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Ashplume Version 1.0-Code
for Contaminated Ash
Dispersal and Deposition

CNWRA 97-004

# ASHPLUME VERSION 1.0 – A CODE FOR CONTAMINATED ASH DISPERSAL AND DEPOSITION

# TECHNICAL DESCRIPTION AND USER'S GUIDE

*Prepared for*

**Nuclear Regulatory Commission**
**Contract NRC-02-93-005**

*Prepared by*

**Center for Nuclear Waste Regulatory Analyses**
**San Antonio, Texas**

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**Mark S. Jarzemba**
**Patrick LaPlante**
**Kevin J. Poor**

**Center for Nuclear Waste Regulatory Analyses**
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# ABSTRACT

The assessment of long-term isolation performance for a geologic repository requires the use of mathematical models that consider the probability and consequences of postulated disruptive scenarios. In the case of the proposed repository at Yucca Mountain, Nevada, volcanism is one of the important disruptive scenarios being considered in site evaluation. A stochastic modeling approach was developed for use in simulating the airborne release of radioactive particulate associated with the basaltic volcanism scenario. The model is implemented in the ASHPLUME code, which will be incorporated into the NRC Total-system Performance Assessment (TPA) code. This user guide is for the standalone version of the ASHPLUME code.

ASHPLUME considers physical factors as eruption energetics, eruption duration, wind velocity, and particle properties to compute the activity areal density as a function of spatial location. Various components of the model are based on empirical relationships and data from observed and monitored cinder cone eruptions analogous to those that likely occurred in the Yucca Mountain region in the past. ASHPLUME calculates ash and spent fuel deposition by location for material emitted during an extrusive volcanic eruption. Illustrative applications of the stochastic model are presented for the cases of a single event realization and a multiple event average realization.

# CONTENTS

# FIGURES

# TABLES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $X(x,y)$ | = | mass of ash per unit area accumulated at location $(x,y)$ in g per $cm^2$ |
| $\rho$ | = | common logarithm of particle diameter $d$, where $d$ is in cm |
| $\rho_{min}$ | = | minimum value of $\rho$ |
| $\rho_{max}$ | = | maximum value of $\rho$ |
| $z$ | = | vertical distance from ground surface, km |
| $H$ | = | height of eruption column above vent, km |
| $x$ | = | x coordinate on the surface of the earth, cm; coordinate oriented in same direction as the prevailing wind |
| $y$ | = | $y$ coordinate on the surface of the earth, cm; coordinate oriented perpendicular to direction of the prevailing wind |
| $Q$ | = | total quantity of erupted material, g |
| $P(z)$ | = | distribution function for particle diffusion at height within $dz$ about $z$ |
| $f(\rho)$ | = | distribution function for particles with a log-diameter within $d\rho$ about $\rho$ normalized per unit mass |
| $C$ | = | constant relating eddy diffusivity and particle fall time, $cm^2$ per $s^{5/2}$ |
| $t$ | = | particle fall time, s |
| $t_s$ | = | particle diffusion time in eruption column, s |
| $u$ | = | wind speed, cm per s |
| $V_0$ | = | particle terminal velocity at sea level, cm per s |
| $\beta$ | = | constant controlling diffusion of particles in eruption column |
| $W_0$ | = | volcanic eruption velocity at vent exit, cm per s |
| $W(z)$ | = | particle velocity as a function of height, and is equal to $W_0\left[1-\frac{Z}{H}\right]$ |
| $Y$ | = | $\frac{\beta(W(z)-V_0)}{V_0}$ |
| $Y_0$ | = | $\frac{\beta(W_0-V_0)}{V_0}$ |
| $\psi_a, \psi_p$ | = | density of air and particles in g per $cm^3$ |
| g | = | gravitational acceleration constant, 980 cm per $s^2$ |
| $\eta_a$ | = | viscosity of air in g per cm-s |
| F | = | shape factor for particles; for an elliptically shaped particle with principal axis of $a$, $b$, and $c$, $F$ is equal to $(b+c)/2a$ where a is the longest axis |
| $\rho^a$ | = | log-diameter of ash particle size, with particle size in cm |
| $\rho^a_{mean}$ | = | mean of log-diameter of ash particle size, with particle size in cm |
| $\sigma_d$ | = | standard deviation of log particle size |
| $\rho^f$ | = | log-diameter of fuel particle size, with particle size in cm |

## LIST OF SYMBOLS (Cont'd)

| | | |
|---|---|---|
| $\rho^f_{\min}$ | = | minimum log-diameter of fuel particle size, with particle size in cm |
| $\rho^f_{\max}$ | = | maximum log-diameter of fuel particle size, with particle size in cm |
| $\rho^f_{\mathrm{mode}}$ | = | mode log-diameter of fuel particle size, with particle size in cm |
| $m(\rho^f)$ | = | distribution function of fuel mass within $d\rho^f$ about normalized per unit mass $\rho^f$ |
| $\rho_c$ | = | incorporation ratio |
| $d^a_{\min}$ | = | minimum ash particle size needed for incorporation, in cm |
| $d^f$ | = | fuel particle size, in cm |
| $q$ | = | total mass of ash ejected in the event in g |
| $U$ | = | total mass of fuel ejected in the event in g |
| $F(\rho)$ | = | cumulative distribution of $f(\rho)$ |

# PREFACE

In accordance with provisions of the Nuclear Waste Policy Act of 1982, the Nuclear Regulatory Commission (NRC) has the responsibility of evaluating and granting a license for any geologic repositories constructed for emplacement of high-level nuclear waste (HLW). This act was amended in 1987 to designate one site in the unsaturated region of tuffaceous rocks of Yucca Mountain in southern Nevada for detailed characterization. The Center for Nuclear Waste Regulatory Analyses (CNWRA) at Southwest Research Institute is a Federally Funded Research and Development Center created to support the NRC in its mission of evaluating and licensing the proposed HLW repository. To meet its licensing function, the NRC will review the application submitted by the U.S. Department of Energy (DOE). One critical section of the license application will deal with assessment of the future performance of the repository system, which has to meet certain minimum standards established by regulations.

To develop capabilities to review the Total-System Performance Assessment (TSPA) in the DOE license application, the NRC and CNWRA are engaged in developing and applying performance assessment (PA) methods and models to existing data. At the time of license application review, these methods may be used to conduct independent PA, if the NRC elects to do so. Because of the large space and time scales involved in estimating repository performance, mathematical models implemented as computer codes are the principal tools for PA. The repository system consists of designed (or engineered) barriers embedded in the natural geological setting. Estimating performance of the total system requires that the behavior of these components be projected under possible future conditions. This effort is obviously a complex task that requires a variety of calculations. The ASHPLUME consequence analysis module code is a part of the Total-system Performance Assessment computer code that performs these calculations.

# ACKNOWLEDGMENTS

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The authors wish to thank Drs. Charles Connor, and Britain Hill for their technical contributions and Mr. Robert Baca, Mr. James Weldy and Dr. Budhi Sagar for their technical and programmatic reviews, Barbara Long for editorial review, and Cathy Garcia for secretarial support.

# QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

**DATA:** No CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

**CODES:** The ASHPLUME Code Version 1.0 has been developed following the procedures described in CNWRA Technical Operating Procedure (TOP)-18 which implements the quality assurance (QA) guidance contained in CWNRA QA Manual.

# 1 INTRODUCTION

## 1.1 REGULATORY BASIS AND TECHNICAL BACKGROUND

The primary regulations applicable to the proposed geological repository for high-level waste (HLW) were promulgated by the Nuclear Regulatory Commission (NRC) in 10 CFR Part 60—Disposal of High-Level Radioactive Wastes in Geologic Repositories. Two sections of 10 CFR Part 60 pertain specifically to postclosure performance. These sections are Part 60.112—Overall System Performance Objective for the Geologic Repository after Permanent Closure; and Part 60.113—Performance of Particular Barriers after Permanent Closure. Part 60.112 makes reference to satisfying the generally applicable environmental standards for radioactivity established by the U.S. Environmental Protection Agency (EPA). Performance measures used in 10 CFR Part 60.113 to define performance of individual barriers (in contrast to the total system) are (i) life of the waste package must exceed specified limits [Part 60.113(a)(ii)(A)—Substantially Complete Containment Requirement]; (ii) release from engineered barriers must be less than specified limits [Part 60.113(a)(1)(ii)(B)— Groundwater Release Requirement]; and (iii) groundwater travel time must be greater than specified limits [Part 60.113(a)(2)—Groundwater Travel Time Requirement]. In the Energy Policy Act of 1992, Congress directed the National Academy of Sciences (NAS) to make recommendations about an environmental standard for the proposed geologic repository located at Yucca Mountain (YM), NV. In their recommendations (National Academy of Sciences, 1995), the NAS proposed that the new environmental standard, to be issued by the Environmental Protection Agency (EPA), be based on the dose to the average member of a small, critical group. The ASHPLUME code will be incorporated in the NRC Total-system Performance Assessment (TPA) code to assess doses to the average member of the critical group in order to evaluate the U.S. Department of Energy (DOE) Total System Performance Assessments (TSPAs). The NRC is currently enhancing their capability to evaluate the DOE TSPAs (including the viability assessment expected in 1998 and the license application expected in 2002) by creating the TPA Version 3.0 code.

