible uncertainty in risk assessments and to apply it to hypothetical and actual problems.

Table 1.1

Uncertainties in Environmental Risk Assessment

Uncertainty Category	Risk Component	
	Adverse Event	Consequence
Variability	X	X
Reducible Uncertainty	X	X

Table 1.2

Summary of Environmental Risk Assessment Methods

Risk Assessment Method	Risk Component		Uncertainty Category	
	Adverse Event	Consequence	Variability	Reducible Uncertainty
Deterministic Risk Assessment		X		
Stochastic Risk Assessment		X	X	Sometimes
Deterministic PRA	X	X		
Stochastic PRA (Nuclear Power)	X	X	X	Sometimes
This Work	X	X	X	X

CHAPTER 2

RESEARCH OBJECTIVES

The goals of this study were to present a framework for incorporating variability and reducible uncertainty in risk assessment and to apply it to hypothetical and actual problems. Specifically, the objectives of this research were:

1. To present a methodology consistent with traditional risk assessment procedures for incorporating variability and reducible uncertainty in characterizing environmental risks.
2. To illustrate the method using a hypothetical example.
3. To apply the method to a regulatory compliance issue at the proposed nuclear waste repository at Yucca Mountain in Nevada.

CHAPTER 3

BACKGROUND

There is not a definitive source on incorporating uncertainty into risk assessment. Consequently, there is a lack of consistency in terminology and taxonomy. For the purposes of the present study, it is convenient to classify risk assessment uncertainties into two general categories: variability and reducible uncertainty. Both of these uncertainties can exist in risk assessment parameters such as porosity, wind direction, and human health risk factors. However, they can also exist in probabilistic quantities such as the annual frequency of an earthquake or the failure rate of a pump.

Variability refers to variations of parameters in time, space and/or among receptors. In the literature, this source of uncertainty is often referred to as irreducible, type A, random or stochastic uncertainty (Bogen and Spear, 1987; IAEA, 1989; Morgan and Henrion, 1990; NRC, 1990; National Research Council, 1994). It includes the random and systematic variations in natural systems and processes. Reducible uncertainty arises from incomplete information about a parameter. It is often referred to as lack of knowledge, type B, subjective uncertainty, error or just uncertainty (Bogen and Spear, 1987; IAEA, 1989; Morgan, 1990; NRC, 1990; National Research Council, 1994).

Variability

Sources

Many parameters vary in time, space and among individuals. For instance, emission rates can fluctuate in time, and transport conditions can change in time and space.

Probabilities can vary in a similar fashion. For instance, the probability of an earthquake varies spatially and temporally. The probability of a nuclear reactor core-melt varies spatially (across different parts of the world), individually (among different companies), and temporally (e.g., as new safety regulations are enacted and safer designs instituted).

Implications for Risk Assessment

Risk can be characterized through the variability in the probability of an adverse event and the ensuing consequences. When an adverse event has large variability in the consequences, the outcome may range from no detrimental effects to catastrophic effects. Conversely, an event with no variability can be considered a binary event where the consequences are certain. For example, nuclear power accidents have large variability since the consequences may range from no effects to catastrophic effects. Conversely, the risk to an individual drowning has no variability in the consequence (i.e., survival or death) and large variability in the event (i.e., variable depending on water conditions).

Variability in risk can be characterized through curves (herein referred to as variability risk curves), which depict both components of risk: on the abscissa, the consequences following an adverse event and on the ordinate, the probability of exceeding a specified magnitude of consequence. These curves can be constructed at different levels of confidence to show the variability in the adverse event likelihood. For instance, if the highest probability for an adverse event is 10^{-3} , then one risk curve can be constructed based on this probability. This curve would represent the 100% confidence level because 100% of the probability values fall below 10^{-3} . Risk curves in this work are constructed at the 5% and 95% confidence level which represents the 90% confidence bound for the

probability of exceeding any given consequence. This is consistent with the nuclear PRA literature (Solomon et al., 1983; Guarro and Cummings, 1989; NRC, 1990).

Examples of variability risk curves are shown in Figure 3.1. Curves are presented for two events, A and B, where the upper curve for each event is the 95% confidence level and lower curve is the 5% confidence level. Event A has large variability in its consequence, as evidenced by the wide range of possible deaths (1 to 1,000 deaths), and small variability in the adverse event, as evidenced by the narrow 90% confidence bound (less than one order of magnitude). Event B, on the other hand, has small variability in the consequences (1 to 20 deaths) and large variability in the adverse event (2 orders of magnitude).

Reducible Uncertainty

Sources

There are numerous sources of reducible uncertainty in risk assessment stemming from assumptions, approximations, and modeling parameters. For instance, the shape of a dose-response curve may not be known, so a linear relationship may be assumed. The release mechanisms of a contaminant from a landfill may not be understood, so the source term may be approximated as a constant or instantaneous release.

Similar to variability, reducible uncertainty may exist in probabilistic quantities. For instance, the probability of an adverse event can be estimated from observation; however, there is a margin of reducible uncertainty in this estimator. Reducible uncertainties may arise from the characterization of variability as well. For instance, if the variability in a population is estimated with analogous data (e.g., data from another site), there is re-

Figure 3.1. Examples of Variability Risk Curves

ducible uncertainty in the frequency distribution. Furthermore, the frequency of rare events is difficult to estimate from observations. Thus, these types of uncertainties can be major contributors to the overall uncertainty of a risk assessment (Gilbert, 1994).

Classical methods can be used to determine the statistical uncertainty in an estimator. For instance, the reducible uncertainty in the mean of a population can be determined through sampling (e.g., sampling distributions with parameters $\bar{x}$ and s). Therefore, some sources of reducible uncertainty in the variability of a population can be described by quantifying its parameters (e.g., reducible uncertainty in the mean and standard deviation of a normally distributed population) (Morgan and Henrion, 1990). Despite the availability of these techniques, quantifying reducible uncertainty can present a problem. For instance, there are not enough occurrences of nuclear reactor core-melts to estimate the uncertainty in the annual frequency using classical statistics. Furthermore, the errors introduced through biases and approximations are hard to quantify without empirical observation (Lichtenstein, 1982). In recent years, Bayesian methods, expert opinion elicitation, and subjective probability theory have been employed in an attempt to address these problems (Dickey, 1980; Kouts et al., 1988; Cooke, 1991; Hora, 1991).

Implications for Risk Assessment

The degree of reducible uncertainty in a risk assessment is an indication of its accuracy. In actuarial risk assessment, where risks are calculated from observations (e.g., risks of insuring teenage drivers), the only source of reducible uncertainty is statistical (i.e., sampling size uncertainty). In environmental risk assessment, where empirical data are

often not available, reducible uncertainty can be a major contributor to the overall uncertainty.

Reducible uncertainty in a risk assessment can be demonstrated by bounding the variability risk curves (herein referred to as overall risk curves). This is illustrated in Figure 3.2 where the dashed lines represent overall uncertainty in the assessment. For instance, the probability of exceeding 10 deaths ranges from 8×10^{-8} to 2×10^{-7} due to variability. However, after including reducible uncertainties the probability of exceeding 10 deaths may be as low as 8×10^{-9} or as high as 8×10^{-7} (at the 5% and 95% confidence levels, respectively). From this, it could be stated that the 90% confidence bound for exceeding 10 deaths is 8×10^{-9} to 8×10^{-7} .

Implications

The purposes of distinguishing variability and reducible uncertainty are two fold. First, the variability risk curves show the best estimate of the risks. That is, in developing the variability risk curves, the assessor applies everything that is known about the situation. Conversely, the reducible risk curves represent what the assessor does not know. In other words, in developing the reducible curves, the assessor quantifies sources of uncertainty that result from the lack of knowledge regarding processes or parameters. Thus, separating uncertainty in a risk curve portrays not only the environmental risks but also portrays information about the assessment.

Figure 3.2. Example of Variability and Overall Uncertainty Curves

CHAPTER 4

LITERATURE REVIEW

The PRA concept was first introduced by the nuclear industry and the NRC in 1975 with the publication of the Reactor Safety Study (RSS), also known as the WASH-1400 study (Rasmussen et al., 1975). The RSS quantified some sources of variability but only gave limited treatment to reducible uncertainty. Since the study, the state of the art has evolved to explicitly include both sources of uncertainty in nuclear power risk assessment. Specifically, this includes the development of a consistent framework for identifying and quantifying sources of uncertainty. Three major studies have provided this framework: the Seismic Safety Margins Research Program (SSMRP) (Cummings, 1986), the Indian Point PRA (State of New York Power Authority, 1982) and the NUREG-1150 study (NRC, 1990). Some of the techniques developed in these studies have been applied in the radioactive waste field as well.

The Reactor Safety Study

In the early 1970's, the U.S. Atomic Energy Commission approached Norman Rasmussen, a Massachusetts Institute of Technology nuclear engineering professor, to quantify the safety of light-water reactors. The result of Rasmussen and his team of 60 people was the RSS. The study is considered significant to this research because it represents the first methodology to quantify both components of risk and uncertainty in environmental risk assessment.

The uncertainty analysis in the RSS was mainly limited to the estimation of initiating events which would lead to radiological releases. In doing this, the group used two methodologies developed in the 1960's by the aerospace industry: fault tree and event tree analysis (Douglas, 1982). Fault tree analysis is a top-down method of using logical relationships (e.g., AND, OR, etc.) in analyzing interactions between various systems. For instance, it was used in the RSS for determining how various systems in a power plant could interact to cause a power failure. Event tree analysis, where the basic events are identified first, is the converse of fault tree analysis. The Rasmussen group used event tree analysis to identify various possible outcomes given an initiating event (e.g., the propagation of events resulting from an earthquake). Utilizing fault and event tree analyses, in conjunction with component failure data (e.g., failure rate of a pump), the Rasmussen group was able to determine the overall probabilities of various events such as the probability of a power failure. The component failure data were obtained from various nuclear plants around the country. The variability in these data (e.g., the 5th and 95th percentile estimators for failure rates of a pump) was propagated through the fault and event trees using Monte Carlo techniques to obtain a distribution of core melt frequencies and radionuclide releases.

Several reports followed the publication of the RSS. The study was criticized for not quantifying conservatism accurately, underestimating the error bounds, and neglecting to include sources of uncertainty such as human error and expert judgment. It also lacked an explicit separation of variability and reducible uncertainty (EPRI, 1975; Leverenz and Erdmann, 1975; Lewis et al., 1978; ANS, 1980). The criticisms of the report lead the

NRC to de-emphasize PRA for several years; however, after the Three Mile Island incident, PRA experienced accelerated use by the nuclear community including the NRC (McCormick, 1981).

The Seismic Safety Margin Research Program

The SSMRP improved on treatment of reducible uncertainty by explicitly accounting for it through a two-tier approach. First, expert opinions and experimental results were used to bound the values of reducibly uncertain parameters. Then the reducible uncertainty of different assumptions and models was assessed. Specific techniques were developed to apply this approach in the analysis of seismic events, including correlation of component failures during an earthquake (since failure modes are not independent during seismic events) (Cummings, 1986). The SSMRP methodology was applied to analyzing risks of seismic events; however, its concept was later extended to the PRA studies at Zion (Commonwealth Edison, 1981) and Indian Point (State of New York Power Authority, 1982) power plants. One of the effects of incorporating reducible uncertainty was that the span of the 90% confidence bound increased to a few orders of magnitude as compared to earlier assessments (Bohn, 1980).

Indian Point PRA

The Indian Point PRA was the first industry-sponsored PRA to utilize expert opinion elicitation in quantifying reducible uncertainties. This included techniques for experts to quantify various parameters in the form of distributions as compared to point estimates. In order to incorporate these distributions, an uncertainty propagation

technique was developed that could account for arbitrary distribution shapes (as compared to the customary log-normal distributions) (State of New York Power Authority, 1982).

NUREG-1150

The NRC completed the NUREG-1150 study to estimate the off-site risks from severe accidents at five light water reactors (NRC, 1990). The two principal objectives of the NUREG-1150 study were to provide a current assessment of severe accident risks at specific nuclear power plants of different designs and to develop a set of PRA models and results that would set priorities for safety issues and future research. The SSMRP methodology was generalized and improved by emphasizing the separation of variability and reducible uncertainties.

NUREG-1150 identified and quantified major sources of reducible uncertainty in the models and assumptions used in PRA studies. Furthermore, it formalized the use of expert opinions through a multi-outcome approach to event tree analysis. In this approach, multi-outcome nodes were incorporated into the event trees that model the course of an accident sequence. For instance, three outcomes of an earthquake could be small, medium and large. Experts could then be polled for assigning weights to the various outcomes. In this way, a discretized distribution of outcomes resulted for each event. This reducible uncertainty along with the variability in failure rates (i.e., uncertainty considered in the RSS) was propagated through the event trees by Latin Hypercube Sampling, a Monte Carlo based sampling scheme (Iman et al., 1980). The techniques developed in NUREG-1150 are often used as the definitive approach for incorporating uncertainty in PRA (Wang, 1989; Camp, 1990).

Nuclear Waste Applications

The concepts developed in the nuclear power field have also been utilized in assessing the risks of disposing nuclear wastes. Summerling and Thompson (1992) presented a PRA methodology for the post-closure risks of a potential repository in the United Kingdom. The goal of this work was to predict the number of fatal cancers that would occur in the next million years. In order to deal with temporal uncertainty (variability and reducible), Monte Carlo was used to simulate possible evolutions of the environmental system (e.g., climate change). For each evolution, a separate Monte Carlo simulation was performed to calculate the radiological risk for the given climate evolution. The work incorporated field data and expert opinions in quantifying many of the uncertainties. Distinction between variability and reducible uncertainties was not made; however, the authors indicated the importance of such a distinction.

Smith and Tsai performed a PRA for the pre-closure risks of a proposed facility at Yucca Mountain (1993). The purpose of the project was to calculate off-site radiological doses to the public from potential accidents within the repository. Uncertainty in the adverse events were quantified from historical data and field studies. The consequences of the accidents were assessed by using a mix of deterministic and probabilistic methods. Although no explicit distinction between the sources of uncertainty was made in the results, the authors did point out important sources of reducible uncertainty for future work.

Implications

PRA represents a major advance in assessing risks since it incorporates both components of risk. Despite its advantages, early techniques did not adequately address variability and reducible uncertainties. Furthermore, the PRA concept has not been applied effectively outside the nuclear field. Recent advances by the nuclear industry have provided the basis for a methodology that is applicable to all environmental risk assessments.

CHAPTER 5

DESCRIPTION OF METHODOLOGY

In order to incorporate and characterize all sources of uncertainties in risk assessment, a two-step approach was taken in this study. In the first step, appropriate models were adopted and the sources of variability were identified and quantified. These uncertainties were propagated through the deterministic models via a modified Monte Carlo technique and variability risk curves were constructed. In the second step, the sources of reducible uncertainty were combined with the variability. All sources of uncertainty were then propagated through the risk models and the overall risk curves were constructed.

Variability Analysis

Developing models to quantify each component of risk was the first step of this methodology. For the adverse event, this required adopting appropriate probabilistic models for estimating the occurrence and magnitude of the event (e.g., probability of an earthquake and resulting magnitude). For the consequences, this included adopting models for quantifying the ensuing consequences once the adverse event has occurred.

Once the models were developed, the sources of variability were identified and characterized. This required that each of the parameters varying in time, space or among receptors be described through either probability density functions or histograms. In this stage of the assessment, the best estimate of the variability was used. For instance, if site specific data showed that the porosity could be approximated by a normal distribution

with a specified mean and standard deviation, these parameters were used for estimating the variability in the porosity. Uncertainty in the site specific data (e.g., due to poor sample size, measurement error, etc.) was later treated as reducible uncertainty.

One important factor in quantifying variability accurately is recognizing correlations among variables. As an example, the variability of body weights and inhalation rates within a population are not independent. Therefore, variables were correlated by developing relationships between the correlated variables and one uncertain variable. For instance, the body weights of a population could be treated as one source of variability, and an inhalation rate to body weight ratio be used in correlating the two parameters. Any reducible uncertainties arising from correlations were considered in the next step of this methodology.

Once the models were adopted and sources of variability characterized, the next step was to use the Monte Carlo based software package, @RISK, to model the variability in the assessment (Palisade, 1994). This software allowed uncertain parameters to be quantified through 24 various distribution types (e.g., normal, triangular, uniform, arbitrary, etc.). Once the parameters were characterized by these distributions, the Latin Hypercube Sampling technique was used to make a large number of realizations. For each realization, a value was randomly selected for each variable parameter and one occurrence of the adverse event and one consequence was calculated (e.g., probability of radiological release and consequent dose). After a fixed number of realizations, which was dependent on the complexity of the assessment, the resulting data set was manipulated into the

variability risk curves. The procedure for constructing risk curves is provided in the next chapter.