## 1.2 TOTAL-SYSTEM PERFORMANCE ASSESSMENT BACKGROUND

Performance assessment (PA) plays an important role in determining if the proposed HLW geological repository system will satisfy the applicable regulatory standards specified in 10 CFR Part 60. The determination is to be accomplished, upon completion of adequate site characterization efforts by the DOE, by comparing estimated values of regulatory performance measures with minimum acceptable values for the same performance measures as specified in the regulations. Hence, PA models are being designed and developed for use in estimating or bounding future repository performance. The NRC has conducted two Iterative Performance Assessment (IPA) exercises to date. The first IPA (Nuclear Regulatory Commission, 1992) was conducted by executing several codes and then synthesizing the results into a TSPA. The second exercise, NRC IPA Phase 2 (Nuclear Regulatory Commission, 1995), broadened the scope, used more site specific models and also produced a TSPA code entitled TPA Version 2.0. As discussed in the previous section, the NRC is currently updating this code to a Version 3.0. TPA Version 3.0 will include:

- updated consequence models for physical processes and scenarios
- improved parameter importance analysis capabilities
- streamlined scope for consequence modules
- streamlined methodology for data transfer between consequence modules, and
- more flexible design to accommodate changes in consequence modules

The organization of the TPA Version 3.0 code is shown in figure 1-1. The TPA Version 3.0 code is a combination of an executive driver, consequence modules and utility modules (not shown). The executive driver controls the probabalistic sampling of input parameters, the flow of data between consequence modules and the generation of output files. Consequence modules, one of which is the ASHPLUME code, are primarily responsible for calculating the radiation doses to the receptor population for the sampled set of input parameters. Utility modules are coding constructs that are common to many of the consequence modules. The ASHPLUME code was written as a result of significant progress in the state of knowledge (since IPA Phase 2) of the consequences that a volcanic eruption may have on the proposed repository.

## 1.3 PURPOSE OF THE ASHPLUME MODULE

The ASHPLUME code, a consequence module of the TPA code, is used to evaluate consequences of extrusive volcanic events in the vicinity of YM. The ASHPLUME code receives the mass of spent-fuel extruded in the event from VOLCANO and a set of sampled parameters (described in this report) from the EXEC as input. From this input, ASHPLUME generates the areal mass density of spent fuel at the compliance point as output. This output is used by the consequence modules ASHREMOVE and DCAGS to calculate time-dependent doses at the compliance point.

## 1.4 REPORT CONTENT

A description of the technical design of the ASHPLUME code is presented in chapter 2. It also presents assumptions made and code limitations. Features of the software are provided in chapter 3. Chapter 4 shows the input files and parameters used in execution of the ASHPLUME code, while chapter 5 describes the output. Chapter 6 lists the references. Listings of code output are contained in appendices A and B, and the Software Requirements Document for the ASHPLUME code is contained in appendix C.

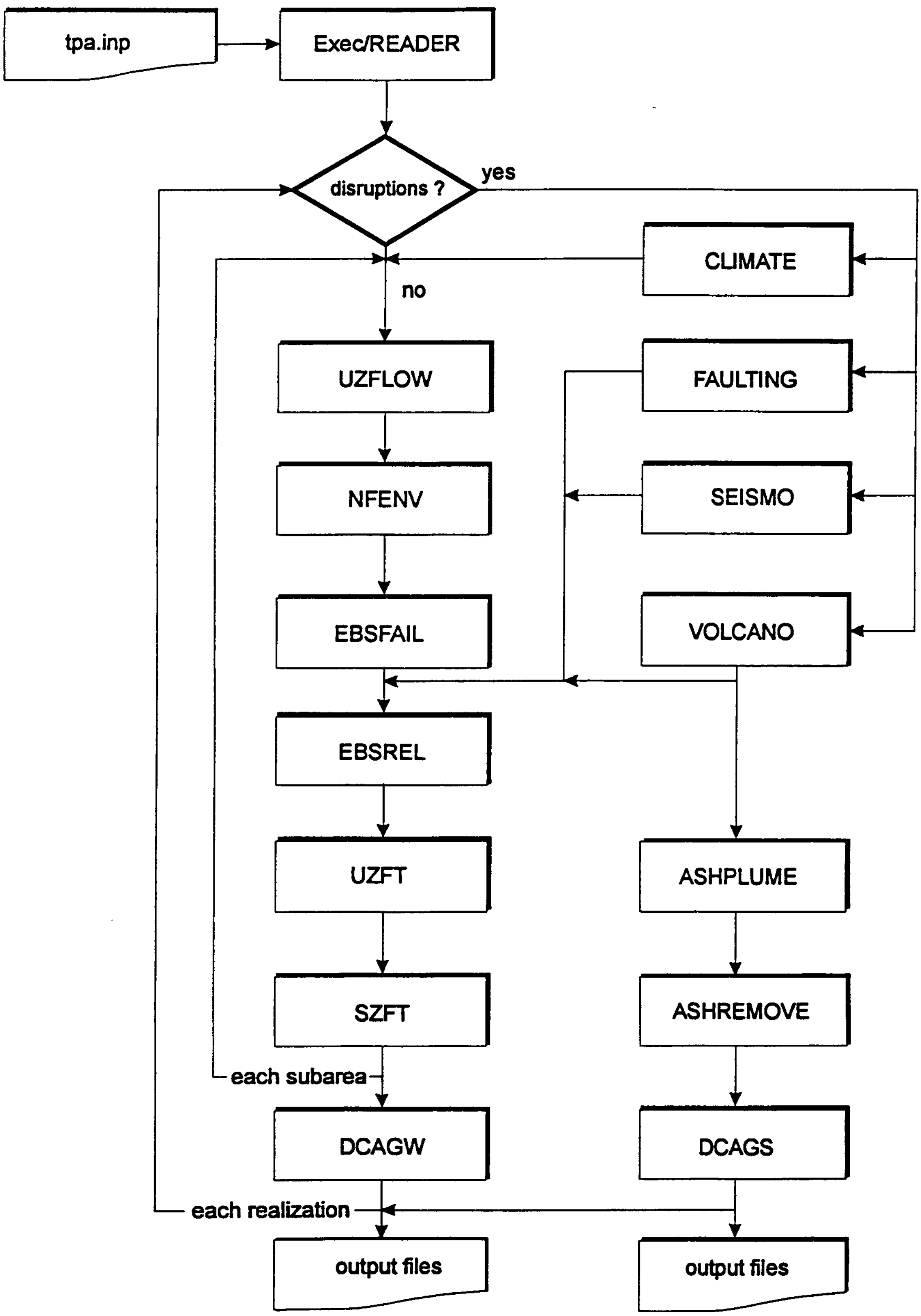


**Figure 1-1. Organization of the TPA computer code**

# 2 ASHPLUME CONSEQUENCE MODULE TECHNICAL DESIGN

## 2.1 OVERVIEW

The proposed HLW repository at YM is located within a region of past volcanic activity. This volcanic field consists of eight basaltic cinder cones formed by volcanic activity within the last one million years and numerous cinder cones formed within the last five million years (Bradshaw and Smith, 1994; Champion, 1991; Faulds et al., 1994; Heizler et al., 1994; Langheim et al., 1993; Sawyer et al., 1994). As is typical for volcanic fields of this kind located throughout western North America, volcanic activity in the YM region (YMR) is characterized by the formation of new cinder cones at a low recurrence rate. Recent estimates of the probability of a new basaltic cinder cone forming within the area of the proposed repository range from 0.0001 to 0.001 for a 10,000-yr period (Crowe and Perry, 1989; Connor and Hill, 1995; Ho et al., 1991; Margulies et al., 1992; Smith et al., 1990). Although probability estimates will likely be refined, current estimates are large enough to be of regulatory concern and must be addressed in PA. Also, if the period of regulatory concern is extended beyond 10,000 yr, the consequences of volcanic releases may become more important in assessing post-closure performance.

Basaltic volcanism can encompass a variety of eruption styles, depending on eruption energy. The energy of basaltic eruptions varies from effusive activity, where the predominate product is lava flows, to explosive activity, resulting in fragmentation of the magma into scoria fragments and transportation of scoria into the atmosphere as pyroclasts. This latter style of activity generally results in the formation of cinder cones, such as those found in the YMR. Explosive volcanic activity of this kind has the potential to cause dispersal of radionuclides through the biosphere. This dispersion can be modeled using approaches originally developed to study the dispersal of ash after volcanic eruptions (Suzuki, 1983).