Reducible Uncertainty Analysis

The second step was to incorporate reducible uncertainty into the analysis. The procedure was similar to treating the variability; however, some degree of subjectivity was required. Specifically, judgments regarding the implications of various assumptions, models and approximations were made. In some cases, a quantitative estimate of reducible uncertainty was found in the literature (e.g., empirical comparisons between real world behavior and model predictions). Bayes formula was used for quantifying uncertainties in the occurrence of rare events. Conservative uncertainty factors were used if no other reasonable method was available.

Once the sources of reducible uncertainty were identified and characterized, the software package was utilized to model the overall uncertainty in the assessment. The overall risk curves were generated and overlaid onto the variability risk curves, e.g., Figure 3.1.

CHAPTER 6

SAMPLE APPLICATION

To demonstrate the methodology, two assessments were performed in this work. In the first, the consequences following a release of toxic gas were assessed. The second example involves a regulatory compliance issue at the potential nuclear waste repository at Yucca Mountain in Nevada.

Description of Risk Assessment

In the first application, the accidental release of toxic gas is initiated by an earthquake. The gas is stored in an above ground tank which is elevated several feet in the air. The adverse event in this case is the failure of the support system during an earthquake. The uncertainties in this assessment are summarized in Table 6.1.

Variability Analysis

The annual frequency of the release was calculated by

$$f_{event} = f_e \cdot p_{fe}(M), \quad (6.1)$$

where

f_{event} = annual frequency of a release (yr.⁻¹),

f_e = annual frequency of an earthquake (earthquake/yr.),

$p_{fe}(M)$ = probability of support system failure given earthquake of magnitude, M (earthquake⁻¹).

In this example, one earthquake has occurred in the area in the last 250 years. Therefore, the annual frequency of an earthquake, f_e , was estimated to be 4×10^{-3} yr⁻¹. The

Table 6.1

Summary of Uncertainties in Sample Application

Uncertainty Category	Risk Component	
	Adverse Event, f_{event}	Consequences, R_{event}
Variability	<ul style="list-style-type: none"> • Magnitude of earthquake, M <ul style="list-style-type: none"> – lognormal($\mu_M=4$, $\sigma_M=0.98$) • Failure during earthquake, f_{fe} <ul style="list-style-type: none"> – correlated to magnitude of earthquake, M, via cumulative normal($\mu_f=4$, $\sigma_f=1$) 	<ul style="list-style-type: none"> • Coefficient, A <ul style="list-style-type: none"> – normal($\mu_A=5$, $\sigma_A=2$) • Coefficient, B <ul style="list-style-type: none"> – uniform($B_1=1$, $B_2=2$) • Coefficient, C <ul style="list-style-type: none"> – triangular(min=2, expected=4, max=6)
Reducible Uncertainty	<ul style="list-style-type: none"> • Annual frequency of an earthquake, f_e <ul style="list-style-type: none"> – histogram (see Table 6.2) • Failure during an earthquake, f_{fe} <ul style="list-style-type: none"> – μ_f=uniform(min=3, max=5) – σ_f=uniform(min=0.5, max=1.5) 	<ul style="list-style-type: none"> • Variability of coefficient, A <ul style="list-style-type: none"> – μ_A=uniform(min=4, max=6) – σ_A=uniform(min=1.5, max=2.5) • Variability of coefficient, B <ul style="list-style-type: none"> – B_1=uniform(min=0.8, max=1.2) – B_2=uniform(min=1.8, max=2.2)

probability of a support failure, $p_{fe}(M)$, was estimated via a cumulative normal distribution as shown in Figure 6.1 (Kaplan et al., 1989). The variability in the magnitude of an earthquake was taken to be log-normally distributed with a mean of 4 and standard deviation of 0.98 (NRC, 1991).

The generic consequences following the toxic release were calculated from

$$R_{event} = \frac{A \times B}{C}, \quad (6.2)$$

where

R_{event} = consequences following adverse event,

A, B, C = coefficients.

The coefficients in Equation 6.2 were taken to be subject to variability as given in Table 6.1.

Reducible Uncertainty Analysis

Reducible uncertainty in the occurrence of the event was considered from two sources: the annual frequency of an earthquake and the probability of a support system failure. Since only one earthquake has occurred in the last 250 years, there is statistical uncertainty in the estimated frequency. In order to quantify this uncertainty, Bayes formula was utilized. Bayes formula is

$$p(f_n|B) = \frac{p(f_n) \cdot p(B|f_n)}{\sum_n p(f_n) \cdot p(B|f_n)}, \quad (6.3)$$

where

B = statement "there has been 1 earthquake in 250 years,"

f_n = n^{th} hypothesis for actual frequency of an earthquake,

Figure 6.1. Reliability of Support System for Seismic Events (Kaplan et al., 1989)

$p(f_n|B)$ = probability of hypothesis, f_n , given B ,

$p(f_n)$ = probability of hypothesis, f_n ,

$p(B|f_n)$ = probability that B has occurred given that f_n is correct.

In using Bayes formula, the assessor must assign "prior" beliefs to each hypothesis. This reflects the Bayesian concept of probability, where a probability represents a subjective quantity regarding individual beliefs about an event (Morgan and Henrion, 1990). For instance, if historical records only date back to 250 years, the assessor may believe that the actual frequency of an earthquake is less than once in 250 years. Thus, the assessor would assign a higher probability, $p(f_n)$, to the lower frequency hypotheses, f_n . For this analysis, the probability of each hypothesis, $p(f_n)$, was assigned an equal chance of being correct. The probability that 1 earthquake has occurred in 250 years (given that the frequency hypothesis, $p(B|f_n)$, is correct) was determined from the Poisson distribution as given by

$$p(B|f_n) = \frac{(f_n \cdot y)^x}{x!} \cdot \exp(-f_n \cdot y), \quad (6.4)$$

where

x = number of observed earthquakes (i.e., 1),

y = observation period (i.e., 250 years).

The results of using Bayes Formula are given in Table 6.2.

The next source of reducible uncertainty is the failure rate of the support system. For this example, the parameters μ_M and σ_M of the distribution in Figure 6.1 were taken to be uniformly distributed between 3 and 5 and 0.5 and 1.5, respectively.

The variability in the coefficients A and B in Equation 6.2 were taken to have reducible uncertainties as summarized in Table 6.1.

Table 6.2

Use of Bayes Formula for Quantifying Earthquake
Frequency Uncertainty

	Hypothesis for Frequency of Earthquake, f_n					
	10^{-4}	$10^{-3.5}$	10^{-3}	$10^{-2.5}$	10^{-2}	$10^{-1.5}$
$p(B f_n^*)$	0.0244	0.0731	0.195	0.359	0.252	0.00291
$p(f_n)$	0.167	0.167	0.167	0.167	0.167	0.167
$p(f_n) \cdot p(B f_n)$	0.00407	0.0122	0.0325	0.0598	0.0342	0.000485
$p(f_n B)$	0.0284	0.0852	0.227	0.418	0.239	0.00338

* B represents the statement "1 earthquake has occurred in 250 years."

Results

The @RISK software package was utilized in obtaining 100 pairs of frequencies, f_{event} , and consequences, R_{event} , for the variability and reducible uncertainty analyses, as shown in Figures 6.2 and 6.3. The risk curves were constructed from

$$f^n(R_{event} > x) = f^n_{event} \cdot p(R_{event} > x), \quad (6.5)$$

where

$f^n(D > x)$ = annual frequency at the n^{th} confidence level (i.e., 5% or 95%) of exceeding x consequences (yr^{-1}),

f^n_{event} = annual frequency at the n^{th} confidence level of a release (failures/yr.),

$p(R_{event} > x)$ = probability of a tank failure leading to more than x consequences (failure $^{-1}$).

From Figure 6.2, the values of f^n_{event} at the 5% and 95% confidence levels were obtained for both analyses. By multiplying these results with values for $p(R_{event} > x)$ from Figure 6.3, the risk curves Figure 6.4 were obtained. The solid lines of Figure 6.4 represent the risk curves based on the variability analysis at the 5% and 95% confidence level. The dashed lines represent the overall risk curves, at the 5% and 95% confidence level, after incorporating both variability and reducible uncertainty into the analysis.

Figure 6.2. Event Distribution

Figure 6.3. Consequence Distribution

Figure 6.4. Risk Curves for Toxic Gas Release

CHAPTER 7
ASSESSMENT OF THE EXPLORATORY STUDIES FACILITIES
NORTH TUNNEL AT YUCCA MOUNTAIN

Background

Yucca Mountain

The Department of Energy (DOE) was charged with developing a nuclear waste system for transporting, storing, and disposing commercial high-level nuclear wastes by the Nuclear Waste Policy Act of 1982. The DOE outlined several options for the permanent disposal of nuclear wastes. Only geological repositories and seabed disposal were considered feasible. In 1986, the seabed research was discontinued, and the Nuclear Waste Policy Amendments of 1987 dictated that a site at Yucca Mountain in Nevada be characterized to determine its suitability as a geological repository (Lynch and Hunter, 1992).

Yucca Mountain is located adjacent to the Nevada Test Site about 70 miles northwest of Las Vegas. It is situated in an arid area of the Great Basin just east of Death Valley, California. The hydrological system of the area is characterized by low precipitation, deep water tables, and closed topographic and groundwater basins that contain all surface-water flow within the area. Along with the hydrological advantages of Yucca Mountain, the site does not contain any commercially attractive resources such as oil, coal, or precious metals. Furthermore, the area is geologically stable with no major volcanic or seismic activity occurring over the last 2 million years (Lynch and Hunter,

1992). The repository would be built about 200 to 400 meters above the water table in a volcanic tuff that sorbs certain radionuclides (TRW, 1993).

Conceptual designs of the proposed repository include surface and subsurface facilities. The surface facilities encompass any waste handling operations required prior to emplacement in addition to offices, labs and waste acceptance facilities. The subsurface facilities are divided into two parts: disposal and mining. According to current designs, the repository would store approximately 70,000 metric tons of uranium (MTU) with a operating life of about 20 years (Lynch and Hunter, 1992).

Exploratory Studies Facility

At present, site characterization of Yucca Mountain is the single largest element of the DOE's high-level radioactive waste program. Expected to be completed within the next decade, the characterization will lead to a recommendation to the President and Congress as to the suitability of the site. Present characterization is focused on determining both surface and subsurface properties of the mountain. For the subsurface characterization, an Exploratory Studies Facility (ESF) is being built.

Application of Proposed Risk Approach

Since some parts of the ESF are to be incorporated into the repository (if built), certain items are subject to regulations affecting the repository. 10 CFR 60 dictates that any repository item essential to the prevention of an accident leading to an off-site dose of 500 mrem at any time during the operating phase be subject to special quality assurance

procedures (NRC, 1986b). A DOE administrative procedure (AP-6.17Q) stipulates that these accidents have a probability of occurrence greater than $1 \times 10^{-6} \text{ yr}^{-1}$ (DOE, 1992).

This analysis was limited to one component of the ESF, the north tunnel. The tunnel is being drilled during the construction of the ESF. If the repository is ultimately built, waste packages being transported into the main repository would pass through the tunnel. (TRW, 1993). The safety of the north tunnel support system (as defined by 10 CFR 60) was assessed in this work. The adverse event of interest is a spontaneous rock fall that ruptures a waste package while being transported through the north tunnel. If a rock fall can result in an off-site dose greater than 500 mrem and occur more than once in a million years, then the walls of the tunnel would be considered important to safety. Under this classification, special procurement procedures which are subject to strict quality assurance guidelines would be instituted for construction. These procedures increase the cost of construction considerably.

Description of Risk Assessment

The risk assessment procedure for the north tunnel is summarized in Figure 7.1. This procedure differs from the previous examples in that there is no health effects model since 10 CFR 60 dictates a risk criterion based on committed dose. The sources of variability and reducible uncertainty in this assessment are summarized in Table 7.1. Sample calculations are presented in Appendix A.

Figure 7.1. Summary of Yucca Mountain Risk Assessment

Table 7.1

Summary of Uncertainties in North Tunnel Risk Assessment

Uncertainty Category	Risk Component	
	Adverse Event	Consequence
	Rock fall hitting waste package.	Magnitude of equivalent dose at off-site boundary
Variability	<ul style="list-style-type: none"> • Probability of rock fall striking package Number of waste packages received annually, $N_{packages}$ • Magnitude of rock fall, M 	<ul style="list-style-type: none"> • Source Term <ul style="list-style-type: none"> • Inventory of radionuclides in waste package, A_i <ul style="list-style-type: none"> • Assembly type (i.e., BWR or PWR spent fuel) • Burnup • Decay time • Release of radionuclides <ul style="list-style-type: none"> • Waste package response to rock fall, $\varepsilon(M)$ • Fractional release, $f_{i,j}^R(\varepsilon)$ • Transport <ul style="list-style-type: none"> • Transport in tunnel <ul style="list-style-type: none"> • Distance for transport in tunnel, l • Velocity of ventilation air, u_{air} • Atmospheric transport <ul style="list-style-type: none"> • Atmospheric stability • Wind speed and direction

Table 7.1 (continued)

Summary of Uncertainties in North Tunnel Risk Assessment

Uncertainty Category	Risk Component	
	Adverse Event	Consequence
	Rock fall hitting waste package.	Magnitude of equivalent dose at off-site boundary
Reducible Uncertainty	<ul style="list-style-type: none"> • Probability of rock fall striking package <ul style="list-style-type: none"> • Frequency of rock fall, f_r • Probability of filter failure, p_s 	<ul style="list-style-type: none"> • Source term <ul style="list-style-type: none"> • Fractional inventory of radionuclides, f_{ij} • Waste package response to rock fall <ul style="list-style-type: none"> • Model uncertainties • Transport <ul style="list-style-type: none"> • Transport in tunnel <ul style="list-style-type: none"> • Settling velocity, v_t • Atmospheric transport <ul style="list-style-type: none"> • Deposition model uncertainty • Settling velocity, v_d • Transport model uncertainty

Variability Analysis

Source Term

Variability in the source term is from three sources. The occurrence of the adverse event varies yearly depending on the number of waste packages received. Next, the magnitude of a radiological release depends on the size of the rock fall. Finally, the radionuclide inventory of waste packages varies depending on several factors.

Assumptions

Since current design information for the ESF is preliminary, several assumptions about the ESF structure and repository operations were required. Although the repository is to receive both commercial and defense wastes, this analysis was limited to boiling water reactor (BWR) and pressurized water reactor (PWR) spent nuclear fuel (SNF) from commercial power reactors. Defense high-level waste was not considered because the variability of the radionuclide inventory is difficult to characterize and the vitrified waste is considered to be in a more stable form than the SNF (Ma et al., 1992a). Based on the latter consideration, considering only commercial SNF yields a conservative estimate of the risks. It was also assumed that the outer shell of a waste package is comprised of 45 centimeter thick stainless steel and that the BWR packages and PWR packages hold 54 and 21 assemblies respectively (TRW, 1993).

Adverse Event Frequency

The annual frequency of the adverse event was calculated by

$$f_{event} = f_r \cdot p_{hr} \cdot p_s, \quad (7.1)$$

where

f_{event} = annual frequency of rock fall striking waste package (hits/yr.),

f_r = annual frequency of a rock fall (rock fall/yr.),

$p_{h|r}$ = probability of rocks hitting waste package given a rock fall (hit/rock fall),

p_s = probability of scenario (discussed later).

From records of rock falls in commercial mines, the observed frequency of rock falls, f_r , was found to be 470 in 4,449 mining years (Smith and Tsai, 1994). This suggests a frequency of 0.106 rock falls/yr.

The waste package is to be carried from the surface into the main repository on a railed transporter coupled to a small locomotive (TRW, 1993). The transporter is in the north tunnel for a fraction of the total operational time of the repository. Also, the transporter only contains one waste package for the first trip into the repository. When a loaded transporter is in the north tunnel, there is a further probability that a rock fall would strike it. The probability of a rock fall hitting the waste package was calculated from

$$P_{h|r} = P_1 \cdot P_{2|1}, \quad (7.2)$$

where

p_1 = probability of transporter carrying a waste package through north tunnel,

$p_{2|1}$ = probability that the loaded transporter is hit by a rock fall given the transporter is in the north tunnel.

The probability that a loaded transporter is in the north tunnel was calculated from

$$p_1 = N_{\text{packages}} \cdot t_e, \quad (7.3)$$

where

N_{packages} = number of waste packages emplaced annually (packages/yr.),

t_e = time to emplace each package (yr./package).