To assess the radiation doses that may occur after a basaltic eruption, the distribution of radionuclides into the biosphere after such an event needs to be estimated. It is assumed that ash particles from the eruption are carriers of radionuclides. Methods used previously to estimate radionuclide dispersal by volcanism (Wescott et al., 1995) theorize that the ash cloud travels with a gaussian plume, released at a stack height one half the volcanic column height. Application of the gaussian plume model presumes that a plume of contaminants travels in the same direction as the prevailing wind (x-direction), but may be somewhat depressed toward the Earth surface due to gravitational settling. Contaminants in the plume follow a gaussian distribution in dimensions perpendicular to the direction of travel (y- and z-directions).

The gaussian plume model is suitable for modeling airborne and ground concentrations of contaminants for a point source release of contaminants above the surface of the earth (the stack height). A point source approximation may not be appropriate for a volcanic eruption because a volcanic eruption column is a line source of contaminants in the upward direction. Also, the gaussian plume model does not accurately account for the effects of gravitational settling of volcanic particles with large diameters (i.e., centimeters). This shortcoming may lead to the gaussian plume model predicting much greater particle ranges than would be the case in reality and hence wider radionuclide distributions than would normally be expected after a basaltic eruption. This wider distribution of radionuclides may tend to underestimate the radiation exposure of persons in a critical group. The critical group is defined as a small, homogenous group (generally ones to several tens of people) who are at the highest risk of incurring additional health effects from the proposed repository. Using a critical group has recently been recommended as the standard of measuring compliance for YM (National Academy of Sciences, 1995).

Models to predict the distribution of ash after an eruption have been developed with the intention of relating eruption magnitude to ash dispersion (Suzuki, 1983; Hopkins and Bridgeman, 1985; Glaze and Self, 1991). The ASHPLUME code uses a model first described in Suzuki (1983) that relates eruption magnitude to ash distribution which is modified to relate eruption magnitude to spent fuel distribution for YM based on a few simple assumptions. The model described in this report uses Monte Carlo sampling to determine power and duration of the eruption, along with other properties of the ash particulates, and develops a spent fuel distribution from those sampled parameters. The spent fuel distribution can be translated into radionuclide distribution which can then be used to model dose to man.

Following the approach of Suzuki (1983), it is assumed that energy is released steadily throughout the eruption. This assumption is valid for high mass flow eruptions that are relatively brief. Typically, basaltic cinder cones are active over periods of several months to years. During this period, individual eruptions occur which are well characterized by steady eruption columns. For example, throughout the nine-year eruption of Paricutin, in Mexico, the volcano generally experienced a low-level of activity punctuated by short periods of energetic, steady-state eruptions lasting hours to weeks during which an ash column continuously emanated from the cinder cone. Most of the ash dispersed by the Paricutin cinder cone was emitted during these short intervals (Luhr and Simkin, 1993). Similar periods of energetic, steady-state activity are reported during most cinder cone eruptions (Self et al., 1974; Fedotov and Markhinin, 1983; Connor et al., 1993). This type of activity is variously termed violent strombolian, plinian, or sub-plinian. Some eruptions at cinder cones are not well represented by steady-state eruption models. These include normal strombolian, phreatic, and phreatomagmatic eruptions. Such eruptions are best represented as detonations or short explosions (Wilson et al., 1978). In general, normal strombolian activity will produce a less dispersed ash blanket. The model in Suzuki (1983) does not capture ash dispersion related to this style of activity.

The model developed by Suzuki (1983) is appropriate for particles of mean diameter greater than about 15-30 micrometers. This cutoff is generally accepted to be the lower limit for the importance of gravitational settling of particles (Cember, 1983; Heffter and Stunder, 1993). For particle sizes less than about 15 micrometers, atmospheric turbulence is great enough to keep the particle aloft longer than would be predicted by the model. Since the typical mean diameter of ash particles after an eruption is generally much larger than 15 micrometers (Suzuki, 1983), this model is useful for calculating the distribution of the vast majority of ash, and hence, radionuclides, released.

## 2.2 MATHEMATICAL THEORY

The mathematical model described in Suzuki (1983) can be summarized by the equation that describes the areal density of accumulated ash on the earth surface after an eruption:

$$X(x,y) = \int_{\rho=\rho_{min}}^{\rho_{max}} \int_{z=0}^{H} \frac{5QP(z)f(\rho)}{8\pi C(t+t_s)^{5/2}} \exp\left[\frac{5\{(x-ut)^2+y^2\}}{8C(t+t_s)^{5/2}}\right] d\rho dz \qquad (2\text{-}1)$$

where

| | |
|---|---|
| $X(x,y)$ | = mass of ash per unit area accumulated at location $(x,y)$ in g per $cm^2$ |
| $\rho$ | = common logarithm of particle diameter $d$, where $d$ is in cm |
| $\rho_{min}$ | = minimum value of $\rho$ |
| $\rho_{max}$ | = maximum value of $\rho$ |
| $z$ | = vertical distance from ground surface, km |
| $H$ | = height of eruption column above vent, km |
| $x$ | = x coordinate on the surface of the earth, cm; coordinate oriented in same direction as the prevailing wind |
| $y$ | = $y$ coordinate on the surface of the earth, cm; coordinate oriented perpendicular to direction of the prevailing wind |
| $Q$ | = total quantity of erupted material, g |
| $P(z)$ | = distribution function for particle diffusion out of the column within $dz$ about height $z$ |
| $f(\rho)$ | = distribution function for particles with a log-diameter within $d\rho$ about $\rho$ normalized per unit mass |
| $C$ | = constant relating eddy diffusivity and particle fall time, $cm^2$ per $s^{5/2}$ |
| $t$ | = particle fall time, s |
| $t_s$ | = particle diffusion time in eruption column, s |
| $u$ | = wind speed, cm per s |

The assumptions used in Suzuki (1983) to derive Eq. (2-1) are; (i) erupted material consists of a finite quantity of volcanic ash particles, (ii) the distribution of diameter of the released particles has a single mode, (iii) all particles fall at the terminal velocity and finally accumulate on the ground, and (iv) particles have a probability to diffuse out of the eruption column during upward travel in the column. These assumptions are more realistic for modeling volcanic releases of radionuclides than the assumptions used in the gaussian plume model (i.e., a point source of radionuclides released at a single height above the vent) provided the ash particles are the carrier media for the released radionuclides.

The probability density distribution function for particle diffusion out of the eruption column $P(z)$ is given by (Suzuki, 1983)

$$P(z) = \frac{\beta W_0 Y \exp(-Y)}{V_0 H\{1-(1+Y_0)\exp(-Y_0)\}} \qquad (2\text{-}2)$$

where

$$Y = \frac{\beta(W(z)-V_0)}{V_0}$$

$$Y_0 = \frac{\beta(W_0-V_0)}{V_0}$$

$\beta$ = constant controlling the diffusion of particles out of the eruption column

$W_0$ = volcanic eruption velocity at vent exit, cm per s

$W(z)$ = particle velocity as a function of height, and is equal to $W_0 \left[1 - \frac{Z}{H}\right]$

$V_0$ is the particle terminal velocity at sea level. This quantity is given by (Suzuki, 1983)

$$V_0 = \frac{\psi_p g d^2}{9\eta_a F^{-0.32} + \sqrt{81\eta_a^2 F^{-0.64} + \frac{3}{2}\psi_p \psi_a g d^3 \sqrt{1.07 - F}}} \tag{2-3}$$

where

$\psi_a, \psi_p$ = density of air and particles in g per $cm^3$

g = gravitational acceleration constant, 980 cm per $s^2$

$\eta_a$ = viscosity of air in g per cm-s

F = shape factor for particles; for an elliptically shaped particle with principal axis of *a, b,* and *c*, *F* is equal to $(b+c)/2a$ where a is the longest axis

In the ASHPLUME code, the particle density is a function of the particle log-diameter $\left[\psi_a(\rho^a)\right]$ and varies linearly between user input values $\left[\psi_a(\rho^a_{low}) \text{ and } \psi_a(\rho^a_{hi})\right]$. For values of $\rho^a$ below or above the user defined range, the ash particle density is set to either $\psi_a(\rho^a_{low})$ or $\psi_a(\rho^a_{hi})$ depending on whether $\rho^a$ is less or greater than the defined range. Data from Suzuki (1983) indicates that $\psi_a(\rho^a_{low})$ and $\psi_a(\rho^a_{hi})$ should be 2.5 and 0.8 g per $cm^3$, meaning that larger ash particles are less dense due to incorporation of more gas bubbles.

The particle fall time is given by (Suzuki, 1983)

$$t = 0.752 \times 10^6 \left[\frac{1 - \exp(-0.0625z)}{V_0}\right]^{0.926} \tag{2-4}$$

where $t$ is in s, $V_0$ is in cm per s, and $z$ is particle location in km above the vent. Particle size follows a log-normal distribution (Suzuki, 1983). For a detailed derivation of Eq. (2-1) through (2-4), the reader is referred to Suzuki (1983).

For use in TSPAs, the necessary quantity to track is the mass of spent fuel per unit area as a function of position after ash, released from the eruption that penetrates the proposed repository, settles on the surface of the earth. To calculate this quantity, a model for spent fuel incorporation into ash was created. This model requires the introduction of a new function to determine the mass of fuel per unit

$$f(\rho^a) = \frac{1}{\sqrt{2\pi}\,\sigma_d} \exp\left( -\frac{(\rho^a - \rho^a_{\mathrm{mean}})^2}{2\sigma_d^2} \right) \tag{2-5}$$

where

$\rho^a$ = log-diameter of ash particle size, with particle size in cm
$\rho^a_{\mathrm{mean}}$ = mean of log-diameter of ash particle size, with particle size in cm
$\sigma_d$ = standard deviation of log particle size
$f(\rho^a)$ = normalized (per unit mass) probability distribution for ash mass as a function of $\rho^a$

The assumed mass of fuel as a function of the log-diameter of the fuel $[m(\rho^f)]$ is defined as (the log-triangular distribution):

$$
\begin{aligned}
m(\rho^f) &= k_1(\rho^f - \rho^f_{\mathrm{min}}) && \rho^f_{\mathrm{min}} < \rho^f \le \rho^f_{\mathrm{mode}} \\
m(\rho^f) &= k_2(\rho^f - \rho^f_{\mathrm{mode}}) + k_1(\rho^f_{\mathrm{mode}} - \rho^f_{\mathrm{min}}) && \rho^f_{\mathrm{mode}} < \rho^f \le \rho^f_{\mathrm{max}} \\
m(\rho^f) &= 0 && \text{otherwise}
\end{aligned}
\tag{2-6}
$$

where

$$k_1 = \frac{2}{(\rho^f_{\mathrm{max}} - \rho^f_{\mathrm{min}})(\rho^f_{\mathrm{mode}} - \rho^f_{\mathrm{min}})}$$

$$k_2 = -\frac{2}{(\rho^f_{\mathrm{max}} - \rho^f_{\mathrm{min}})(\rho^f_{\mathrm{max}} - \rho^f_{\mathrm{mode}})}$$

where

$\rho^f$ = log-diameter of fuel particle size, with particle size in cm
$\rho^f_{\mathrm{min}}$ = minimum log-diameter of fuel particle size, with particle size in cm
$\rho^f_{\mathrm{max}}$ = maximum log-diameter of fuel particle size, with particle size in cm

$\rho^f_{mode}$ = mode log-diameter of fuel particle size, with particle size in cm

$m(\rho^f)$ = distribution function for fuel mass within $d\rho^f$ about $\rho^f$ normalized per unit mass

Motivation for limiting the amount of fuel mass available for incorporation into volcanic ash particles of a given size is that for smaller volcanic ash particles an amount of fuel mass will be too large to be incorporated into these small particles. For example, a 1 cm fuel particle cannot be incorporated into a 0.5 cm volcanic ash particle. Assuming a cutoff on the ratio of incorporable fuel diameter to volcanic ash diameter of 1:10 is equivalent to assuming an incorporation ratio $(\rho_c)$ of 1. Mathematically, the incorporation ratio is defined as

$$\rho_c = \log_{10}\left(\frac{d^a_{min}}{d^f}\right) \tag{2-7}$$

where

$d^a_{min}$ = minimum ash particle size needed for incorporation, in cm

$d^f$ = fuel particle size, in cm

Another example, $\rho_c$ equal to 0.3, is equivalent to allowing all fuel mass of size less than or equal to one-half of the volcanic ash particle size to be available for incorporation.

To determine $FF(\rho^a)$, the fuel fraction (ratio of fuel mass to ash mass) as a function of $\rho^a$, one must consider that all fuel particles of size smaller than $(\rho^a - \rho_c)$ have the ability to *simultaneously* be incorporated into volcanic ash particles of size $\rho^a$ or larger. The fuel fraction as a function of $\rho^a$ is determined by summing all the incremental contributions of fuel mass to the volcanic ash mass from fuel sizes smaller than $(\rho^a - \rho_c)$. An expression for the fuel fraction is given as

$$FF(\rho^a) = \frac{U}{Q} \cdot \int_{\rho=-\infty}^{\rho=\rho^a} \frac{m(\rho - \rho_c)}{1 - F(\rho)}\, d\rho \tag{2-8}$$

where

$Q$ = total mass of ash ejected in the event in g

$U$ = total mass of fuel ejected in the event in g

$F(\rho^a)$ = cumulative distribution of $f(\rho^a)$

This equation assumes the resulting contaminated particles follow the same size distribution as the original volcanic ash particles. This seems reasonable since for most events sampled in these analyses, the total mass of volcanic ash is on the order of $10^{13}$ to $10^{15}$ g and for most events, only several waste packages are disrupted ($10^7$ g of fuel each). The integrand of Eq. (2-1) is multiplied by $FF(\rho^a)$ and then recalculated to find the spent fuel density at the (x,y) location.

## 2.3 CONSEQUENCE ANALYSIS AND SIMULATION PROCESS

The ASHPLUME code will operate in either a stochastic or nonstochastic mode. Upon execution of the model, the user is prompted to input either a 1 (stochastic mode) or a 2 (nonstochastic mode). In both modes the user is given the option of generating particle size distribution information for ash and fuel at the grid locations. Given values for the model parameters, the distribution of spent fuel after an eruption is calculated by evaluating Eq. (2-1) through (2-7). To incorporate this methodology into existing PAs, the parameter distributions and interrelationships must be sampled. Section 4 describes the program input parameter sampling incorporated with this model.

For each simulation, Eq.(2-1) is numerically integrated to calculate distribution of the spent fuel and volcanic ash on the surface of the earth resulting from a basaltic eruption assumed to disrupt the repository. The wind velocity (speed and direction), energy, and duration of the volcanic event are sampled or manually input according to the procedures outlined in section 4.

# 3 ASHPLUME SOFTWARE AND HARDWARE

The ASHPLUME code was written in standard FORTRAN 77, compiled with a SUN f77 compiler, and operated on a SUNO 4.1 operating system. It can also be run using personal computer systems with FORTRAN 77 compliant compilers (e.g., Microsoft Fortran V. 5). The main program of the ASHPLUME code reads input files, defines simulation system configuration, calls subroutines to locate and characterize events, and outputs results. ASHPLUME contains 25 subroutines and 16 defined functions. Table 3-1 lists and describes the purpose of the subroutines while table 3-2 lists and describes the defined functions. After definition of the desired deposition locations and reading of input data, the subroutines *ashcalca* and *ashcalcf* call the additional functions and subroutines needed to integrate the equations described in section 2 and calculate the location-specific ash and fuel depositions. Input parameter definitions and descriptions are presented in section 4.

Before running the ASHPLUME code, the parameters in the input file *ashplume.in* must be present and complete. Compiling and running the ASHPLUME code on the SUNOS 4.1 operating system requires the following commands after the command prompt:

**f77 ashplume.f_options_executablename** <enter>
**executablename** <enter>

The first line creates the executable file from the source code file *ashplume.f*, while the second line runs the executable file. When executing the code, the user is prompted for input when the user wants stochastic sampling with multiple volcanos or one volcano with specific user input parameters. Depending on the choice on this option, the user is prompted for either the number of volcanos to evaluate or for specific parameter input for the single volcano. Either way the user is then asked whether particulate size information is desired at the dose points. If particle size information is desired, the user inputs a (1), if not, the user inputs a (2).