According to data given in Lynch and Hunter, approximately 3,000 MTU of SNF are to be emplaced annually (1991). This figure includes about 3,900 PWR assemblies and 6,500 BWR assemblies. This corresponds to approximately 186 waste packages of PWR assemblies and 125 waste packages of BWR assemblies for a total number of packages, N_{packages} , of 311 per year. However, this number is expected to vary. This variability was characterized with a normal distribution with a mean of 311 and standard deviation of 25. Given that the transporter travels at 2.25 m/s and the north tunnel is about 2,000 meters in length, the time to emplace the waste, t_e , is approximately 15 minutes (2.82×10^{-5} years/package) (TRW, 1993; Smith and Tsai, 1994). The probability the transporter is hit by a rock fall when in the tunnel (i.e., p_{21}) is given by geometry. Since the transporter is expected to be 5 meters in length, the probability of a rock fall hitting the transporter is 2.5×10^{-3} .

Radiological Release

If a rock fall hits a waste package, energy is transferred to the waste package. The package deforms during this process, possibly rupturing a fraction of the SNF rods in the package. If the deformation exceeds the elastic limits of the package material, radionuclides from 2 areas of the assemblies could be released: the cladding gap and SNF

pellets. SNF consists of fuel pellets surrounded by a zircaloy cladding. A fraction of certain radionuclides in the pellets diffuse into the gap between the pellets and cladding. These radionuclides exist in either a gaseous or volatile state. The volatile elements have a significant vapor pressure such that any breach of the cladding results in a strong driving force from the solid to gaseous state. Once outside the high temperatures of the SNF, the volatile elements condense on particulate matter within the repository. The second mode of release is radionuclides attached to the SNF. It has been found that when uranium dioxide pellets are subjected to an impact, respiratory sized particulate matter (i.e., particle diameters of less than 10 μm) is released (Lorenz et al., 1980; Mecham et al., 1981; Jardine et al., 1982). Encompassing these processes, the source term given in Figure 7.2 was used in this work. The activity of each radionuclide released was determined from

$$S_i = A_i \cdot \sum_j f_{i,j}^R(\varepsilon), \quad (7.4)$$

where

S_i = release of isotope i , Bq (Ci),

A_i = inventory of isotope i in waste package, Bq (Ci),

$f_{i,j}^R(\varepsilon)$ = fractional release of isotope i in category j (j =gap, or SNF) from total waste package inventory as a function of the strain, ε , imparted by a rock fall with magnitude, M .

Waste Package Inventory. There are three variables that dictate the radionuclide inventory in any given waste package. The most important factor is the type of SNF in the waste package. The radionuclide inventory is also dependent on the burnup of each assembly in the package. Burnup is a measure of the amount of energy obtained from the fuel in a reactor. It is expressed as thermal energy produced for each metric ton of

Figure 7.2. Summary of Source Term

uranium in the assembly (GWd/MTU). Third, the time out of the reactor is important to the amount of radioactive decay which has occurred.

The activity of each waste package was determined from

$$A_i = \sum_{a=1}^{N_a} A_{i,a}(\text{type}, \text{burnup}, \text{decay}), \quad (7.5)$$

where

A_i = activity of isotope i in waste package, Bq, (Ci),

$A_{i,a}$ = activity of isotope i in assembly a for given SNF type, burnup, and decay, Bq, (Ci),

N_a = number of assemblies in package (e.g., 54 if BWR package, 21 if PWR package).

As mentioned before, the repository is expected to emplace approximately 3,900 PWR and 6,500 BWR assemblies per year. Thus, given a waste package is hit by a rock fall, the conditional probability of a BWR and PWR waste package being struck is about 0.4 and 0.6, respectively (EIA, 1991; Lynch and Hunter, 1991). The variation in the burnup for both BWR and PWR assemblies is shown in Figure 7.3 (DOE, 1984; Ma et al., 1991). In this analysis, the variability in the BWR and PWR cooling times are taken to be the same and is given in Figure 7.4 (DOE, 1986; Ma et al., 1991).

The radionuclide inventory of each assembly comprising the waste package was determined from

$$A_{i,a}(\text{type}, \text{burnup}, \text{decay}) = \bar{A}_{i,a}(\text{type}, \text{burnup}, \text{decay}) \cdot m_a, \quad (7.6)$$

where

$A_{i,a}$ = inventory of isotope i in assembly a for given SNF characteristics, Bq, (Ci),

Figure 7.3. Variability in Spent Nuclear Fuel Burnup

Figure 7.4. Variability in Spent Nuclear Fuel Decay Time for BWR and PWR Assemblies

$\bar{A}_{i,a}$ = normalized inventory of isotope i in assembly a for given SNF characteristics, Bq/MTU, (Ci/MTU),

m_a = mass loading of uranium in assembly a (MTU).

The normalized inventories (i.e., fuel type, burnup, and decay time) for each of the 24 SNF types are given in Tables 7.2 and 7.3 (DOE, 1993). The variability in the uranium loading is shown in Figures 7.5 and 7.6 (DOE, 1993).

Waste Package Release. The fractional releases of each isotope was calculated from

$$f_{i,j}^R(\varepsilon) = f_{i,j} \cdot f_j(\varepsilon) \cdot f_{rods}(\varepsilon), \quad (7.7)$$

where

$f_{i,j}$ = fraction of isotope i in release category j ,

$f_j(\varepsilon)$ = fraction of category j released from strain ε ,

$f_{rods}(\varepsilon)$ = fraction of rods in package ruptured from strain ε .

Isotopes of Xe, Kr, I, Br, Cs, Rb, Sr, Ba, Te, Se, and Sb exist in the gap (Rasmussen et al., 1975). Upon emplacement in the repository, the SNF would have decayed for at least 10 years, so only isotopes of Kr, Sr, I, Cs, and Ba were considered. The fractional inventory of these isotopes in the gap (i.e., $f_{i,gap}$) was determined from literature. The maximum values were utilized in the variability analysis and are given in Table 7.4. Because of the discrepancies in the literature, uncertainty in these values was considered to be reducible. The fraction of isotopes existing in the SNF ($f_{i,SNF}$) was determined by the mass balance

$$f_{i,gap} + f_{i,SNF} = 1, \quad (7.8)$$

Table 7.2

BWR Radionuclide Inventories (Ci/MTU)

Isotope	25000 GWd/MTU (2.6% Enrichment)				35000 GWd/MTU (3.2% Enrichment)				45000 GWd/MTU (3.61% Enrichment)			
	Years Out of Reactor				Years Out of Reactor				Years Out of Reactor			
	10	15	20	30	10	15	20	30	10	15	20	30
Fe-55	1.34E+02	3.54E+01			1.57E+02	4.13E+01	5.25E+02		1.68E+02			
Co-60	1.55E+03	8.02E+02	4.15E+02	1.12E+02	1.96E+03	1.01E+03	2.60E+02	1.41E+02	2.24E+03	1.16E+03	6.01E+02	1.61E+02
Ni-63	2.16E+02	2.08E+02	2.00E+02	1.85E+02	2.81E+02	2.70E+02	2.59E+03	2.41E+02	3.32E+02	3.20E+02	3.08E+02	2.86E+02
Kr-85	3.60E+03	2.60E+03	1.88E+03	9.87E+02	4.94E+03	3.58E+03	4.71E+04	1.36E+03	5.89E+03	4.26E+03	3.09E+03	1.62E+03
Sr-90	4.25E+04	3.77E+04	3.35E+04	2.64E+04	5.97E+04	5.30E+04	4.71E+04	3.71E+04	7.27E+04	6.45E+04	5.73E+04	4.51E+04
Y-90	4.25E+04	3.77E+04	3.35E+04	2.64E+04	5.97E+04	5.30E+04		3.71E+04	7.27E+04	6.45E+04	5.73E+04	4.52E+04
Ru-106	4.00E+02				5.05E+02				5.68E+02			
Rh-106	4.00E+02				5.04E+02				5.68E+02			
I-129	2.44E-02	2.44E-02	2.44E-02	2.44E-02	3.57E-02	3.57E-02	3.57E-02	3.57E-02	4.56E-02	4.56E-02	4.56E-02	4.56E-02
Sb-125	1.11E+03	3.18E+02	9.10E+01		1.47E+03	4.20E+02	1.20E+02		1.72E+03	4.92E+02	1.41E+02	
Te-125m	2.71E+02	7.76E+01	2.22E+01		3.58E+02	1.02E+02			4.19E+02	1.20E+02		
Cs-134	3.63E+03	6.76E+02	1.26E+02		6.75E+03	1.26E+03	2.34E+02		9.81E+03	1.83E+03	3.40E+02	
Cs-137	6.20E+04	5.52E+04	4.92E+04	3.90E+04	9.00E+04	8.02E+04	7.14E+04	5.67E+04	1.13E+05	1.01E+05	8.97E+04	7.12E+04
Ba-137m	5.86E+04	5.22E+04	4.65E+04	3.69E+04	8.52E+04	7.59E+04	6.76E+04	5.36E+04	1.07E+05	9.53E+04	8.49E+04	6.74E+04
Ce-144	1.04E+02				1.11E+02				1.09E+02			
Pr-144	1.04E+02				1.11E+02				1.09E+02			
Pm-147	7.72E+03	2.06E+03	5.50E+02	3.92E+01	7.85E+03	2.10E+03	5.59E+02	3.98E+01	7.58E+03	2.02E+03	6.02E+02	3.84E+01
Sm-151	3.26E+02	3.13E+02	3.01E+02	2.79E+02	4.28E+02	4.12E+02	3.96E+02	3.67E+02	5.21E+02	5.01E+02	4.82E+02	4.47E+02
Eu-154	2.80E+03	1.87E+03	1.25E+03	5.59E+02	5.36E+03	3.58E+03	2.40E+03	1.07E+03	7.97E+03	5.33E+03	3.56E+03	1.59E+03
Eu-155	1.08E+03	5.35E+02	2.66E+02	6.57E+01	2.04E+03	1.02E+03	5.05E+02	1.25E+02	3.12E+03	1.55E+03	7.72E+02	1.91E+02
Pu-238	1.70E+03	1.63E+03	1.57E+03	1.45E+03	4.18E+03	4.01E+03	3.86E+03	3.57E+03	7.57E+03	7.28E+03	7.00E+03	6.47E+03
Pu-239	2.89E+02	2.89E+02	2.89E+02	2.89E+02	3.44E+02	3.44E+02	3.44E+02	3.44E+02	3.95E+02	3.95E+02	3.95E+02	3.95E+02
Pu-240	3.84E+02	3.84E+02	3.85E+02	3.85E+02	5.36E+02	5.38E+02	5.39E+02	5.41E+02	6.85E+02	6.88E+02	6.91E+02	6.96E+02
Pu-241	7.53E+04	5.92E+04	4.65E+04	2.87E+04	9.44E+04	7.42E+04	5.83E+04	3.60E+04	1.09E+05	8.59E+04	6.76E+04	4.17E+04
Am-241	1.68E+03	2.20E+03	2.60E+03	3.15E+03	2.15E+03	2.80E+03	3.30E+03	3.99E+03	2.53E+03	3.28E+03	3.87E+03	4.66E+03
Cm-244	9.80E+02	8.09E+02	6.68E+02	4.56E+02	3.59E+03	2.97E+03	2.45E+03	1.67E+03	8.33E+03	6.88E+03	5.68E+03	3.87E+03

Table 7.3

PWR Radionuclide Inventories (Ci/MTU)

Isotope	35000 GWd/MTU (3.43% Enrichment)				45000 GWd/MTU (4.00% Enrichment)				55000 GWd/MTU (4.50% Enrichment)			
	Years Out of Reactor				Years Out of Reactor				Years Out of Reactor			
	10	15	20	30	10	15	20	30	10	15	20	30
Fe-55	2.33E+02	6.14E+01			2.55E+02	6.74E+01			2.91E+02	7.67E+01		
Co-60	2.41E+03	1.25E+03	6.45E+02	1.73E+02	2.77E+03	1.43E+03	7.43E+02	1.99E+02	3.16E+03	1.64E+03	8.49E+02	2.28E+02
Ni-63	4.10E+02	3.94E+02	3.80E+02	3.52E+02	4.77E+02	4.60E+02	4.43E+02	4.10E+02	5.71E+02	5.49E+02	5.29E+02	4.91E+02
Kr-85	5.08E+03	3.68E+03	2.66E+03	1.39E+03	6.26E+03	4.53E+03	3.28E+03	1.72E+03	7.40E+03	5.36E+03	3.88E+03	2.03E+03
Sr-90	6.04E+04	5.36E+04	4.76E+04	3.75E+04	7.54E+04	6.70E+04	5.95E+04	4.69E+04	9.03E+04	8.02E+04	7.12E+04	5.61E+04
Y-90	6.04E+04	5.36E+04	4.76E+04	3.75E+04	7.55E+04	6.70E+04	5.95E+04	4.69E+04	9.04E+04	8.02E+04	7.12E+04	5.61E+04
Ru-106	5.32E+02				6.15E+02				6.86E+02			
Rh-106	5.32E+02				6.15E+02				6.86E+02			
I-129	3.33E-02	3.33E-02	3.33E-02	3.33E-02	4.25E-02	4.25E-02	4.25E-02	4.25E-02	5.11E-02	5.11E-02	5.11E-02	5.11E-02
Sb-125	1.31E+03	3.75E+02	1.07E+02		1.58E+03	4.52E+02	1.29E+02		1.80E+03		1.47E+02	
Te-125m	3.20E+02	9.14E+01			3.85E+02	1.10E+02			4.39E+02	5.15E+02		
Cs-134	5.93E+03	1.10E+03	2.06E+02		8.89E+03	1.66E+03	3.08E+02		1.21E+04	1.26E+02	4.18E+02	
Cs-137	8.65E+04	7.71E+04	6.87E+04	5.45E+04	1.10E+05	9.80E+04	8.73E+04	6.93E+04	1.33E+05	2.25E+03	1.06E+05	8.38E+04
Ba-137m	8.19E+04	7.29E+04	6.50E+04	5.15E+04	1.04E+05	9.27E+04	8.26E+04	6.55E+04	1.26E+05	1.19E+05	9.99E+04	7.93E+04
Ce-144	1.40E+02				1.45E+02				1.48E+02	1.12E+05		
Pr-144	1.40E+02				1.45E+02				1.48E+02			
Pm-147	9.14E+03	2.44E+03	6.51E+02	4.64E+01	9.05E+03	2.42E+03	6.45E+02	4.59E+01	8.78E+03	2.34E+03	6.25E+02	4.45E+01
Sm-151	3.93E+02	3.78E+02	3.64E+02	3.37E+02	4.82E+02	4.64E+02	4.46E+02	4.13E+02	5.28E+02	5.08E+02	4.89E+02	4.53E+02
Eu-154	4.49E+03	3.00E+03	2.00E+03	8.95E+02	6.79E+03	4.54E+03	3.04E+03	1.36E+03	9.07E+03	6.06E+03	4.05E+03	1.81E+03
Eu-155	1.64E+03	8.17E+02	4.06E+02	1.00E+02	2.52E+03	1.25E+03	6.23E+02	1.54E+02	3.37E+03	1.68E+03	8.33E+02	2.06E+02
Pu-238	2.95E+03	2.83E+03	2.72E+03	2.52E+03	5.38E+03	5.17E+03	4.97E+03	4.60E+03	8.21E+03	7.89E+03	7.59E+03	7.01E+03
Pu-239	3.60E+02	3.60E+02	3.60E+02	3.59E+02	4.13E+02	4.13E+02	4.13E+02	4.13E+02	4.45E+02	4.45E+02	4.45E+02	4.45E+02
Pu-240	5.15E+02	5.16E+02	5.16E+02	5.17E+02	6.59E+02	6.61E+02	6.62E+02	6.64E+02	8.28E+02	8.31E+02	8.34E+02	8.37E+02
Pu-241	8.45E+04	6.64E+04	5.22E+04	3.23E+04	9.83E+04	7.73E+04	6.07E+04	3.75E+04	1.01E+05	7.96E+04	6.26E+04	3.87E+04
Am-241	1.88E+03	2.47E+03	2.92E+03	3.53E+03	2.22E+03	2.90E+03	3.42E+03	4.14E+03	2.30E+03	3.00E+03	3.54E+03	4.27E+03
Cm-244	1.77E+03	1.46E+03	1.21E+03	8.24E+02	4.02E+03	3.32E+03	2.74E+03	1.87E+03	7.13E+03	5.89E+03	4.86E+03	3.32E+03

Figure 7.5. Variability in Initial Uranium Loading for a BWR Assembly

Figure 7.6. Variability in Initial Uranium Loading for a PWR Assembly

Table 7.4

Maximum Values for Isotopic Fractions, f_{ij}

Radioisotope	$f_{i,gap}$	Reference
^{85}Kr	0.30	NRC, 1972; Hartman and Miller, 1991; Ma et al., 1992a,b
^{90}Sr	10^{-4}	Smith and Tsai, 1994
^{129}I	0.30	Smith and Tsai, 1994
^{134}Cs	0.05	NRC, 1983a
^{137}Cs	0.05	NRC, 1983a
^{137m}Ba	10^{-4}	Smith and Tsai, 1994

The categorical release fractions (i.e., $f_f(\epsilon)$) and the fraction of rods ruptured (i.e., $f_{rods}(\epsilon)$) are given by the point values in Table 7.5 (NRC, 1987; Smith and Tsai, 1994). As shown in Table 7.5, krypton gas is released more readily than other isotopes in the gap, therefore is treated uniquely from other releases. In order to compute the parameters in Table 7.5 for intermediate strains, the relationships in Table 7.6 were developed by curve fitting the data points given in Smith and Tsai (1994). As shown, these relationships have limits at lower and upper strains. Below the threshold strain, the waste package was taken to remain sealed.