## 3.1 USER SUPPORT

For technical assistance contact

M.S. Jarzemba
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
P.O. Drawer 28510
San Antonio, TX 78228-0510
210/522-6828

or

R.G. Baca
Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
P.O. Drawer 28510
San Antonio, TX 78228-0510
210/522-3805

**Table 3-1. ASHPLUME code subroutines**

| Subroutine | Description |
|---|---|
| userinput | Prompts the user for parameter input when the single specified volcano option is selected |
| outheader | Generates output header blocks |
| ashcalca | Calculates ash deposition densities at the dose points |
| ashcalcf | Calculates fuel deposition densities at the dose points |
| inputdata | Reads input data and stochastically calculates parameters when the multiple stochastic volcano option has been selected |
| histf | Calculates fuel particulate size distribution at the dose point |
| triangular | Returns a value sample from a log-triangular distribution |
| winddirect | Selects wind direction |
| windspeed | Selects wind speed for a given a wind direction |
| qromb4 | Numerical integrator for calculation of fuel particulate distribution with size at the dose point |
| trapzd4 | Used by qromb4 for calculation of fuel particulate distribution with size at the dose point |
| polint4 | Used by qromb4 for calculation of fuel particulate distribution with size at the dose point |
| qromb3 | Numerical integrator for calculation of fuel fraction of ash as a function of rho |
| trapzd3 | Used by qromb3 for calculation of fuel fraction of ash as a function of rho |
| polint3 | Used by qromb3 for calculation of fuel fraction of ash as a function of rho |
| qromb2 | Numerical integrator for calculation of fuel deposition at the dose point |
| trapzd2 | Used by qromb2 for calculation of fuel deposition at the dose point |
| polint2 | Used by qromb2 for calculation of fuel deposition at the dose point |
| qromb1 | Numerical integrator for ash deposition at the dose point |
| trapzd1 | Used by qromb1 to calculate ash deposition at the dose point |
| polint1 | Used by qromb1 to calculate ash deposition at the dose point |
| qgaus | Base numerical integration routine for determining fuel and ash distributions |
| gauleg | Used by qgaus to calculate fuel and ash distributions |
| filename | Produces output for storing particle size distribution at the dose points |
| rand | Generates uniformly distributed random numbers between 0 and 1 |

**Table 3-2. ASHPLUME code defined functions**

| Function | Description |
|---|---|
| dinnerf | Calculates inner integration of Eq. (2-1) after the integrand is multiplied by FF($\rho^a$) |
| dinnera | Calculates inner integration of Eq. (2-1) |
| dintegrandf | Integrand for fuel deposition |
| dintegranda | Integrand for ash deposition |
| tf | Calculates particle fall time as a function of height |
| ts | Calculates particle diffusion time in the eruption column |
| f | Probability density function (PDF) for ash mass as a function of log-particle diameter |
| dm | PDF for fuel mass as a function of log-particle diameter |
| FF | Calculates the fuel fraction as a function of log-diameter |
| FFintegrand | Integrand of Eq. (2-8) |
| Fcumm | Uses a table lookup to yield the cumulative distribution function from the standard normal distribution |
| P | Calculates the PDF for particle diffusion out of the eruption column |
| v0 | Calculates terminal fall velocity at sea level |
| ashden | calculated contaminated ash density as a function of rho |
| FFintegrandhist | Integrand for calculating particle size distributions at the dose point |
| dma | Reads in the ash deposition at the current dose point |

# 4 INPUT DATA

## 4.1 LISTING OF INPUT FILE *ashplume.in*

The *ashplume.in* file is created by the model user and defines the distributions and parameters described previously for input to the ASHPLUME model. An example listing of the input file (that is format free) is as follows:

```
sample problem             ! code run title
0.d0     0.d0              ! xmin, xmax in km
-20.d0   -30.d0            ! ymin, ymax in km
1                          ! numptsx - must be less than 500
3                          ! numptsy - must be less than 500
4.80d0   6.86d0            ! tlogmin, tlogmax in sec
9.41     11.55             ! powlogmin, powlogmax-logs of power in W
-2.0d0   -0.3d0            ! betalogmin, betalogmax-logs
-2.0d0   -1.0d0   1.0d0    ! dmeanmin, dmeanmed, dmeanmax-logs of d in cm
0.1d0    1.0d0             ! dsigmamin, dsigmamax
0.8      2.5               ! ashdenmin, ashdenmax in g/cm3
-2.d0    -1.d0             ! ashrholow, ashrhohi
0.5d0                      ! fshape
0.001293d0 1.8d-04         ! airden in g/cm3, airvis in g/cm-s
400.d0                     ! c in cm2/s5/2
10.d0                      ! dmax in cm
0.01d0 0.1d0 1.d0          ! fdmin, fdmean, fdmax all in cm
0.001d0                    ! hmin in km
1.d-10d0                   ! acutoff in g/cm2
1.0d0                      ! rhocut-incorporable fuel size ratio cutoff
1.d7                       ! Uran- total mass of fuel in g
```

Table 4-1 gives short descriptions of the variables listed in the *ashplume.in* file shown above. When a single realization with user defined parameters is requested, the user is prompted to input values for: event duration, column height, beta, mean ash particle diameter, standard deviation of ash distribution (log-normal), rhocut, mass of fuel to incorporate, wind speed, wind direction, and initial eruption velocity. Parameters still taken from the *ashplume.in* file in this mode are: receptor location grid setup, air density and viscosity, fuel particle size characteristics, ash particle shape parameter (F), eddy diffusivity constant (c), maximum ash particle diameter for transport (dmax), and cutoff ash blanket density (acutoff). When the receptor grid locations include (0,0), the point will be skipped during execution since the model is not valid at the vent locations. More complete descriptions of the variables and derivations of the values is contained in section 4.2.

**Table 4-1.** ***Ashplume.in*** **file variable listing**

| Input Variable | Description |
|---|---|
| xmin, xmax | defines the range of distances from the modeled event in the x-direction (km) |
| ymin, ymax | defines the range of distances from the modeled event in the y-direction (km) |
| numptsx | identifies the number of receptor points calculated within the x-direction range |
| numptsy | identifies the number of receptor points calculated within the y-direction range |
| tlogmin, tlogmax | minimum and maximum values for the log of event duration (t in s) |
| powerlogmin, powerlogmax | minimum and maximum values for the log of event power (P in W) |
| betalogmin, betalogmax | minimum and maximum values for the log of beta |
| dmeanmin, dmeanmed, dmeanmax | minimum, mode, and maximum values for the log of mean ash particle diameter (d in cm) |
| dsigmamin, dsigmamax | minimum and maximum values for the log of ash particle standard deviation |
| ashdenmin, ashdenmax | minimum and maximum ash density values corresponding to ashrhohi and ashrholow ($g/cm^3$) |
| ashrholow, ashrhohi | minimum and maximum values of ash log-diameter for density calculation |
| fshape | particle shape factor |
| airden, airvis | air density (g/cc) and air viscosity (gm/cm-s) |
| c | constant relating eddy diffusivity to particle fall time ($cm^2/s^{5/2}$) |
| dmax | maximum particle diameter for transport (cm) |
| fdmin, fdmean, fdmax | minimum, mode, and maximum fuel particle log-diameters |
| hmin | minimum height on the eruption column considered during transport (km) |
| acutoff | threshold limit on ash accumulation; lower ash accumulations truncated to zero ($g/cm^2$) |
| rhocut | incorporation ratio |
| Uran | total mass of fuel available for incorporation (g) |

## 4.2 PARAMETER SAMPLING

### 4.2.1 Wind Speed and Direction

The wind velocity (speed and direction) is an important parameter for predicting the distribution of ash after a volcanic eruption. This report uses data found in the *Site Characterization Plan* (U.S. Department of Energy, 1988) to characterize the wind velocity distribution at YM. Furthermore, the cited report contains wind information at various altitudes. For simplicity, it is assumed the data for wind vectors at a height of 5,000 ft are sufficient to characterize the wind velocity to which the entire eruption column would be exposed.

The *Site Characterization Plan* shows the percent occurrences (1,922 total observations) of wind direction measured at 5,000 ft above the YM site. Direction is listed in 16 angles (e.g., NNW, SSW, ENE, etc.). In addition to the percent occurrences of wind direction, the *Site Characterization Plan* also presents the average wind speed as a function of direction. These data were summarized from Quiring (1968) and obtained from observations made from 1957 to 1964. These data form the basis of the Monte Carlo sampling of wind velocity for this report/user guide.

A uniform deviate ($r_1$) on [0,1] is drawn to stochastically determine the wind direction that a volcanic eruption column would experience at YM. Depending on the value of the wind direction, average wind speed in that direction is determined. Table 4-2 shows the relationship between the uniform deviate and the wind direction and average speed. The deviate range column is determined by fractional observations (of total observations) of the wind direction from the DOE (1988) where deviate range is the range of values that $r_1$ would have to be in to sample the given wind direction for a particular realization.

To calculate the wind speed, it is presumed wind speeds follow an exponential distribution. The exponential distribution is used as an approximation to the Weibull distribution recommended by Curtis and Eagleson (1982). The exponential distribution for wind speed is assumed to have a parameter $\lambda$ that is the inverse of the average wind speed from table 4-2. To Monte Carlo sample the wind speed given a particular direction, another uniform, random deviate ($r_2$) is drawn on [0,1]. The wind speed ($u$) in cm per s is given by

$$u = \frac{-\ln(1-r_2)}{\lambda(r_1)} \qquad (4\text{-}1)$$

#### 4.2.1.1 Eruption Parameters

A number of relationships exist in the literature that describe how eruption parameters are correlated. These correlations are described in this section. A key parameter for the Suzuki (1983) model is eruption column height, calculated from tephra mass-flow rate (Jarzemba, 1996). Original implementations of the model in Jarzemba (1996) and Jarzemba and LaPlante (1996) used preliminary tephra mass-flow rates. These rates have been examined in detail for analog basaltic volcanos and expanded to more accurately represent the mass-flow rates deduced for YMR volcanos. Measured column heights, eruption durations, and calculated tephra mass-flow rates for these analog volcanos are provided in table 4-3. Sources for observed data are Heimaey (Self et al., 1974), Paricutin (Luhr and Simkin, 1993), Tolbachik (Budnikov et al., 1983; Fedotov et al., 1983), Cerro Negro 1947 (McKnight, 1995),

Table 4-2. Range of uniform deviate corresponding to wind direction

| Wind Direction (Relation to due east-degrees) | Deviate Range | Average Wind Speed (cm/s) |
|---|---|---|
| E (0) | [0.000000 , 0.017804] | 320 |
| E by NE (22.5) | (0.017804 , 0.053412] | 450 |
| NE (45) | (0.053412 , 0.136498] | 670 |
| N by NE (67.5) | (0.136498 , 0.267058] | 720 |
| N (90) | (0.267058 , 0.376848] | 640 |
| N by NW (112.5) | (0.376848 , 0.430260] | 460 |
| NW (135) | (0.430260 , 0.460923] | 310 |
| W by NW (157.5) | (0.460923 , 0.482684] | 250 |
| W (180) | (0.482684 , 0.496532] | 240 |
| E by SE (-22.5) | (0.496532 , 0.523238] | 410 |
| SE (-45) | (0.523238 , 0.563792] | 470 |
| S by SE (-67.5) | (0.563792 , 0.635998] | 530 |
| S (-90) | (0.635998 , 0.776448] | 580 |
| S by SW (-112.5) | (0.776448 , 0.887228] | 540 |
| SW (-135) | (0.887228 , 0.953499] | 480 |
| W by SW (-157.5) | (0.953499 , 0.985151] | 340 |
| Calm (N/A) | (0.985151 , 1.000000] | 0.0 |

**Table 4-3. Observed column heights and eruption durations for nine basaltic volcanic eruptions analogous to YMR volcanoes**

| Observed | | | Calculated | | | | |
|---|---|---|---|---|---|---|---|
| | Column H (km) | Eruption duration (s) | Height H (km) | Power Q (W) | Magma density t (kg/m$^3$) | Tephra mass-flow v (m$^3$/s) | Magma temp T (°K) |
| Heimaey 1973 | 2 | $2.25\times10^6$ | 2.2 | $4.89\times10^9$ | 2600 | 2.3 | 1325 |
| Paricutin 1943 | 4–6 | $7.26\times10^6$ | 4.0 | $5.73\times10^{10}$ | 2530 | 26.6 | 1375 |
| Tolbachik Cone 1 | 6–10 | $1.21\times10^6$ | 4.8 | $1.14\times10^{11}$ | 2640 | 49.6 | 1400 |
| Tolbachik Cone 2 | 2–3 | $3.28\times10^6$ | 3.5 | $3.18\times10^{10}$ | 2610 | 14.0 | 1400 |
| Cerro Negro 1947 | 4–6.5 | $8.64\times10^5$ | 3.5 | $3.35\times10^{10}$ | 2600 | 15.9 | 1325 |
| Cerro Negro 1968 | 1–1.5 | $3.63\times10^6$ | 1.9 | $2.62\times10^9$ | 2600 | 1.2 | 1325 |
| Cerro Negro 1971 | 6 | $6.05\times10^5$ | 3.8 | $4.85\times10^{10}$ | 2600 | 23.0 | 1325 |
| Cerro Negro 1992 | 6.5 | $6.39\times10^4$ | 6.4 | $3.64\times10^{11}$ | 2600 | 172.1 | 1325 |
| Cerro Negro 1995 | 2 | $3.46\times10^5$ | 2.4 | $7.95\times10^9$ | 2600 | 3.8 | 1325 |

Cerro Negro 1968 (Viramonte and Di Scalia, 1970; Taylor and Stoiber, 1973), Cerro Negro 1971 (Viramonte et al., 1971; Rose et al., 1973), Cerro Negro 1992 (Connor et al., 1993; Hill, et al., 1996), and Cerro Negro 1995 (Hill, et al., 1996). These eruptions range in total magmatic volume from 0.01 km$^3$ (Cerro Negro 1995) to 0.9 km$^3$ (Paricutin). After correcting for erosion, Quaternary YMR volcanos range in total magmatic volume from 0.001 km$^3$ (Northern Cone) to 0.2 km$^3$ (Quaternary Crater Flat). Pliocene volcanos have estimated volumes up to at least 1 km$^3$. The historically active analog volcanos in table 4-3 thus represent the same scale of basaltic volcanic features as found in the YMR.

Considering the evidence presented in table 4-3, the log of the eruption duration (T, in seconds) was sampled uniformly over [4.80, 6.86]. The log of the eruption power (P, in watts) was sampled uniformly over [9.41,11.55]. Wilson et al. (1978) describes the following relationship between the volcanic power ($P$) and volcanic column height ($H$):

$$H = 0.0082P^{0.25} \tag{4-2}$$

where $H$ is in km and $P$ is in watts.

The literature also contains other volcanic parameter interrelationships. Assuming that the volcanic power has been determined by the means described previously, the mass ejection rate of material from the volcano ($\dot{Q}$) in g per sec is given in Walker et al. (1984) as

$$\dot{Q} = 1{,}000\left(\frac{H}{0.24}\right)^4 \tag{4-3}$$

and therefore

$$Q = \dot{Q}T \tag{4-4}$$

where $T$ is the event duration in seconds and it has been assumed that mass ejection rate is constant over duration of the event.

The eruption velocity at the vent exit ($W_0$) is given by

$$W_0 = \frac{\dot{Q}}{\psi_p \pi r_v^2} \tag{4-5}$$

where $r_v$ is the vent radius in cm. An expression for the volcanic vent radius is extracted from Wilson and Head (1981) to be

$$\log_{10}(r_v) = -0.069 + 2\log_{10}(\psi_p) + 0.274\log_{10}(\dot{Q}) \tag{4-6}$$

Equations (4-1) through (4-6) describe how to determine the important volcanic parameters for calculating ash distributions (and hence, spent fuel distributions) after a basaltic eruption is presumed to have occurred. These parameters are determined from Monte Carlo sampling that stochastically determines the volcanic energy and time duration from the stated ranges and distributions.

#### 4.2.1.2 Particle Properties

**Mean Particle Diameter ($d_m$)**

Suzuki (1983) gives a range of values for mean particle diameter that spans three orders of magnitude from 0.01 cm to 10 cm. In most Suzuki (1983) examples, 0.1 cm is used for the mean particle diameter. Data from another source (Walker et al., 1970) for the terminal fall velocity of pyroclasts would seem to suggest that the mean particle diameter is on the order of 0.1 cm. For these reasons, it is assumed that the $d_m$ for a volcanic event has a log-triangular distribution where the minimum common logarithm of $d_m$ is -2.0 and the maximum common logarithm of $d_m$ is 1.0. The mode value for the common logarithm of $d_m$ is inferred to be -1.0.

**Standard Deviation of the Mean Particle Diameter $(\sigma_d)$**

Suzuki (1983) uses a range for the standard deviation of the mean particle diameter of [0.1, 2.0]. It is assumed in this report that $\sigma_d$ follows a log-uniform distribution (as opposed to a strictly uniform distribution) where the common logarithm of $\sigma_d$ is distributed on the range [-1.0 , 0.3].

Constant Controlling Ash Dispersion $(\beta)$

Suzuki (1983) uses a range for this parameter of [0.01 , 0.5]. Since the parameter range spans more than one order of magnitude, a log-uniform distribution for $\beta$ is presumed. These particle properties, along with eruption and wind speed and direction parameters described previously, complete the set of information required for a given realization of radioactivity distribution after a volcanic eruption.

# 5 DESCRIPTION OF OUTPUT

## 5.1 ASHPLUME OUTPUT FILES

Two types of output files can be created during execution of the ASHPLUME code. The first type, the *ashplume.out* file, lists the input parameters for each individual volcano generated and the ash and fuel deposition densities for each location specified by the grid defined in the *ashplume.in* file. The second type of output file is created when requested by the user and consists of particle size distribution information. A separate file of this type is created for each location for ash and for spent fuel, for each event. Appendix B contains examples of both types. The filenames contain the type, location, and volcanic realization number (in order) for these files. For example, "ashhxm005yp010v001" denotes that the particle size contained in the file is for ashh at x equal to minus 005 km, y equal to plus 010 km for volcanic realization number 001.