Waste Package Response. Smith and Tsai (1994) estimated the strain imparted on a waste package for various rock fall magnitudes. Rock fall magnitude is quantified as the energy transferred per length of waste package. In this way, the rock fall magnitude is expressed as an energy loading per length. The amount of strain that a 45 cm thick stainless steel package experiences over various magnitudes is shown in Figure 7.7. The waste package response was given by

$$\log \epsilon = 0.764 \cdot (\log M - 8.155), \quad (7.9)$$

where

ϵ = strain imparted on waste package (m/m),

M = magnitude of rock fall (J/m).

Rock fall Magnitude. The variability in the rock fall magnitude was based on site-specific data regarding the size and distribution of rock fractures. The fracture characteristics were divided into 5 categories describing the quality of the rock. For regions in the rock where the fractures are large (i.e., higher quality of rock), the size of

Table 7.5

Waste Package Response to Induced Strains

Strain, ϵ	Effects	Fractional Releases, $f_i(\epsilon)$ and $f_{rods}(\epsilon)$			
		Gap		SNF	Rods
		Volatiles $f_{gap}(\epsilon)$	Krypton $f_{gap}(\epsilon)$	$f_{SNF}(\epsilon)$	$f_{rods}(\epsilon)$
0.002	Elastic deformation. Acceleration may cause small fraction (<3%) of fuel rods to leak. No leakage from waste package.	10^{-6}	10^{-4}	0	$3 \cdot 10^{-2}$
0.02	Plastic deformation. Some leaks in non-welded seals. Acceleration may lead to 3% to 10% of fuel rods to leak.	10^{-1}	1	10^{-8}	10^{-1}
0.3	Plastic deformation. Leaks expected in welded and non-welded seals. All fuel rods ruptured with particulate release.	1	1	10^{-4}	1

Table 7.6

Fractional Release Relationships

Release Mode	Equation	Constraints	
Gap (except ^{85}Kr)	$\log(f_{gap}) = 2.24 \cdot \{1 - 0.286 \cdot \exp(-0.95 \cdot \log(\epsilon))\}$	$f_{gap} = 0$ for $\epsilon < 0.002$	$f_{gap} = 1$ for $\epsilon > 0.20$
^{85}Kr	$\log(f_{gap}) = 4 \cdot \log(\epsilon) + 6.795$	$f_{gap} = 0$ for $\epsilon < 0.002$	$f_{gap} = 1$ for $\epsilon > 0.02$
SNF	$\log(f_{SNF}) = -\frac{16}{2^n} - 3 + n$ where $n = \log\left(\frac{\epsilon}{10^{-3}}\right)$	$f_{SNF} = 0$ for $\epsilon < 0.02$	$f_{SNF} = 10^{-2}$ for $\epsilon > 0.30$
Fraction of rods ruptured	$\log(f_{rods}) = 0.704 \cdot \log(\epsilon) + 0.314$	$f_{rods} = 0$ for $\epsilon < 0.002$	$f_{rods} = 1$ for $\epsilon > 0.30$

Figure 7.7. Waste Package Response to Rock-Falls

rocks in a rock fall are correspondingly large. Based on this, Smith and Tsai calculated the range of magnitudes for each category (1994). The variability in the rock fall magnitude is summarized in Table 7.7. The magnitude of a rock fall was determined by first sampling a rock quality defined by the distribution in Table 7.7. Next, the magnitude was chosen uniformly from the corresponding limits for that rock quality.

Environmental Transport

Variability in the radioactive particle sizes results in uncertainty of transport mechanisms such as settling, dispersion and filtration. Varying conditions of the repository ventilation system affect the transport of the radionuclides inside the tunnels. Furthermore, prevailing meteorological conditions at the time of release result in variations in the transport of radionuclides to the off-site boundary.

Following the release of radionuclides from a waste package, the radionuclides travel through the ventilation system of the repository. Before exiting the repository, a fraction of the particulate matter and condensed volatile compounds are removed in the tunnels. During normal operations, air is vented from the entrance of the north tunnel through the emplacement drifts and out a stack. However when radioactivity is detected in the repository, the ventilation air is directed through a bank of HEPA filters, thus attenuating a fraction of the particulate radionuclides (TRW, 1993). The remaining radionuclides are released from the stack where the gaseous/volatile compounds and particulate matter are dispersed into the atmosphere and/or deposited on the ground. Based on these processes, three transport mechanisms were considered: gravitational

Table 7.7

Variability in Rock Fall Magnitude

Rock Quality	Percent Observed	Magnitude, M (MJ/m)	
		Lower Limit	Upper Limit
1	19.1	0.13	0.54
2	36.5	0.16	0.67
3	26.5	0.21	0.88
4	11.7	0.31	1.33
5	6.1	0.58	2.47

settling in the repository, filtration of the particulate matter, and dispersion in the atmosphere and deposition on the ground.

Two scenarios were considered for the transport of the radioactive plume. First, a rock fall could occur where radionuclides are filtered through the HEPA filter. Conversely, a rock fall could occur where the HEPA filter or ventilation system fails. The probability of this scenario, p_s , (see Equation 7.1) was estimated to be 5×10^{-2} /accident (Ma et al., 1992).

Assumptions

Current designs for the ventilation system indicate two different options. For this analysis, the ventilation system was assumed to consist of one bank of HEPA filters and a 25 meter stack. The other option includes two banks of HEPA filters, making the design scenario considered in this work more conservative.

The depletion of the radioactive particulate matter and volatile compounds was calculated from an approach dictated by the regulations. The transport of radionuclides in the environment was calculated from (NRC, 1983b; NRC, 1986b; DOE 1992)

$$C/S = R \cdot (1 - FIL) \cdot \lambda/Q \cdot DEP, \quad (7.10)$$

where

C/S = depletion factor (s/m^3),

R = fraction transported through repository tunnels,

FIL = filtering efficiency,

$\kappa/Q =$ dispersion coefficient (s/m^3),

$DEP =$ fraction transported through atmosphere.

Removal in Repository

Suspended radionuclides would be deposited in the tunnels due to gravitational settling and diffusion from the air towards the walls of the tunnel. For respiratory sized particles, both mechanisms were considered of equal importance (Smith and Tsai, 1994). Deposited particles may also become resuspended due to turbulence in the tunnels. However, resuspension was considered negligible assuming no subsequent rock falls (Ma et al., 1990).

The fraction transported through the tunnels for all isotopes except krypton was given by (Smith and Tsai, 1994)

$$R = \exp\left(-\frac{4 \cdot v_t \cdot l}{d \cdot u_{air}}\right), \quad (7.11)$$

where

$v_t =$ settling velocity (inside repository) (m/s),

$l =$ distance from point of rupture to exit of ventilation system (m),

$d =$ diameter of tunnels (m),

$u_{air} =$ ventilation air velocity (m/s).

The settling velocity of the radioactive plume is a function of the particle size distribution and conditions inside the repository such as the roughness of the tunnel walls. Smith and Tsai suggest a settling velocity of 4×10^{-2} cm/s, which accounts for both gravitational settling and diffusion (1994). The distance from the point of rupture to the

exit of the ventilation system, l , was approximated as uniformly distributed between the north tunnel and the ventilation stack. Based on current designs, the diameter of the north tunnel, d , would be 7.6 meters (TRW, 1993). Furthermore, variations in the ventilation air velocity, u_{air} , was accounted for with a uniform distribution between 0.3 m/s and 7.6 m/s (Jurani, 1992; TRW, 1993).

HEPA Filter Efficiency

HEPA filters are designed to remove all particles from a gas stream with a minimum efficiency of 99.97% (Novick and Higgins, 1989). This efficiency represents the attenuation for particulate matter with a diameter of 0.3 micrometers. The estimated percentage of respiratory sized particulate matter with diameters less than 1 micrometers is 0.7% implying this efficiency is somewhat conservative (Ma et al., 1990). It should be noted that gases are not attenuated through HEPA filters.

Atmospheric Dispersion

The dispersion coefficient was calculated from

$$\chi/Q = \frac{1}{u \cdot \pi \cdot \sigma_y \cdot \sigma_z} \cdot \exp\left(-\frac{h^2}{2 \cdot \sigma_z^2}\right), \quad (7.12)$$

where,

σ_y = lateral plume spread (m),

σ_z = vertical plume spread (m),

h = stack height (m),

u = wind velocity (m/s).

Values for the lateral and vertical plume spread were estimated from the relationships (Vogt, 1977)

$$\sigma_y(x) = (a_1 \cdot \ln(x) + a_2) \cdot x \text{ and} \quad (7.13)$$

$$\sigma_{z(x)} = \frac{1}{2.15} \cdot \exp(b_1 + b_2 \cdot \ln(x) + b_3 \cdot \ln^2(x)), \quad (7.14)$$

where

x = distance to off-site boundary (m),

a_1, a_2, b_1, b_2, b_3 = diffusion coefficients for Pasquill-Gifford atmospheric stability class (see Table 7.8.).

The distance to the off-site boundary was determined from current design information and on-site meteorological data (EG&G, 1994; SAIC, 1994). Following an NRC approach, the area surrounding the repository was divided into 16 sectors (NRC, 1983b). The percentage of the time with which the wind was observed to blow into each sector and the corresponding distance to the off-site boundary is given in Figure 7.8. The procedure for utilizing the meteorological data is given in Appendix C.

The wind velocity and atmospheric stability was also quantified using the meteorological data (SAIC, 1994). The resulting distribution of observed velocities and stability classes are given in Table 7.9. The stability was randomly chosen from the distribution listed in Table 7.9 (listed vertically under "Frequency"). Then a velocity class was randomly chosen from the distribution corresponding to the selected stability. Finally, a velocity was uniformly selected from the limits in the velocity class.

Table 7.8

Diffusion Coefficients for Evaluating σ_y and σ_z

Coefficient	Stability Class					
	A	B	C	D	E	F
a_1	-0.0234	-0.0147	-0.0117	-0.0059	-0.0059	-0.0029
a_2	0.3500	0.2480	0.1750	0.1080	0.0880	0.0540
b_1	-0.8800	-0.9850	-1.1860	-1.3500	-2.8800	-3.8000
b_2	0.1520	0.8200	0.8500	0.7930	1.2550	1.4190
b_3	0.1475	0.0168	0.0045	0.0022	-0.0420	-0.0550

Figure 7.8. Observed Variability in Wind Rose Data and Distance to Conceptual Controlled Access Boundary (CCAB)

Table 7.9

Observed Variability in Atmospheric Conditions

Stability	Percent Observed	Velocity Class*						
		0	1	2	3	4	5	6
A	0.240	0.014	0.400	0.586	0.000	0.000	0.000	0.000
B	0.096	0.001	0.105	0.480	0.414	0.000	0.000	0.000
C	0.061	0.001	0.092	0.101	0.710	0.096	0.000	0.000
D	0.157	0.002	0.120	0.315	0.314	0.198	0.038	0.013
E	0.149	0.004	0.182	0.756	0.058	0.000	0.000	0.000
F	0.296	0.011	0.676	0.313	0.000	0.000	0.000	0.000

* Velocity classes are given as,

Class	Velocity (m/s)
0	0.0 - 0.4
1	0.5 - 1.8
2	1.9 - 3.3
3	3.4 - 5.4
4	5.5 - 8.5
5	8.6 - 10.8
6	10.9 - 50.0

Dry Deposition

The fraction of the volatile elements and particulate matter that reach the off-site boundary was calculated from (Van der Hoven, 1968)

$$DEP = \left[\exp \int_0^x \frac{\exp\left(-\frac{h^2}{2 \cdot \sigma_z^2}\right)}{\sigma_z} \cdot dx \right]^{-\frac{v_d}{u} \sqrt{\frac{2}{\pi}}} \quad (7.15)$$

where

v_d = settling velocity (outside repository) (m/s).

Evaluating the dry deposition in a tractable manner required rearranging Equation 7.15 to

$$DEP = \{\exp(Y)\}^{-\frac{v_d}{u} \sqrt{\frac{2}{\pi}}} \quad (7.16)$$

where

$$Y = \int_0^x \left(\frac{\exp\left(-\frac{h^2}{2 \cdot \sigma_z^2}\right)}{\sigma_z} \cdot dx \right)$$

The expression for Y was numerically evaluated for varying distances of x and was found to follow a nearly linear relationship for each stability class. From this work, Y for any given stability was estimated from

$$Y = m \cdot x + b + e, \quad (7.17)$$

where

m, b = linear regression coefficients,

e = random error.

The coefficients m , b and e are dependent on the stability class. The random error, which is a reducible uncertainty, was approximated by a normal distribution with a mean of zero and standard deviation of s . The results are given in Table 7.10.

The settling velocity was determined from a fractured SNF particle size distribution found in the literature (Sehmel, 1980; Ma et al., 1990). From this distribution, a mass weighted settling velocity of 1.2 cm/s was calculated.

Exposure

Uncertainty in the exposure term was not included in this assessment. Even though there would be variability in the population exposed, the regulations dictate that the 50 year equivalent dose commitment to adults be calculated (NRC, 1986b; DOE, 1992).

The primary pathways for the dose were determined to be internal inhalation of the radioactive particulate matter and external exposure from submersion in the plume of krypton-85. Since 10 CFR 60 dictates that the off-site equivalent dose to any organ is not to exceed 500 mrem, the equivalent doses to the gonads, breasts, lungs, red marrow, bone, skin and thyroid were initially calculated. The bone and skin were found to be the organs receiving the highest equivalent doses from internal and exposure, respectively. The effective equivalent dose was calculated in this analysis as well.

Table 7.10

Linear Deposition Model Parameters

Stability	m	b	s	r^2
A	8.99×10^{-5}	7.949	0.0468	0.925
B	1.40×10^{-3}	20.737	1.12	0.900
C	4.71×10^{-3}	20.887	0.473	0.998
D	8.04×10^{-3}	26.528	2.25	0.982
E	1.63×10^{-2}	9.502	1.46	0.998
F	2.17×10^{-2}	-14.762	2.26	0.998

The off-site dose was calculated following the methods dictated by the regulations (NRC, 1977; NRC, 1986b; DOE, 1992). Specifically, for the inhalation pathway, the equivalent and effective doses were calculated from

$$H_{bone/E,50} = BR \cdot C/S \cdot \sum_i S_i \cdot h_{bone/E,50} \quad (7.18)$$

where

$H_{bone/E,50}$ = internal equivalent dose to the bone and effective equivalent dose, E , Sv (mrem),

BR = breathing rate (m^3/s),

$h_{bone/E,50}$ = bone and effective equivalent dose conversion factor for isotope i , Sv/Bq, (mrem/Ci).

Since the krypton gas is not attenuated by deposition or filtration, the dose from submersion was given by

$$H_{skin,ext} = \chi/Q \cdot S_{Kr} \cdot h_{skin,ext} \quad (7.19)$$

where

$H_{skin,ext}$ = equivalent dose to the skin, Sv (mrem),

$h_{skin,ext}$ = skin equivalent dose conversion factors for ^{85}Kr , Sv- m^3/Bq -s (mrem- m^3/Ci -s).

The equivalent dose conversion factors were obtained from Eckerman et al. (1988) and DOE (1988).

Sources of Reducible Uncertainty

Quantifying the reducible uncertainty for this example was difficult since there is no operational experience with a geologic repository. However, an attempt was made for

this assessment by considering the sources of reducible uncertainty in the source term and transport model.

Reducible uncertainties are introduced from several sources in the source term. Specifically, lack of knowledge about the adverse event stems from the methods used in quantifying the frequency and magnitude. There is statistical uncertainty in the estimated frequency. Furthermore, the frequency was based on analogous data from the mining industry covering calendar years 1983-1991. However, since compliance of the north tunnel (constructed under current mining standards) was assessed in this work, the uncertainty in the analogous dataset was considered negligible. Therefore, only statistical uncertainty was considered. Bayes formula was used to calculate the distribution of frequency values given in Table 7.11.