## 5.2 ASHPLUME EXAMPLES

Two examples of the use of the ASHPLUME code are presented to illustrate its use. The first example demonstrates the user-input capability and the verification of the code by comparison with results found in Suzuki (1983). The second example is a stochastic simulation taken from Jarzemba (1996). A single event realization for this stochastic realization is also presented.

### 5.2.1 Example 1, User Input Case

This example illustrates the single event user input case and verifies the ASHPLUME code by comparison with results contained in Suzuki (1983). The input data set used for this case is presented in table 5-1.

Figure 5-1(a) demonstrates ASHPLUME code results using input listed in table 5-1. The data set in table 5-1 describes a volcanic eruption also investigated by Suzuki (1983). Figure 5-1(b) shows these same results as calculated by Suzuki (1983). This comparison does not show any added features of the code, but instead is shown to provide user confidence in the correctness of the code. Also, this comparison does not authenticate any of the subroutines that are used solely to calculate the fuel distribution after an event.

### 5.2.2 Example 2, Stochastic Simulation Case

Example 2 illustrates the ASHPLUME code used in the stochastic simulation mode. Figure 5-2 displays the ash distribution contours averaged over 200 realizations for a 140 km by 140 km square centered on the proposed repository. As one can see from figure 5-2, the ash contours (and hence, spent fuel contours) are not circular, meaning that the critical group may not necessarily be the group located nearest the repository (irrespective of direction), if only volcanism was considered as a release mechanism. These areas of elevated deposition (relative to areas of equal distance from the repository but in a different direction) would represent areas of elevated health risk to a postulated critical group from a basaltic eruption at YM. Table 5-2 shows properties used in example 2 that were deterministically chosen together with the source of the information. Stochastically chosen parameters were different for each realization of the multiple event example and are therefore not presented here.

**Table 5-1. Input parameter values for Example 1, User Input Case**

| Input Parameter | Value |
|---|---|
| Total ash mass (g) | $10^{15}$ |
| Column height (km) | 10 |
| Eruption velocity (cm/s) | $10^4$ |
| Mean particle diameter (cm) | 0.1 |
| Particle diameter standard deviation ($\sigma$) | 0.4 |
| Wind speed (cm/s) | $10^3$ |
| Event duration (s) | 331.785 |
| Initial eruption velocity (cm/s) | 10,000 |
| beta | variable (0.02, 0.1, 0.5) |
| Wind direction (degrees from due east) | -90 |
| rhocut | 1 |
| Uran | $10^7$ (any) |
| Ash density (g/cm$^3$) | 0.8 |
| Particle shape parameter | 0.5 |
| Air density (g/cm$^3$) | 0.001293 |
| Air viscosity (g/cm-s) | 0.00018 |
| Eddy diffusivity (cm$^2$/s$^{5/2}$) | 400 |

**Table 5-2. Deterministic parameter list**

| Parameter Description | Value | Source |
|---|---|---|
| Ash density (g/cc) | 0.8 | Suzuki (1983) |
| Shape factor | 0.5 | Suzuki (1983) |
| Air density (g/cm$^3$) | 0.00129 | Sears et al. (1983) |
| Air viscosity (g/cm-s) | 0.00018 | Sears et al. (1983) |
| C (cm$^2$/s$^{5/2}$) | 400 | Suzuki (1983) |

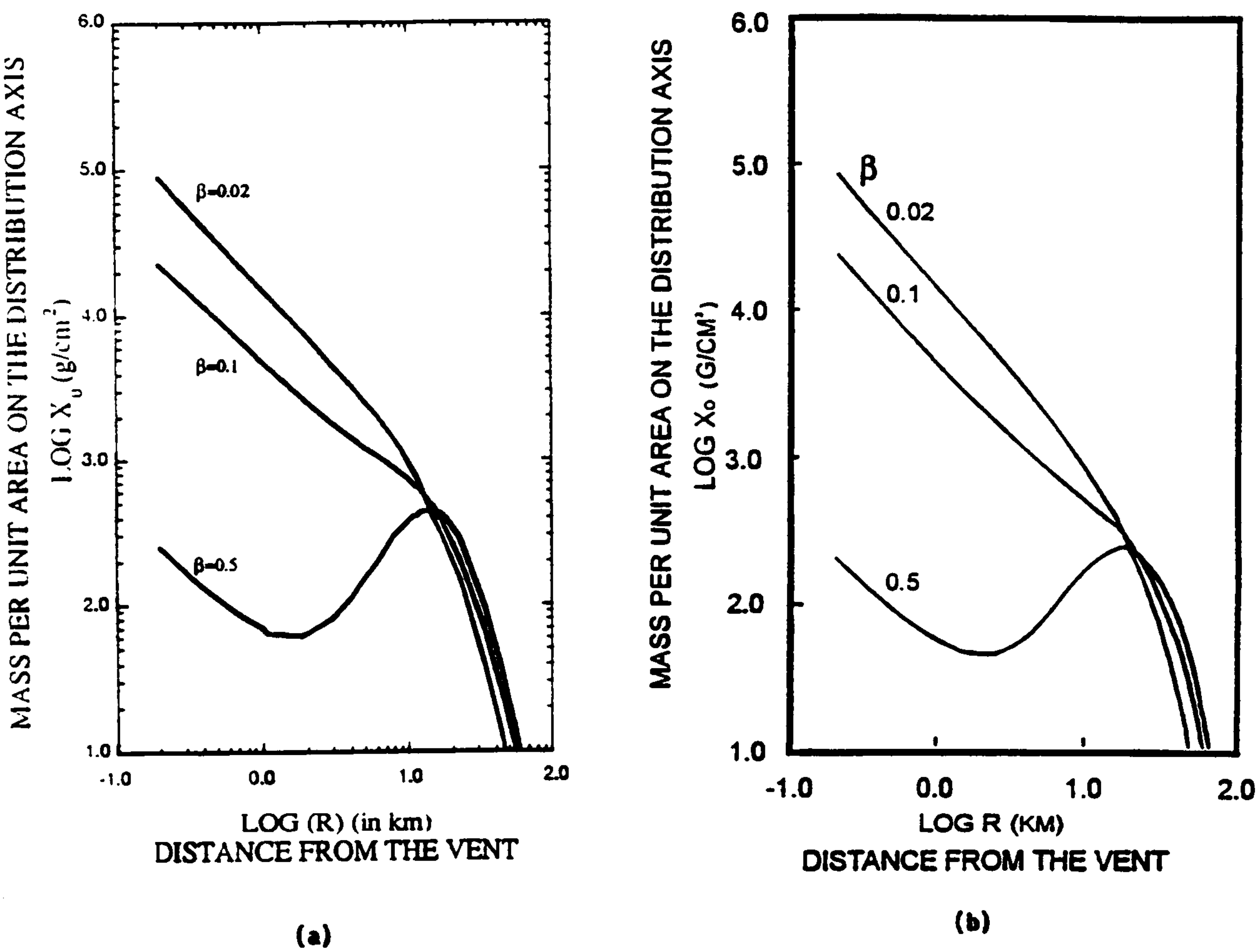


**Figure 5-1. Example 1, user input case as calculated by ASHPLUME (a), compared with the same case as calculated by Suzuki (1983) (b)**