Other sources of reducible uncertainty in the source term result from the waste package response and release models. Smith and Tsai compared their strain model to a finite element model used in an NRC study (1994). It was found that strain was underpredicted within a factor of 1.4. Therefore, the model results were multiplied by an uncertainty factor uniformly distributed between 1 and 2. This uncertainty factor was also considered to incorporate the errors between the actual model used in the literature and the curve fit used in Equation 7.7. For the fractions of each isotope residing in the gap, $f_{i,gap}$, values found in the literature were utilized. A summary of the values and the distributions used for quantifying the uncertainty is given in Table 7.12. The uncertainty in the fraction of rods ruptured, f_{rods} , and the fractional release of radionuclides in each

Table 7.11

Use of Bayes Formula in Quantifying Rock Fall Frequency Uncertainty

	Hypothesis for Frequency of Rock fall, f_n									
	$10^{-2.50}$	$10^{-2.25}$	10^{-2}	$10^{-1.75}$	$10^{-1.50}$	$10^{-1.25}$	10^{-1}	$10^{-0.75}$	$10^{-0.50}$	$10^{-0.25}$
$P(B^* f_r)$	0.003	0.006	0.010	0.018	0.032	0.056	0.100	0.178	0.316	0.026
$P(f_r)$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$P(B f_r)P(f_r)$	0.0003	0.0006	0.0010	0.0018	0.0032	0.0056	0.0100	0.0178	0.0316	0.0026
$P(f_r B)$	0.0207	0.0360	0.0614	0.101	0.158	0.223	0.262	0.222	0.107	0.0185

* B is the statement "470 rock falls have occurred in 4,449 mining-years."

Table 7.12

Uncertainty in Isotopic Gap Fractions, $f_{i,gap}$

Isotope, i	$f_{i,gap}$	Reference	Distribution Type	Minimum	Maximum
^{85}Kr	.30	NRC, 1972; Hartman and Miller, 1991; Ma et al., 1992a,b	Uniform	0.2	0.4
^{90}Sr	10^{-6}	Rasmussen et al., 1975; NRC, 1983	Log-uniform	10^{-6}	10^{-4}
	10^{-4}	Smith and Tsai, 1994			
^{129}I	.30	Smith and Tsai, 1994	Triangular	0.017	0.30
	.10	NRC, 1972		(.10 expected)	
	.017	NRC, 1983a			
^{134}Cs	.05	NRC, 1983a	Log-Uniform	10^{-4}	10^{-1}
	4.1×10^{-4}	Lorenz et al., 1980			
^{137}Cs	.05	NRC, 1983a	Log-Uniform	10^{-4}	10^{-1}
	4.1×10^{-4}	Lorenz et al. 1980			
^{137m}Ba	10^{-4}	Smith and Tsai, 1994	Log-Uniform	10^{-6}	10^{-4}
	10^{-6}	NRC, 1983a			

isotopic category, f_j , was quantified by multiplying the threshold strains as given in Table 7.5 by an uncertainty factor uniformly distributed between 0.5 and 1.5.

The reducible uncertainty in the transport term was considered from three sources: deposition inside and outside the repository, and atmospheric dispersion. First, uncertainty in predicting the deposition inside the repository was considered due to ignoring particle resuspension. Including resuspension would effectively decrease the settling velocity, v_t . Therefore, uncertainty in v_t was quantified with a log-triangular distribution between 4×10^{-3} cm/s and 4×10^{-2} cm/s with an expected value of 4×10^{-2} cm/s. Uncertainty in the deposition outside of the repository was considered from the method used to calculate Equation 7.15 and the settling velocity, v_d . The errors in the linear fit were accounted for by treating the random error, e , as a normal distribution with a mean of zero and standard deviation of s (see Table 7.10). The uncertainty in the settling velocity, v_d , was quantified with a uniform distribution with limits of 0.6 and 1.8 cm/s (MacDougall et al., 1987; Ma et al., 1990). The final source of reducible uncertainty was the error in the Gaussian plume model. Studies have found that the model is generally accurate within a factor of 3 (LaGrega et al., 1994). Therefore, a correction factor uniformly distributed between 1/3 and 3 was applied to Equation 7.12.

Results and Conclusions

After 1,000 realizations for simulating the scenario where the filters are working properly, the maximum observed equivalent doses, at the 100% confidence level, to the skin and bone were calculated to be 240 mrem and 50 mrem respectively. Furthermore,

the effective equivalent dose was found to be 4.8 mrem. Since these results are below the 500 mrem dose criteria, this scenario was ignored.

The results based on 1,000 realizations for the scenario in which the filtering system fails are given in Figures 7.9 through 7.11. Since the maximally exposed organ was found to be the bone, the applicability of the north tunnel to 10 CFR 60 is dictated by the off-site equivalent dose to bone. From Figure 7.10, the 90% overall confidence bound for exceeding an equivalent bone dose of 500 mrem is 9.5×10^{-10} to $1.8 \times 10^{-8} \text{ yr}^{-1}$. In addition, the maximum observed frequency (i.e., 100% confidence level) for exceeding 500 mrem is $4.9 \times 10^{-8} \text{ yr}^{-1}$. Based on the assumptions in this work (Table 7.13), the support system for the north tunnel is not subject to the items important to safety classification. However, because failure of the filtering system was found to lead to a dramatic increase in the off-site dose to bone (approximately fifty times greater), special consideration of this system may be warranted.

The results of this assessment can be used in other ways besides testing compliance to 10 CFR 60. For instance, 88% and 55% of the hypothetical rock falls did not breach the waste package in the variability and reducible analyses, respectively. Incorporating the frequency of rock falls, the annual frequency of a radiological release was calculated to be 2.4×10^{-8} and $1.7 \times 10^{-7} \text{ yr}^{-1}$ as shown by the 95% variability and overall risk curves, respectively.

Figure 7.9. Risk Curves for Exploratory Studies Facility North Tunnel (Equivalent Dose to Skin Following Filtration System Failure)

Off-Site Bone Dose (mrem)

Figure 7.10. Risk Curves for Exploratory Studies Facility North Tunnel (Equivalent Bone Dose Following Filtration System Failure)

Figure 7.11. Risk Curves for Exploratory Studies Facility North Tunnel (Effective Equivalent Dose Following Filtration System Failure)

Table 7.13

Decision Parameters

Variable	Value	Source
Package thickness	45 cm	TRW, 1993
Package capacity	52 BWR 21 PWR	TRW, 1993
Transporter speed	2.5 m/s	Smith and Tsai, 1994
Drift diameter	7.6 m	TRW, 1993
Stack height	25 m	No design information found.
Number HEPA filters	1	Smith and Tsai, 1994
Ventilation Air Velocity	0.3 m/s - 7.6 m/s	TRW, 1993; Jurani, 1992

CHAPTER 8

DISCUSSION

The obvious purpose of environmental risk assessment is to determine the risks posed by environmental contamination. Thus, characterization of risks is an important component of any risk assessment approach. In this area, the methodology is a valuable tool since variability and reducible uncertainty is differentiated. The key advantage of this distinction is that the use of conservatism is effectively shifted from the assessor to the risk manager. The assessor explicitly communicates the various degrees and sources of conservatism to the risk managers. In turn, the risk managers determine the degree of conservatism warranted by the decision making process (Covello and Merkhofer, 1993). This feature also lends the methodology to an iterative analysis of risks. That is, in initial assessments, the reducible uncertainty may be so large that decision making is postponed or enacted temporarily. By using sensitivity analysis, the major sources of reducible uncertainty can be reduced through research and field studies. In subsequent assessments, the 90% reducible confidence bound decreases until a permanent decision can be made.

Many risk assessments have not attempted to quantify the adverse event component of risk. Thus, one potential obstacle identified at the beginning of this research was the applicability of such an approach to all environmental risk situations. For some situations, the event uncertainty may not be quantifiable through empirical data or published literature. The field of expert elicitation deals with this dilemma and has made considerable progress. In fact, it has gained acceptance with numerous regulatory agencies

(Feagans and Biller, 1978; EPA, 1981; NRC, 1990). While this research did not deal with expert elicitation, it is felt that this emerging field can be used with this approach, thus increasing its flexibility.

The proposed method adds two additional stages to the assessment process: uncertainty and statistical analyses. In addition to the traditional risk assessment procedures, the assessor must make an earnest attempt in identifying and quantifying the sources of uncertainty. Since accurate quantification of variability and reducible uncertainties would require site-specific studies and research, this stage would most likely increase monetary costs. The other additional stage of this approach is that the generated dataset must be analyzed. Analyzing the results in this research required considerable effort. However, several statistical software packages exist which could overcome this problem. It should be noted that the calculation stage of these assessments did not require additional effort. There are two reasons for this. First, since the Monte Carlo technique utilized the traditional risk models, setting up the assessment was comparable to other risk approaches. Second, the software package used readily incorporated uncertain parameters in a spreadsheet form (Palisade, 1994). Thus, the propagation of uncertainties represented a relatively small part of the effort.

CHAPTER 9

RECOMMENDATIONS

Four areas for future research were identified in this work: (1) quantifying the uncertainty in the Monte Carlo approaches, (2) application of the method for regulatory compliance issues, (3) utilization of sensitivity techniques and (4) utilizing the methodology in a decision making problem.

The first area for future development is determining the accuracy of Monte Carlo approaches. There are two sources of reducible uncertainty introduced from the random calculations: number of realizations taken and parameter distributions used. In the assessments performed in this work, the number of realizations were increased until the results did not change dramatically. However, there is statistical uncertainty in the resulting risk curves that was not taken into account. That is, if the assessments in this work were performed again, the results would vary slightly. Thus, a method to quantify the statistical uncertainty would be useful; however, communicating this uncertainty in a risk curve would most likely be inappropriate. Rather, it could be used in determining the number of realizations to take in performing the assessment. The second source of reducible uncertainty stems from the parameter distributions used. For instance, historical data can be used directly in the form of a histogram or be estimated with a continuous distribution such as a normal curve. The implications of parameter characterization through discretized and continuous distributions need to be addressed.

Utilizing this methodology for regulatory compliance issues needs further work. For instance, the NRC and DOE do not provide guidance for the incorporation of uncertainties in determining items important to safety. Based on the most conservative results (i.e., 100% overall risk curve), it was determined in this work that the north tunnel did not fall under the items important to safety classification. However, if the assessment for the north tunnel yielded the risk curves in Figure 9.1 (where the boxed region identifies the items important to safety region), the applicability of the tunnel to 10 CFR 60 would not be obvious. Solomon et al. (1983) and Apostolakis (1989) discuss approaches for incorporating uncertainties in regulatory decision making. However, until regulatory agencies adopt guidelines for uncertainty analysis (e.g., what confidence level is required for compliance), this methodology may not be acceptable for determining compliance.

Another area for future research is the utilization of sensitivity techniques for determining critical sources of uncertainties. This methodology used in conjunction with an effective sensitivity analysis technique would increase its utility considerably. Since variability and reducible uncertainties are distinguished in this methodology, sensitivity techniques could be used in determining which reducible uncertainties contribute the most to the overall uncertainty, thus guiding minimization of reducible uncertainty.

The last area for future research is incorporating this method in a decision making problem. For instance, current designs of Yucca Mountain are preliminary. Using this methodology for developing risk curves of different design options could provide insight into the optimum design configuration in terms of risk. Furthermore, this parametric analysis could be extended by determining the sensitivity of various decision parameters.

Figure 9.1. Hypothetical Results for North Tunnel

Coupling the results with monetary estimates of the various schemes, a cost-benefit analysis of risk and capital costs could be performed to aid in the design process.

APPENDICES

Appendix A

Supporting Derivations and Calculations for Assessment of North Tunnel at Yucca Mountain (Chapter 7)

Atmospheric Transport

On-site meteorological data coupled with current design information was used for quantifying the variability in atmospheric transport. In December 1985, the Yucca Mountain Site Characterization Project began monitoring hourly meteorological conditions at five observation sites around the proposed repository. The intent of the monitoring program was to conform with Clean Air Act requirements in the Nuclear Waste Policy Act (SAIC, 1993). Since 1985, four more sites have been added to the monitoring program. For this assessment, only the data from the Coyote Wash site was incorporated into the assessment. This site was chosen due to its proximity to the north tunnel of the ESF.

A FORTRAN code was written to analyze the data in the following way. First, the data were segregated into the six Pasquill-Gifford stability classes. For each class, the data were further segregated into 7 velocity classes, and the area surrounding the monitoring site was divided into 16 sectors (NRC[b], 1983). The frequency in which the wind was observed to blow into each sector was then determined. The FORTRAN code and output is given in Appendix D.

Sample Calculations

The sample calculations are based on the input parameters given in Table A.1. Resulting parameters are given in Table A.2. The sample calculations are based on a PWR package being impacted with a force of 2.5×10^6 MJ/m. Furthermore, the accident occurs 2,500 meters from the ventilation stack and the HEPA filter is not operating.

Table A.1
Sample Input Parameters

Decision Parameters	Symbol	Value Units	Uncertainty	Distribution	Expected Value	Parameters	Source
Length of Waste Package		5 m	Fixed at 0				TRW, 1993
Package Thickness		45 cm	Fixed at 0				TRW, 1993
Package Capacity (BWR)		52	Fixed at 0				TRW, 1993
Package Capacity (PWR)		21	Fixed at 0				TRW, 1993
Transporter Speed		2.25 m/s	Fixed at 0				Smith and Tsai, 1994
Number HEPA Filters		1	Fixed at 0				Smith and Tsai, 1994
Ventilation Velocity	u_{air}	3.65 m/s	Variability	Uniform	3.65	0.3	7.6 TRW, 1993; Jurani, 1990
Stack Height	h	25 m	Fixed at 0				None
Length of North Tunnel		2000 m	Fixed at 0				TRW, 1993
Diameter of Tunnels	d	7.6 m	Fixed at 0				TRW, 1993
Source Term Parameters	Symbol	Value Units	Uncertainty	Distribution	Expected Value	Parameters	Source
Annual Number Packages Received	$N_{packages}$	311 packages/year	Variability	Normal	311	$\sigma = 25$	Lynch and Hunter, 1992
Frequency of Rock Fall	F_r	1.06E-01 falls/mine-yr.	Reducible	Empirical			Smith and Tsai, 1994
Probability of Filter Failure	p_s	0.05 /demand	Reducible	Uniform	0.05	0.01	0.1 Ma et al., 1992a,b
Energy of Rock Fall	E	2.5 MJ/m	Variability	Empirical			Smith and Tsai, 1994
Waste Package Damaged		PWR	Variability	Discrete	40/ 60 BWR/PWR		EIA, 1984; Ma et al., 1992
Fraction Kr-85 in Gap	$f_{Kr,gap}$	0.3	Reducible	Uniform	0.3	0.2	0.4 See Table 8.14
Fraction Sr-90	$f_{Sr,gap}$	1.00E-04	Reducible	Log-Uniform	1.00E-05	1.00E-06	1.00E-04 See Table 8.14
Fraction I-129	$f_{I,gap}$	3.00E-01	Reducible	Triangular	1.00E-01	1.70E-02	3.00E-01 See Table 8.14
Fraction Cs	$f_{Cs,gap}$	5.00E-02	Reducible	Log-Uniform	3.16E-03	1.00E-04	1.00E-01 See Table 8.14
Fraction Ba-137	$f_{Ba,gap}$	1.00E-04	Reducible	Log-Triangular	1.00E-05	1.00E-04	1.00E-06 See Table 8.14
Strain Threshold Gases	$s_{t/gas}$	2.00E-03 m/m	Fixed at 0				Smith and Tsai, 1994
Strain Threshold Volatiles	$s_{t/vol}$	2.00E-03 m/m	Fixed at 0				Smith and Tsai, 1994
Strain Threshold Particulates	$s_{t/part}$	2.00E-02 m/m	Fixed at 0				Smith and Tsai, 1994
Strain Threshold for Rod Rupture	$s_{t/rod}$	2.00E-02 m/m	Fixed at 0				Smith and Tsai, 1994
Threshold Uncertainty Factor		1.00E+00	Reducible	Uniform	1	0.5	1.5 Smith and Tsai, 1994; Subjective
Strain Uncertainty Factor		1	Reducible	Uniform	1	1	2 Smith and Tsai, 1994
Transport Parameters	Symbol	Value Units	Uncertainty	Distribution	Expected Value	Parameters	Source
Gravitational Settling Velocity	v_s	0.04 cm/s	Reducible	Log-Triangular	0.04	0.004	0.04 Ma et al., 1990; Smith and Tsai, 1994; Subjective
Distance from Accident to Stack	l	2.50 km	Variability	Uniform	3	1	5 TRW, 1993
Filtration Efficiency	FIL	0.00000	Fixed at 0				Novak and Higgins, 1989
Downwind Sector		13	Variability	Empirical	See Figure 8.8		SAIC, 1994
Stability		3	Variability	Empirical	See Table 8.9		SAIC, 1994
Velocity Class		2	Variability	Empirical	See Table 8.9		SAIC, 1994
Velocity	u	0.5 m/s	Variability	Empirical	See Table 8.9		SAIC, 1994
Distance to CCAB	x	4.1 km	Variability	Correlated to Downwind Sector			EG&G, 1994
Equation 8.17 Error Standard Deviation	s		Reducible	Correlated to Stability			See Table 8.10
Settling Velocity	v_d	1.2 cm/s	Reducible	Uniform	1.2	0.6	1.8 MacDougall et al., 1987; Ma et al., 1990; Subjective
Transport Uncertainty Factor		1	Reducible	Uniform	1	0.33333333	3 LaGrega et al., 1994
Exposure Parameters	Symbol	Value Units	Uncertainty	Distribution	Expected Value	Parameters	Source
Breathing Rate	BR	3.50E-04 m ³ /s	Fixed at 0 (See text)				Eckerman et al., 1987

Table A.2

Sample Calculations

OUTPUTS	Symbol	Value Units	Equation
Frequency of Event	f_{event}	1.16E-07 /yr	8.1
Resulting Dose to Skin	H_{skin}	1.62E+01 mrem	8.19
Resulting Dose to Bone	H_{bone}	1.26E+03 mrem	8.18
Resulting Dose to Body	H_E	8.66E+02 mrem	8.18 and 8.19
Source Term	Symbol	Value Units	Equation
Time to Emplace Wastes	t_e	14.8 min/package	
Probability Transporter in Tunnel	p_1	0.008765996	8.3
Probability Transporter Struck	$p_{2 1}$	0.0025	
Probability of Rock-Fall Hitting Package	$p_{h r}$	2.1915E-05	8.2
Frequency of Scenario	f_{event}	1.16E-07 /yr.	8.1
Strain of Waste Package	s	0.0455 m/m	8.9
Gap Release Fraction (Except krypton)	f_{gap}	0.885	Table 8.6
Gap Release Fraction (krypton)	f_{gap}	1	Table 8.6
SNF Release Fraction	f_{SNF}	3.86E-07	Table 8.6
Fraction Rods Ruptured	f_{rods}	0.233	Table 8.6
Transport	Symbol	Value Units	Equation
Deposition of Particulates through Tunnel	R	8.66E-01	8.11
Diffusion Coefficient	a_1	-0.0117	Table 8.8
Diffusion Coefficient	a_2	0.175	Table 8.8
Diffusion Coefficient	b_1	-1.186	Table 8.8
Diffusion Coefficient	b_2	0.85	Table 8.8
Diffusion Coefficient	b_3	0.0045	Table 8.8
Horizontal Dispersion	sig_y	318.4 m	8.13
Vertical Dispersion	sig_z	228.3 m	8.14
Dispersion Coefficient	X/Q	8.71E-06 s/m ³	8.12
Deposition Coefficient Slope	m	0.00471	Table 8.10
Deposition Coefficient Intercept	b	20.887	Table 8.10
Deposition Coefficient	Y	40.198	8.17
Deposition	DEP	4.63E-01	8.16
Depletion Factor	C/S	3.49E-06 s/m ³	8.1
Exposure	Symbol	Value Units	Equation
Off-Site Dose to Bone	H_{bone}	1.26E+03 mrem	8.18
Off-Site Dose to Skin	H_{skin}	1.62E+01 mrem	8.19
Off-Site Dose to Body	H_E	8.66E+02 mrem	8.18 and 8.19

Source Term

Adverse Event

Based on Equation 7.4, the probability that the transporter is in the north tunnel at the time of the rock fall is given by

$$p_1 = \left\{ \frac{2000[m]}{2.25[m/s]} \right\} \cdot \left\{ 3.17 \times 10^{-8} \left[\frac{yr}{s} \right] \right\} \cdot 311 \left[\frac{1}{yr} \right] = 8.77 \times 10^{-3}.$$

The probability that the transporter is hit by a rock fall is found by

$$p_{hr} = 8.77 \times 10^{-3} \cdot \left\{ \frac{5[m]}{5000[m]} \right\} = 2.19 \times 10^{-5}.$$

The annual frequency of a rock fall hitting a waste package and the filtering system failing is therefore given from

$$f_{event} = 0.106 \left[\frac{1}{yr} \right] \cdot 2.19 \times 10^{-5} \cdot 0.05 = 1.16 \times 10^{-7} \left[\frac{1}{yr} \right].$$

Waste Package Response

Before calculating the release terms, first the strain imparted on the waste package following a 2.5 MJ/m rock fall is given from

$$\log \varepsilon = 0.764 \cdot \{ \log(2.5 \times 10^6) - 8.155 \}, \text{ or}$$

$$\varepsilon = 0.0455.$$

Waste Package Release

For this strain, the fraction of isotopes released from the gap and SNF is given from Table 7.6

$$\log f_{gap} = 2.24 \cdot \{1 - 0.286 \cdot \exp(-0.95 \cdot \log(0.0455))\}, \text{ or}$$

$$f_{gap} = 0.885.$$

For ^{85}Kr , $\epsilon > 0.02$ so

$$f_{gap} = 1.$$

For the fractional release of SNF

$$n = \log\left(\frac{0.0455}{10^{-3}}\right) = 1.65.$$

$$\log f_{SNF} = -\frac{16}{2^{1.65}} - 3 + 1.65, \text{ or}$$

$$f_{SNF} = 3.87 \times 10^{-7}.$$

The fraction of rods ruptured at this strain level is also given from Table 7.6,

$$\log f_{rods} = 0.704 \cdot \log(0.0455) + 0.314, \text{ or}$$

$$f_{rods} = 0.234.$$

Waste Package Inventory

The inventory of the PWR waste package used in this example is given in Table A.3. Using the activities from Table A.3 and the fractional parameters from above and Table 7.4, the activity of each isotope released can be calculated from Equation 7.1. The results are shown in Table A.4.

Transport

The fraction of volatiles and SNF transported through the repository is given from Equation 7.11,

Table A.3

Inventory of Sample Waste Package

Assembly, <i>a</i>	1	2	3	4	5	6	7	8	9	10	11
Burnup Category (Footnote 1)	2	1	3	2	3	3	2	1	2	3	3
Decay Category, (Footnote 2)	1	2	3	1	4	2	4	2	3	1	3
Loading, (MTU)	0.425	0.4	0.381	0.427	0.5	0.388	0.441	0.428	0.419	0.438	0.508
Fe-55	1.09E+02	2.45E+01	0.00E+00	1.09E+02	0.00E+00	2.98E+01	0.00E+00	2.63E+01	0.00E+00	1.27E+02	0.00E+00
Co-60	1.18E+03	4.98E+02	3.23E+02	1.18E+03	1.14E+02	6.36E+02	8.79E+01	5.33E+02	3.11E+02	1.38E+03	4.31E+02
Ni-63	2.03E+02	1.58E+02	2.02E+02	2.04E+02	2.45E+02	2.13E+02	1.81E+02	1.69E+02	1.85E+02	2.50E+02	2.69E+02
Kr-85	2.66E+03	1.47E+03	1.48E+03	2.67E+03	1.02E+03	2.08E+03	7.58E+02	1.57E+03	1.37E+03	3.24E+03	1.97E+03
Sr-90	3.21E+04	2.14E+04	2.71E+04	3.22E+04	2.81E+04	3.11E+04	2.07E+04	2.29E+04	2.49E+04	3.96E+04	3.62E+04
Y-90	3.21E+04	2.14E+04	2.71E+04	3.22E+04	2.81E+04	3.11E+04	2.07E+04	2.29E+04	2.49E+04	3.96E+04	3.62E+04
Ru-106	2.61E+02	0.00E+00	0.00E+00	2.63E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.01E+02	0.00E+00
Rh-106	2.61E+02	0.00E+00	0.00E+00	2.63E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.00E+02	0.00E+00
I-129	1.81E-02	1.33E-02	1.95E-02	1.81E-02	2.55E-02	1.98E-02	1.87E-02	1.42E-02	1.78E-02	2.24E-02	2.60E-02
Sb-125	6.71E+02	1.50E+02	5.61E+01	6.74E+02	0.00E+00	0.00E+00	0.00E+00	1.60E+02	5.41E+01	7.88E+02	7.48E+01
Te-125m	1.64E+02	3.66E+01	0.00E+00	1.64E+02	0.00E+00	2.00E+02	0.00E+00	3.91E+01	0.00E+00	1.92E+02	0.00E+00
Cs-134	3.78E+03	4.42E+02	1.59E+02	3.79E+03	0.00E+00	4.87E+01	0.00E+00	4.73E+02	1.29E+02	5.29E+03	2.12E+02
Cs-137	4.67E+04	3.08E+04	4.02E+04	4.69E+04	4.19E+04	8.72E+02	3.05E+04	3.30E+04	3.66E+04	5.83E+04	5.36E+04
Ba-137m	4.42E+04	2.92E+04	3.81E+04	4.44E+04	3.96E+04	4.60E+04	2.89E+04	3.12E+04	3.46E+04	5.51E+04	5.07E+04
Ce-144	6.15E+01	0.00E+00	0.00E+00	6.17E+01	0.00E+00	4.35E+04	0.00E+00	0.00E+00	0.00E+00	6.48E+01	0.00E+00
Pr-144	6.15E+01	0.00E+00	0.00E+00	6.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.48E+01	0.00E+00
Pm-147	3.85E+03	9.76E+02	2.38E+02	3.87E+03	2.23E+01	9.09E+02	2.02E+01	1.04E+03	2.70E+02	3.85E+03	3.18E+02
Sm-151	2.05E+02	1.51E+02	1.86E+02	2.06E+02	2.26E+02	1.97E+02	1.82E+02	1.62E+02	1.87E+02	2.31E+02	2.48E+02
Eu-154	2.89E+03	1.20E+03	1.54E+03	2.90E+03	9.05E+02	2.35E+03	5.98E+02	1.28E+03	1.27E+03	3.97E+03	2.06E+03
Eu-155	1.07E+03	3.27E+02	3.17E+02	1.08E+03	1.03E+02	6.50E+02	6.79E+01	3.50E+02	2.61E+02	1.48E+03	4.23E+02
Pu-238	2.29E+03	1.13E+03	2.89E+03	2.30E+03	3.51E+03	3.06E+03	2.03E+03	1.21E+03	2.08E+03	3.60E+03	3.85E+03
Pu-239	1.76E+02	1.44E+02	1.70E+02	1.76E+02	2.22E+02	1.73E+02	1.82E+02	1.54E+02	1.73E+02	1.95E+02	2.26E+02
Pu-240	2.80E+02	2.06E+02	3.18E+02	2.81E+02	4.19E+02	3.23E+02	2.93E+02	2.21E+02	2.77E+02	3.63E+02	4.24E+02
Pu-241	4.18E+04	2.66E+04	2.38E+04	4.20E+04	1.93E+04	3.09E+04	1.65E+04	2.84E+04	2.54E+04	4.43E+04	3.18E+04
Am-241	9.43E+02	9.87E+02	1.35E+03	9.47E+02	2.14E+03	1.16E+03	1.82E+03	1.06E+03	1.43E+03	1.01E+03	1.80E+03
Cm-244	1.71E+03	5.85E+02	1.85E+03	1.72E+03	1.66E+03	2.28E+03	8.26E+02	6.26E+02	1.15E+03	3.12E+03	2.47E+03

1 - Category 1 = 35,000 (GWd/MTU), 2 = 45,000 (GWd/MTU) and 3 = 55,000 (GWd/MTU)

2 - Category 1 = 10 years, 2 = 15 years, 3 = 20 years, 4 = 30 years

Table A.3 (continued)

Inventory of Sample Waste Package

Assembly, <i>a</i>	12	13	14	15	16	17	18	19	20	21	WASTE PACKAGE INVENTORY, <i>A</i> / (Ci)
Burnup Category (Footnote 1)	2	1	1	3	2	3	1	2	2	1	
Decay Category, (Footnote 2)	3	2	4	1	4	4	2	3	2	2	
Loading, (MTU)	0.231	0.363	0.44	0.508	0.363	0.4	0.545	0.444	0.436	0.386	
Fe-55	0.00E+00	2.23E+01	0.00E+00	1.48E+02	0.00E+00	0.00E+00	3.34E+01	0.00E+00	2.94E+01	2.37E+01	1.13E+04
Co-60	1.72E+02	4.52E+02	7.62E+01	1.61E+03	7.23E+01	9.11E+01	6.79E+02	3.30E+02	6.25E+02	4.81E+02	4.08E+03
Ni-63	1.02E+02	1.43E+02	1.55E+02	2.90E+02	1.49E+02	1.96E+02	2.15E+02	1.97E+02	2.00E+02	1.52E+02	3.51E+04
Kr-85	7.58E+02	1.34E+03	6.13E+02	3.76E+03	6.24E+02	8.12E+02	2.00E+03	1.46E+03	1.98E+03	1.42E+03	5.57E+05
Sr-90	1.37E+04	1.95E+04	1.65E+04	4.59E+04	1.70E+04	2.24E+04	2.92E+04	2.64E+04	2.92E+04	2.07E+04	5.57E+05
Y-90	1.37E+04	1.95E+04	1.65E+04	4.59E+04	1.70E+04	2.25E+04	2.92E+04	2.64E+04	2.92E+04	2.07E+04	1.17E+03
Ru-106	0.00E+00	0.00E+00	0.00E+00	3.49E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.17E+03
Rh-106	0.00E+00	0.00E+00	0.00E+00	3.48E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.80E-01
I-129	9.82E-03	1.21E-02	1.46E-02	2.60E-02	1.54E-02	2.04E-02	1.81E-02	1.89E-02	1.85E-02	1.28E-02	4.31E+03
Sb-125	2.98E+01	1.36E+02	0.00E+00	9.14E+02	0.00E+00	0.00E+00	2.04E+02	5.74E+01	1.97E+02	1.45E+02	1.19E+03
Te-125m	0.00E+00	3.32E+01	0.00E+00	2.23E+02	0.00E+00	0.00E+00	4.98E+01	0.00E+00	4.80E+01	3.53E+01	2.28E+04
Cs-134	7.12E+01	4.01E+02	0.00E+00	6.13E+03	0.00E+00	0.00E+00	6.02E+02	1.37E+02	7.22E+02	4.26E+02	7.71E+05
Cs-137	2.02E+04	2.80E+04	2.40E+04	6.76E+04	2.51E+04	3.35E+04	4.20E+04	3.88E+04	4.27E+04	2.97E+04	7.75E+05
Ba-137m	1.91E+04	2.65E+04	2.27E+04	6.39E+04	2.38E+04	3.17E+04	3.97E+04	3.67E+04	4.04E+04	2.81E+04	4.38E+04
Ce-144	0.00E+00	0.00E+00	0.00E+00	7.51E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.63E+02
Pr-144	0.00E+00	0.00E+00	0.00E+00	7.51E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.45E+04
Pm-147	1.49E+02	8.86E+02	2.04E+01	4.46E+03	1.67E+01	1.78E+01	1.33E+03	2.86E+02	1.05E+03	9.42E+02	3.92E+03
Sm-151	1.03E+02	1.37E+02	1.48E+02	2.68E+02	1.50E+02	1.81E+02	2.06E+02	1.98E+02	2.02E+02	1.46E+02	3.51E+04
Eu-154	7.01E+02	1.09E+03	3.94E+02	4.61E+03	4.92E+02	7.24E+02	1.64E+03	1.35E+03	1.98E+03	1.16E+03	1.00E+04
Eu-155	1.44E+02	2.96E+02	4.42E+01	1.71E+03	5.59E+01	8.23E+01	4.45E+02	2.77E+02	5.46E+02	3.15E+02	4.70E+04
Pu-238	1.15E+03	1.03E+03	1.11E+03	4.17E+03	1.67E+03	2.81E+03	1.54E+03	2.21E+03	2.26E+03	1.09E+03	3.63E+03
Pu-239	9.54E+01	1.30E+02	1.58E+02	2.26E+02	1.50E+02	1.78E+02	1.96E+02	1.83E+02	1.80E+02	1.39E+02	6.03E+03
Pu-240	1.53E+02	1.87E+02	2.27E+02	4.21E+02	2.41E+02	3.35E+02	2.81E+02	2.94E+02	2.88E+02	1.99E+02	5.86E+05
Pu-241	1.40E+04	2.41E+04	1.42E+04	5.14E+04	1.36E+04	1.55E+04	3.62E+04	2.70E+04	3.37E+04	2.56E+04	2.73E+04
Am-241	7.91E+02	8.96E+02	1.55E+03	1.17E+03	1.50E+03	1.71E+03	1.35E+03	1.52E+03	1.26E+03	9.53E+02	2.92E+04
Cm-244	6.34E+02	5.31E+02	3.62E+02	3.62E+03	6.80E+02	1.33E+03	7.97E+02	1.22E+03	1.45E+03	5.64E+02	0.00E+00

1 - Category 1 = 35,000 (GWd/MTU), 2 = 45,000 (GWd/MTU) and 3 = 55,000 (GWd/MTU)

2- Category 1 = 10 years, 2 = 15 years, 3 = 20 years, 4 = 30 years

Table A.4

Sample Release Calculations

SNF Releases						
Isotope, <i>i</i>	<i>A_i</i> (Ci)	<i>f</i> <i>LSNF</i>	<i>f</i> <i>SNF</i>	<i>f</i> <i>rods</i>	<i>fR</i> <i>LSNF</i>	<i>S</i> <i>LSNF</i> (Ci)
Fe-55	1.13E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	1.01E-03
Co-60	4.08E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.67E-04
Ni-63	3.51E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.16E-03
Sr-90	5.57E+05	1.00E+00	3.86E-07	2.33E-01	9.00E-08	5.01E-02
Y-90	1.17E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	1.06E-04
Ru-106	1.17E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	1.06E-04
Rh-106	3.80E-01	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.42E-08
Sb-125	1.19E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	1.07E-04
Te-125m	2.28E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	2.05E-03
I-129	4.31E+03	7.00E-01	3.86E-07	2.33E-01	6.30E-08	2.72E-04
Cs-134	7.71E+05	9.50E-01	3.86E-07	2.33E-01	8.55E-08	6.59E-02
Cs-137	7.75E+05	9.50E-01	3.86E-07	2.33E-01	8.55E-08	6.62E-02
Ba-137m	4.38E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.94E-03
Ce-144	2.63E+02	1.00E+00	3.86E-07	2.33E-01	9.00E-08	2.37E-05
Pr-144	2.45E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	2.21E-03
Pm-147	3.92E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.53E-04
Sm-151	3.51E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.16E-03
Eu-154	1.00E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	9.04E-04
Eu-155	4.70E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	4.23E-03
Pu-238	3.63E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	3.26E-04
Pu-239	6.03E+03	1.00E+00	3.86E-07	2.33E-01	9.00E-08	5.43E-04
Pu-240	5.86E+05	1.00E+00	3.86E-07	2.33E-01	9.00E-08	5.28E-02
Pu-241	2.73E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	2.46E-03
Am-241	2.92E+04	1.00E+00	3.86E-07	2.33E-01	9.00E-08	2.63E-03
Cm-244	0.00E+00	1.00E+00	3.86E-07	2.33E-01	9.00E-08	0.00E+00

Gap Releases						
Isotope	<i>A_i</i> (Ci)	<i>f</i> <i>lgap</i>	<i>f</i> <i>gap</i>	<i>f</i> <i>rods</i>	<i>fR</i> <i>lgap</i>	<i>S</i> <i>lgap</i> (Ci)
Kr-85	5.57E+05	3.00E-01	1.00E+00	2.33E-01	7.00E-02	3.90E+04
Sr-90	5.57E+05	1.00E-04	8.85E-01	2.33E-01	2.06E-05	1.15E+01
I-129	4.31E+03	3.00E-01	8.85E-01	2.33E-01	6.19E-02	2.67E+02
Cs-134	7.71E+05	5.00E-02	8.85E-01	2.33E-01	1.03E-02	7.96E+03
Cs-137	7.75E+05	5.00E-02	8.85E-01	2.33E-01	1.03E-02	7.99E+03
Ba-137m	4.38E+04	1.00E-04	8.85E-01	2.33E-01	2.06E-05	9.03E-01

$$R = \exp \left(- \frac{4 \cdot (4 \times 10^{-4} [m/s]) \cdot 2500 [m]}{7.6 [m] \cdot (3.65 [m/s])} \right) = 0.866.$$

Before calculating the dispersion coefficient, the horizontal and vertical dispersion coefficients are calculated from Equations 7.13 and 7.14,

$$\sigma_y = (-0.0117 \cdot \ln(4100 [m]) - 0.175) \cdot 4000 [m] = 318.4 [m], \text{ and}$$

$$\sigma_z = \frac{1}{2.15} \cdot \exp \{ -1.186 - 0.85 \cdot \ln(4100 [m]) + 0.0045 \cdot \ln^2(4100 [m]) \} = 228.3 [m].$$

The dispersion coefficient is calculated from Equation 7.12.

$$\chi/Q = \frac{1}{0.5 [m/s] \cdot \pi \cdot 318.4 [m] \cdot 228.3 [m]} \cdot \exp \left(- \frac{(25 [m])^2}{2 \cdot (228.3 [m])^2} \right) = 8.71 \times 10^{-6} [s/m^3].$$

The dry deposition factor is calculated by first calculating the estimator Y from Equation 7.17,

$$Y = 0.00471 \cdot 4100 [m] + 20.887 = 40.198.$$

The deposition factor is calculated from Equation 7.16,

$$DEP = \left\{ \exp(40.198) \right\}^{\frac{0.012 [m/s]}{0.5 [m/s]} \sqrt{\frac{2}{\pi}}} = 0.463.$$

Since the filters are not operating, the filtration efficiency is zero. Therefore, the depletion factor is determined from Equation 7.10,

$$C/S = 0.866 \cdot (1 - 0) \cdot 8.71 \times 10^{-6} [s/m^3] \cdot 0.463 = 3.49 \times 10^{-6} [s/m^3].$$

Exposure

The calculations of the off-site dose from Equations 7.18 and 7.19 are given in Table A.5. The off-site bone, skin and effective doses are calculated to be 429 mrem, 1.02 mrem and 347 mrem, respectively.

Table A.5

Sample Exposure Calculations

Inhalation Pathway					
Isotope, <i>i</i>	<i>S_i</i> (Ci)	<i>h_{bone,50}</i> (mrem/Ci)	<i>h_{E,50}</i> (mrem/Ci)	<i>h_{bone,50} * S_i</i> (mrem)	<i>h_{E,50} * S_i</i> (mrem)
Fe-55	1.01E-03	1.89E+06	2.69E+06	1.91E+03	2.72E+03
Co-60	3.67E-04	5.00E+07	2.19E+08	1.83E+04	8.03E+04
Ni-63	3.16E-03	3.04E+06	3.10E+06	9.60E+03	9.79E+03
Sr-90	1.15E+01	2.69E+09	1.30E+09	3.11E+10	1.50E+10
Y-90	1.06E-04	1.03E+06	8.44E+06	1.09E+02	8.91E+02
Ru-106	1.06E-04	5.07E+07	4.77E+08	5.35E+03	5.04E+04
Rh-106	3.42E-08	4.96E+04	1.79E+05	1.70E-03	6.13E-03
Sb-125	1.07E-04	1.01E+07	1.22E+07	1.08E+03	1.30E+03
Te-125m	2.05E-03	1.19E+08	7.29E+06	2.44E+05	1.50E+04
I-129	2.67E+02	5.11E+05	1.74E+08	1.36E+08	4.63E+10
Cs-134	7.96E+03	4.07E+07	4.63E+07	3.24E+11	3.68E+11
Cs-137	7.99E+03	2.95E+07	3.19E+07	2.36E+11	2.55E+11
Bs-137m	9.07E-01	1.60E+02	5.60E+05	1.45E+02	5.08E+05
Ce-144	2.37E-05	1.68E+08	3.74E+08	3.98E+03	8.85E+03
Pr-144	2.21E-03	5.00E+02	4.33E+04	1.10E+00	9.55E+01
Pm-147	3.53E-04	3.77E+08	3.92E+07	1.33E+05	1.39E+04
Sm-151	3.16E-03	5.11E+08	3.00E+07	1.61E+06	9.47E+04
Eu-154	9.04E-04	1.94E+09	2.86E+08	1.75E+06	2.58E+05
Eu-155	4.23E-03	5.62E+08	4.14E+07	2.38E+06	1.75E+05
Pu-238	3.26E-04	7.03E+12	3.92E+11	2.30E+09	1.28E+08
Pu-239	5.43E-04	7.81E+12	4.29E+11	4.24E+09	2.33E+08
Pu-240	5.28E-02	7.81E+12	4.29E+11	4.12E+11	2.26E+10
Pu-241	2.46E-03	1.55E+11	8.25E+09	3.82E+08	2.03E+07
Am-241	2.63E-03	8.03E+12	4.44E+11	2.11E+10	1.17E+09
Cm-244	0.00E+00	4.33E+12	2.48E+11	0.00E+00	0.00E+00
$\Sigma (h_{bone/E,50})$				1.03E+12	7.09E+11
Dose Commitment from inhalation, $H_E/bone,50$ (mrem)				1259	866
Submersion Pathway					
Isotope, <i>i</i>	<i>S_i</i> (Ci)	<i>h_{ext,skin}</i> (mrem-m ³ /Ci-s)	<i>DCF_{ext,E}</i> (mrem-m ³ /Ci-s)	<i>h_{ext,skin} * S_i</i> (mrem -m ³ /s)	<i>h_{ext,E} * S_i</i> (mrem)
Kr-85	3.90E+04	4.78E+01	4.84E-01	1.86E+06	1.89E+04
Equivalent dose from submersion (mrem)				16.21	0.1642

Appendix B

Utilization of On-Site Meteorological Data for Yucca Mountain Assessment

Meteorological Analysis Code

** Meteorological Data Program

** Written by Paul Fathauer

** Clemson University

** July 25, 1994

**

** Functions : Takes raw monitoring data in TXT files and segregates data into 16 sectors
 ** to build directional frequency table. From this, the program calculates
 ** velocity/stability tables for each sector and a table for overall data.

** Description

** This program uses 3 modules to perform the analysis.

** A) The first module, 'MET1', takes the text files for each year and merges
 ** into 1 file.

** B) The second module, 'MET2', takes the merged data and partitions it into
 ** 16 different directional sectors. From this, the frequency in which the
 ** wind blows into each sector is calculated.

** C) The third module, 'MET3', takes the merged data and summarizes the
 ** each velocity and stability classes in a table. Writes output to file

** 'MET_SUM.TXT'

PROGRAM MET

INTEGER YEARS

LOGICAL DONT,DO,DELET

PARAMETER (YEARS=7)

CHARACTER *2,YEAR(YEARS)

CHARACTER *5, FILENA,EXT*4, RESPON*2

DATA YEAR/'86','87','88','89','90','91','92'/

DELET=.TRUE.

FILENA='COYOT'

EXT='.TXT'

** Perform merging operation. Notify of proposed merge.

10 FORMAT (///5X,'ABOUT TO ANALYZE',A6,A3,A3

+ ,/5X,'PROCEED (Y/N) ?')

WRITE (*,10) FILENA,YEAR(1),YEAR(YEARS)

READ '(A)',RESPON

DONT=(RESPON.NE.'Y'.AND.RESPON.NE.'y')

IF (DONT) THEN

STOP

END IF

** Merge text files

```

PRINT *, 'MERGING FILES .....'
CALL MET1(FILENA, EXT, YEAR, YEARS, DELET)

** Build directional tables

PRINT *, 'BUILDING WIND DIRECTION TABLE .....'
CALL MET2(FILENA)

** Create velocity/stability table

PRINT *, 'CREATING SECTOR SUMMARY TABLES.....'
CALL MET3(FILENA, YEAR, YEARS)

END

SUBROUTINE MET1(FILENA, EXT, YEAR, YEARS, DELET)
*****
** Merging Module for Meteorological Data Analysis
**
** Functions : 1. Merges yearly files for one site into one file - FILENA
** Requires : 1. Setting length of file name needs to be entered on line : CHARACTER
**              n, FILENAM where n is length of base filename i.e. 'YUCCA85.RFR' n=5
*****
** Define variables and data line
** STRING - This program reads entire line instead of each data input where string is the
**            current line being merged
** FILENA - Base file name
** YEARS - # of years to be evaluated
** YEAR - Array specifying year to be merged
** DONT - Logical decision variable
** I - Counter
** EOF - IOSTAT identifying end of file status
** DELET - Logical controlling how unmerged input files are closed. .TRUE. deletes files
**            and .FALSE. saves them.
*****

CHARACTER *40, STRING

** User input for filename length

INTEGER I, EOF, YEARS
CHARACTER *5, FILENA, EXT*4
CHARACTER *2, YEAR(YEARS)
LOGICAL DELET

** Open new file whose name is base name 'FILENA' with no extension

OPEN (UNIT=10, FILE=FILENA/'.'1', STATUS='NEW')

** Perform merge by appending 1 file at a time to new file

10  FORMAT (A3, $, 3X)
DO 25, I=1, YEARS

```

```

      PRINT 10, YEAR(I)
      OPEN (UNIT=5, FILE=FILENA//YEAR(I)//EXT, STATUS='OLD')
20    READ (5, '(A)', IOSTAT=EOF) STRING
      IF (EOF.EQ.0.AND.STRING.NE.' ') THEN
        WRITE (10, '(A)') STRING
        GOTO 20
      END IF

25    CONTINUE

      CLOSE(10, STATUS='KEEP')
      CLOSE(5, STATUS='KEEP')

30    PRINT *, ''

      END

```

SUBROUTINE MET2(FILENA)

```

*****
**   Data Manipulation Module for Meteorological Data
**   Functions :   1. Separate out bad data
**                  2. Replace zero velocities w/ .1 m/s
**                  3. Separate data into sectors (4 sectors at a time) and store into ASCII
**                  files 'S'+sector no.
**
**   Requirements : 1. All years for observation site are combined.
**
*****
*****
**   Define Variables and Set Data Arrays
**
**   COUNT   - Counter to track number of partitioning passes
**   I        - Counter for Sector arrays : i.e. always 1-16
**   STAB     - Pasquill-Gifford stability number (1-A,6-F)
**   FILENA   - Name of file containing observation data
**   SEC      - Array containing sector file names
**   SECLOW   - Low end of sector range (I)
**   SECHIG   - High end of sector range (I)
**   DIR      - Wind direction (degrees from north)
**   VEL      - Wind Velocity (m/s)
**   D1,D2,D3 - Dummy Variables
**   A,B      - Interval of partitioning into sectors
**   GOOD     - Number of good entries
**   BAD      - Number of bad entries
**   R        - Recovery rate (Percentage of good entries)
*****

```

```

      INTEGER I,A,B,COUNT
      CHARACTER *5 FILENA
      CHARACTER *3 SEC(16)
      REAL SECLOW(16), SECHIG(16), VEL,R,GOOD,BAD
      REAL D1,D2,D3,D4,D5,DIR,STAB
      COMMON /SUMM/R

```

```
DATA SEC/'S1','S2','S3','S4','S5','S6','S7','S8'
+ , 'S9','S10','S11','S12','S13','S14','S15','S16'/
```

** Define upper and lower boundaries for each sectors. Note that the data give degrees from north that
 ** the wind is blowing. Therefore, in order to identify receiving sector, the directions are shifted
 ** 180 degrees.

```
DATA SECLOW/168.75,191.25,213.75,236.25,258.75,281.25
+ ,303.75,326.25,-11.25,11.25,33.75,56.25,78.75,101.25
+ ,123.75,146.25/
```

```
DATA SECHIG/191.25,213.75,236.25,258.75,281.25,303.75
+ ,326.25,348.75,11.25,33.75,56.25,78.75,101.25,123.75
+ ,146.25,168.75/
```

** Count keeps track of number of passes

```
COUNT=1
```

```
A=1
```

```
B=4
```

** Open new files to contain individual sector data

```
10  FORMAT (1X,I3,$)
15  DO 20,I=A,B
    OPEN (UNIT=I+6,FILE=SEC(I)/'.2',STATUS='NEW')
    PRINT 10,I
20  CONTINUE
```

** Open file to be partitioned

```
OPEN (UNIT=5,FILE=FILENA/'.1',STATUS='OLD')
```

```
GOOD=0
```

```
BAD=0
```

** Read in next observation set in file

```
25  READ (5,*,END=45) D1,D2,D3,D4,VEL,DIR,D5,STAB
```

** Filter data for bad data

```
IF (STAB.GT.6.OR.VEL.GT.20.OR.DIR.GT.360) THEN
  BAD=BAD+1
  GOTO 25
END IF
```

```
GOOD=GOOD+1
```

** If velocity is zero, replace with .1 m/s

** See NRC Guidance Doc. 1.111 Section C Part 4

```

IF (VEL.EQ.0) THEN
  VEL=.1
END IF

```

**** Shift wind direction for easier sorting in sector 1**

```

IF (DIR.GT.348.75) THEN
  DIR=DIR-360
END IF

```

**** Sort data into correct sector # and write to file 'S'+sector #**

```

DO 30,I=A,B
  IF (DIR.GT.SECLOW(I).AND.DIR.LT.SECHIG(I)) THEN
    WRITE (I+6,40) VEL,INT(STAB)
  END IF
30  CONTINUE

40  FORMAT (F4.1,I3)

  GOTO 25

```

**** Close open files**

```

45  DO 50,I=A,B
    CLOSE(I+6,STATUS='KEEP')
50  CONTINUE

  R=GOOD/(BAD+GOOD)

```

**** Check to see if program has partitioned data into 16 sectors**

```

IF (COUNT.LT.4) THEN
  A=A+4
  B=B+4
  CLOSE (5,STATUS='KEEP')
  COUNT=COUNT+1
  GOTO 15
END IF

```

**** If done, then close and delete original file (merged from MET1)**

```

CLOSE (5,STATUS='DELETE')

PRINT *,''

END

```

```

SUBROUTINE MET3(FILENA, YEAR, YEARS)

```

**** Sector summary module for Meteorological Data Analysis**

```

** Functions : SUBROUTINE MET3 takes the data from sector
**             files Sn.2 and creates sector occurrence table
**             summarizes in files Sn.REP. These tables show
**             the number of occurrences for each velocity
**             class and stability. Prints a key for the
**             velocity classes in S1.REP
*****

*****
** YEARS - Number of years to analyze
** STAB - Stability class
** J,K,I - Used as counters
** CLASS - Used as counter
** FILENA - Base filename of input file (i.e. YUCCA)
** SEC - Contains filenames for output files (i.e. S2.REP)
** YEAR - Contains the years to evaluate
** VEL - Velocity (m/s)
** LOW,HIGH Upper and lower ranges for velocity classes
** N(a,b)- 2 dimensional array containing number of occurrences
**          in 'a' velocity class and 'b' stability
** T(a,b)- 2- dimensional array containing number of occurrences
**          in 'a' velocity class and 'b' stability for entire data set
** NOBS - Total number of observations in sector n
** TOBS - Total number of observations for entire data set
** SV(a) - Vertical summation of table (i.e. Summation in velocity
**          class a)
** TV(a) - Vertical summation of table for entire dataset.
** SH(b) - Horizontal summation of table (i.e. Summation in stability
**          class b)
** TH(b) - Horizontal summation of table for entire dataset.
**
*****

INTEGER YEARS,STAB,J,K,I,CLASS
CHARACTER *5,FILENA,SEC(16)*3,YEAR(YEARS)*2
REAL VEL,HIGH(7),LOW(7),N(7,6),NOBS(16),SV(7),SH(6)
REAL TV(7),TH(6),T(7,6)

DATA SEC/'S1','S2','S3','S4','S5','S6','S7','S8'
+  , 'S9','S10','S11','S12','S13','S14','S15','S16'/

DATA LOW/0,.5,1.9,3.4,5.5,8.6,10.9/
DATA HIGH/.4,1.8,3.3,5.4,8.5,10.8,50/

5  FORMAT (1X,I3,$)
10 FORMAT (F4.1,I3)

TOBS=0

** Set arrays to 0

DO 20,J=1,7
  DO 15,K=1,6

```

```

        N(J,K)=0
        T(J,K)=0
        SH(K)=0
        TH(K)=0
15     CONTINUE
        SV(J)=0
        TV(J)=0
20     CONTINUE

** Create table for each sector

        OPEN (20,FILE='MET_SUM.TXT',STATUS='NEW')

        DO 100, I=1,16

** Clear total number of observations

        NOBS(I)=0

        PRINT 5,I

** Read in velocities and stabilities from Sn.2 and categorize

        OPEN (30,FILE=SEC(I)/*.2',STATUS='OLD')
25     READ (30,10,END=35) VEL,STAB
        DO 30,CLASS=1,7
        IF (VEL.GE.LOW(CLASS).AND.VEL.LE.HIGH(CLASS)) THEN
            N(CLASS,STAB)=N(CLASS,STAB)+1
            T(CLASS,STAB)=T(CLASS,STAB)+1
            GOTO 25
        END IF
30     CONTINUE

** If data entry wasn't categorized then stop program

        PRINT *, 'ERROR', VEL, STAB
        STOP

35     CLOSE(30,STATUS='KEEP')

** Create table summarizing results in Sn.REP

40     FORMAT(/ "SECTOR SUMMARY FOR ",A5,2A2,5X,'SECTOR #',I2,"")
45     FORMAT("STABILITY",19X,'VELOCITY CLASS")
50     FORMAT(" ",14X,'0',7X,'1',7X,'2',7X,'3',7X,'4',7X,'5',7X
+         , '6',4X,"TOTAL ")
60     FORMAT(" ",6X,'A',2X,7F8.0,F9.0)
61     FORMAT(" ",6X,'B',2X,7F8.0,F9.0)
62     FORMAT(" ",6X,'C',2X,7F8.0,F9.0)
63     FORMAT(" ",6X,'D',2X,7F8.0,F9.0)
64     FORMAT(" ",6X,'E',2X,7F8.0,F9.0)
65     FORMAT(" ",6X,'F',2X,7F8.0,F9.0)
66     FORMAT(" ",2X,'TOTAL',2X,7F8.0,F9.0)
67     FORMAT(/," ",8X,'KEY'/"CLASS",3X,"SPEED (M/S)")

```

```

68  FORMAT(3X,I2,4X,F4.1,' - ',F4.1)
69  FORMAT(/ '"SECTOR SUMMARY FOR ',A5,2A2,5X,'TOTAL')

```

** Calculate horizontal and vertical summations

```

      DO 75, J=1,7
        DO 70, K=1,6
          SV(J)=SV(J)+N(J,K)
          SH(K)=SH(K)+N(J,K)
          TV(J)=TV(J)+N(J,K)
          TH(K)=TH(K)+N(J,K)
          NOBS(I)=NOBS(I)+N(J,K)
          TOBS=TOBS+N(J,K)
70      CONTINUE
75      CONTINUE

      WRITE (20,40) FILENA, YEAR(1), YEAR(YEARS), I
      WRITE (20,*) ''
      WRITE (20,45)
      WRITE (20,50)
      WRITE (20,*) ''
      WRITE (20,60) N(1,1),N(2,1),N(3,1),N(4,1),N(5,1)
+      ,N(6,1),N(7,1),SH(1)
      WRITE (20,61) N(1,2),N(2,2),N(3,2),N(4,2),N(5,2)
+      ,N(6,2),N(7,2),SH(2)
      WRITE (20,62) N(1,3),N(2,3),N(3,3),N(4,3),N(5,3)
+      ,N(6,3),N(7,3),SH(3)
      WRITE (20,63) N(1,4),N(2,4),N(3,4),N(4,4),N(5,4)
+      ,N(6,4),N(7,4),SH(4)
      WRITE (20,64) N(1,5),N(2,5),N(3,5),N(4,5),N(5,5)
+      ,N(6,5),N(7,5),SH(5)
      WRITE (20,65) N(1,6),N(2,6),N(3,6),N(4,6),N(5,6)
+      ,N(6,6),N(7,6),SH(6)
      WRITE (20,66) SV(1),SV(2),SV(3),SV(4),SV(5)
+      ,SV(6),SV(7),NOBS(I)
      WRITE (20,*) ''

```

** If in sector 1, then create key for velocity classes

```

      IF (I.EQ.1) THEN
        WRITE(20,67)
        DO 80, J=1,7
          WRITE(20,68) J-1, LOW(J), HIGH(J)
80      CONTINUE
        END IF

```

** Clear N array for next iteration (sector)

```

      DO 90, J=1,7
        DO 85, K=1,6
          N(J,K)=0
          SH(K)=0
85      CONTINUE
          SV(J)=0

```


90 CONTINUE

100 CONTINUE

** Print sector table for entire dataset.

```

      WRITE (20,69) FILENA, YEAR(1), YEAR(YEARS)
      WRITE (20,*) ''
      WRITE (20,45)
      WRITE (20,50)
      WRITE (20,*) ''
      WRITE (20,60) T(1,1),T(2,1),T(3,1),T(4,1),T(5,1)
+     ,T(6,1),T(7,1),TH(1)
      WRITE (20,61) T(1,2),T(2,2),T(3,2),T(4,2),T(5,2)
+     ,T(6,2),T(7,2),TH(2)
      WRITE (20,62) T(1,3),T(2,3),T(3,3),T(4,3),T(5,3)
+     ,T(6,3),T(7,3),TH(3)
      WRITE (20,63) T(1,4),T(2,4),T(3,4),T(4,4),T(5,4)
+     ,T(6,4),T(7,4),TH(4)
      WRITE (20,64) T(1,5),T(2,5),T(3,5),T(4,5),T(5,5)
+     ,T(6,5),T(7,5),TH(5)
      WRITE (20,65) T(1,6),T(2,6),T(3,6),T(4,6),T(5,6)
+     ,T(6,6),T(7,6),TH(6)
      WRITE (20,66) TV(1),TV(2),TV(3),TV(4),TV(5)
+     ,TV(6),TV(7),TOBS
      WRITE (20,*) ''

```

** Print wind directional table.

```

110 FORMAT ('WIND FREQUENCY TABLE')
120 FORMAT (/5X,'SECTOR',10X,'FREQUENCY')
130 FORMAT (7X,I2,15X,F5.4)

```

```

      WRITE (20,110)
      WRITE (20,120)

```

** Print directional frequency table

```

      DO 140,I=1,16
        WRITE (20,130) I,NOBS(I)/TOBS
140 CONTINUE

      CLOSE (20,STATUS='KEEP')

      PRINT *,''

      END

```

Output for Coyote Wash Monitoring Site

SECTOR SUMMARY FOR COYOT8692 SECTOR # 1

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	6	309	484	0	0	0	0	799
B	0	3	83	48	0	0	0	134
C	0	1	0	28	4	0	0	33
D	0	0	3	25	16	2	0	46
E	0	1	35	7	0	0	0	43
F	7	826	260	0	0	0	0	1093
TOTAL	13	1140	865	108	20	2	0	2148

KEY

CLASS	SPEED (M/S)	
0	0	0.4
1	0.5	1.8
2	1.9	3.3
3	3.4	5.4
4	5.5	8.5
5	8.6	10.8
6	10.9	50

SECTOR SUMMARY FOR COYOT8692 SECTOR # 2

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	12	267	391	0	0	0	0	670
B	0	0	34	15	0	0	0	49
C	0	0	0	19	0	0	0	19
D	0	1	2	8	0	0	0	11
E	0	6	17	3	0	0	0	26
F	11	630	107	0	0	0	0	748
TOTAL	23	904	551	45	0	0	0	1523

SECTOR SUMMARY FOR COYOT8692 SECTOR # 3

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	17	274	385	0	0	0	0	676
B	0	1	20	16	0	0	0	37
C	0	0	0	12	2	0	0	14
D	0	1	1	24	4	1	0	31
E	1	3	21	5	0	0	0	30
F	16	885	144	0	0	0	0	1045
TOTAL	34	1164	571	57	6	1	0	1833

SECTOR SUMMARY FOR COYOT8692 SECTOR # 4

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	22	257	292	0	0	0	0	571
B	0	1	39	21	0	0	0	61
C	0	1	0	10	1	0	0	12
D	0	3	0	15	4	0	0	22
E	0	29	22	8	0	0	0	59
F	16	1230	179	0	0	0	0	1425
TOTAL	38	1521	532	54	5	0	0	2150

SECTOR SUMMARY FOR COYOT8692 SECTOR # 5

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	18	342	283	0	0	0	0	643
B	0	16	64	60	0	0	0	140
C	0	9	16	48	11	0	0	84
D	2	52	256	101	43	0	1	455
E	1	256	230	42	0	0	0	529
F	24	2105	522	0	0	0	0	2651
TOTAL	45	2780	1371	251	54	0	1	4502

SECTOR SUMMARY FOR COYOT8692 SECTOR # 6

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	11	457	267	0	0	0	0	735
B	0	62	161	226	0	0	0	449
C	0	80	46	404	81	0	0	611
D	9	869	2098	708	720	250	89	4743
E	29	973	4790	119	0	0	0	5911
F	31	2415	1713	0	0	0	0	4159
TOTAL	80	4856	9075	1457	801	250	89	16608

SECTOR SUMMARY FOR COYOT8692 SECTOR # 7

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	10	258	105	0	0	0	0	373
B	0	21	53	65	0	0	0	139
C	0	15	0	123	25	0	0	163
D	0	81	131	484	279	55	18	1048
E	0	171	362	87	0	0	0	620
F	9	1021	525	0	0	0	0	1555
TOTAL	19	1567	1176	759	304	55	18	3898

SECTOR SUMMARY FOR COYOT8692 SECTOR # 8

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	9	105	37	0	0	0	0	151
B	0	0	11	7	0	0	0	18
C	0	1	0	8	0	0	0	9
D	0	1	1	24	12	1	1	40
E	0	0	8	3	0	0	0	11
F	4	160	55	0	0	0	0	219
TOTAL	13	267	112	42	12	1	1	448

SECTOR SUMMARY FOR COYOT8692 SECTOR # 9

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	9	89	45	0	0	0	0	143
B	1	0	10	9	0	0	0	20
C	0	0	0	5	0	0	0	5
D	0	3	3	22	11	3	1	43
E	1	2	15	3	0	0	0	21
F	4	72	32	0	0	0	0	108
TOTAL	15	166	105	39	11	3	1	340

SECTOR SUMMARY FOR COYOT8692 SECTOR #10

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	5	67	43	0	0	0	0	115
B	0	1	9	9	0	0	0	19
C	0	0	0	2	0	0	0	2
D	0	0	0	20	7	0	0	27
E	0	2	5	6	0	0	0	13
F	3	67	17	0	0	0	0	87
TOTAL	8	137	74	37	7	0	0	263

SECTOR SUMMARY FOR COYOT8692 SECTOR #11

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	2	66	54	0	0	0	0	122
B	0	0	12	4	0	0	0	16
C	0	0	0	0	0	0	0	0
D	0	0	0	8	4	0	0	12
E	0	1	8	1	0	0	0	10
F	5	75	19	0	0	0	0	99
TOTAL	7	142	93	13	4	0	0	259

SECTOR SUMMARY FOR COYOT8692 SECTOR #12

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	7	105	73	0	0	0	0	185
B	0	0	22	11	0	0	0	33
C	0	2	1	5	0	0	0	8
D	0	0	2	7	0	1	0	10
E	0	3	14	0	0	0	0	17
F	5	90	36	0	0	0	0	131
TOTAL	12	200	148	23	0	1	0	384

SECTOR SUMMARY FOR COYOT8692 SECTOR #13

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	4	343	397	0	0	0	0	744
B	1	42	186	115	0	0	0	344
C	0	15	29	93	2	0	0	139
D	0	7	22	62	19	1	2	113
E	3	8	47	7	0	0	0	65
F	12	169	112	0	0	0	0	293
TOTAL	20	584	793	277	21	1	2	1698

SECTOR SUMMARY FOR COYOT8692 SECTOR #14

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	24	1001	1782	0	0	0	0	2807
B	5	295	671	248	0	0	0	1219
C	2	149	238	156	15	0	0	560
D	1	14	61	109	44	0	0	229
E	0	27	76	14	0	0	0	117
F	8	261	175	0	0	0	0	444
TOTAL	40	1747	3003	527	59	0	0	5376

SECTOR SUMMARY FOR COYOT8692 SECTOR #15

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	20	880	1800	0	0	0	0	2700
B	0	104	494	419	0	0	0	1017
C	0	31	8	251	12	0	0	302
D	0	4	3	68	23	0	0	98
E	0	4	55	15	0	0	0	74
F	16	347	235	0	0	0	0	598
TOTAL	36	1370	2595	753	35	0	0	4789

SECTOR SUMMARY FOR COYOT8692 SECTOR #16

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	12	444	1272	0	0	0	0	1728
B	0	7	647	895	0	0	0	1549
C	0	4	1	1215	168	0	0	1388
D	1	1	137	1023	521	15	0	1698
E	1	2	473	147	0	0	0	623
F	14	618	946	0	0	0	0	1578
TOTAL	28	1076	3476	3280	689	15	0	8564

SECTOR SUMMARY FOR COYOT8692 TOTAL

STABILITY	VELOCITY CLASS							TOTAL
	0	1	2	3	4	5	6	
A	188	5264	7710	0	0	0	0	13162
B	7	553	2516	2168	0	0	0	5244
C	2	308	339	2379	321	0	0	3349
D	13	1037	2720	2708	1707	329	112	8626
E	36	1488	6178	467	0	0	0	8169
F	185	10971	5077	0	0	0	0	16233
TOTAL	431	19621	24540	7722	2028	329	112	54783

Sector	Frequency
--------	-----------

1	0.0392
2	0.0278
3	0.0335
4	0.0392
5	0.0822
6	0.3032
7	0.0712
8	0.0082
9	0.0062
10	0.0048
11	0.0047
12	0.0070
13	0.0310
14	0.0981
15	0.0874
16	0.1563

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