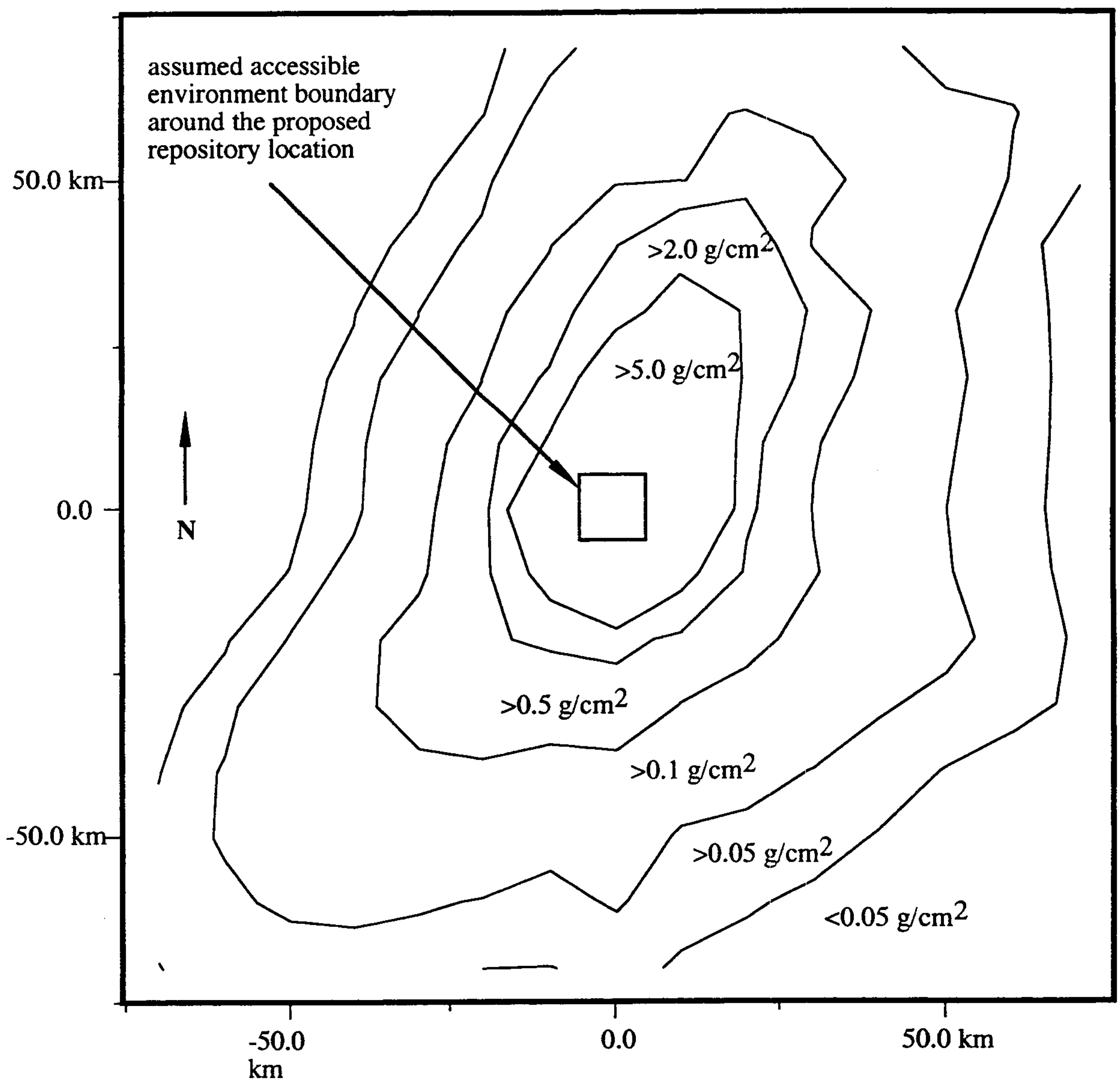


**Figure 5-2. Stochastic simulation example average ash distribution (200 realizations)**

An example isopleth map of the resulting areal density of spent fuel as a function of position for a single realization is provided in figure 5-3. The important simulation parameters sampled in the realization illustrated in figure 5-3 are presented in table 5-3, while the fuel fraction as a function of $\rho^a$ for this case is presented in figure 5-4. The volcanic parameters (and interrelationships) held constant in these analyses have been described previously or in other sections. These parameters include such constants as the particle shape parameter, air viscosity and density, and particle terminal velocity at sea level. Jarzemba and LaPlante (1996) use these results with information on the estimated radionuclide content of spent fuel to calculate radiation dose to receptors through a variety of exposure pathways.

**Table 5-3. Single realization sampled parameter list. The distributions are defined with the parameters shown in the *ashplume.in* file shown on p. 4-1 except where noted.**

| Parameter | Distribution Type | Sampled Value |
|---|---|---|
| Total volcanic ash mass (g) | see section 4 | $3.73 \times 10^{13}$ |
| Event durations (s) | Loguniform | $3.3 \times 10^{4}$ |
| Event power (W) | Lognormal | $8.23 \times 10^{11}$ |
| Column Height (km) | function of power | 7.809 |
| Mean particle diameter (cm) | Logtriangular | 0.068 |
| Standard deviation of particle log-diameter | Loguniform | 0.995 |
| Beta | Loguniform | 0.305 |
| Wind speed (cm/s) | Exponential | 832.4 |
| Wind direction (degrees-related to due east) | see section 4 | −112.5 |
| Mass of fuel ejected (g) | Constant | $10^{7}$ |
| Incorporation ratio | Constant | 1 |
| Minimum fuel log-diameter | Constant | −2 |
| Modal fuel log-diameter | Constant | −1 |
| Maximum fuel log-diameter | Constant | 0 |

## 5.3 CODE LIMITATIONS

Due to the inability of FORTRAN 77 to dynamically allocate computer memory, the ASHPLUME code has two limitations in the size of problems that it can execute. The first limit is that the number of grid locations in the x and y directions (numptsx and numptsy in the *ashplume.in* file) must be less than 500. The second limit is that the number of realizations when the code is run in stochastic mode must be less than 1,000. Another limitation of the code that is unrelated to the size of problems that can be run is that the problem title (located on the first line of the input file) must be less than 60 characters long.

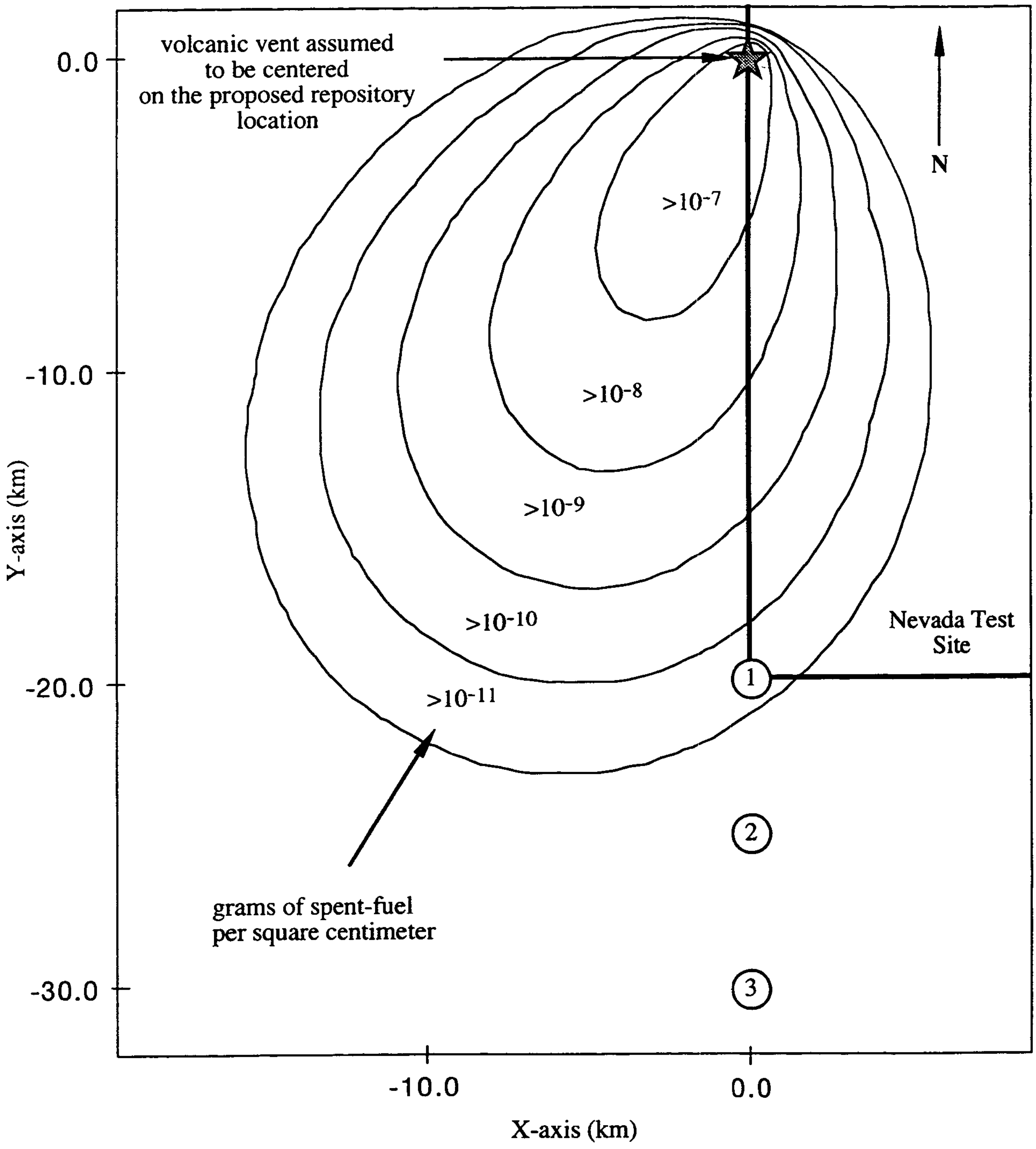


**Figure 5-3. Spent fuel isopleth map for a single event; all densities shown are in g of spent fuel/cm $^2$**

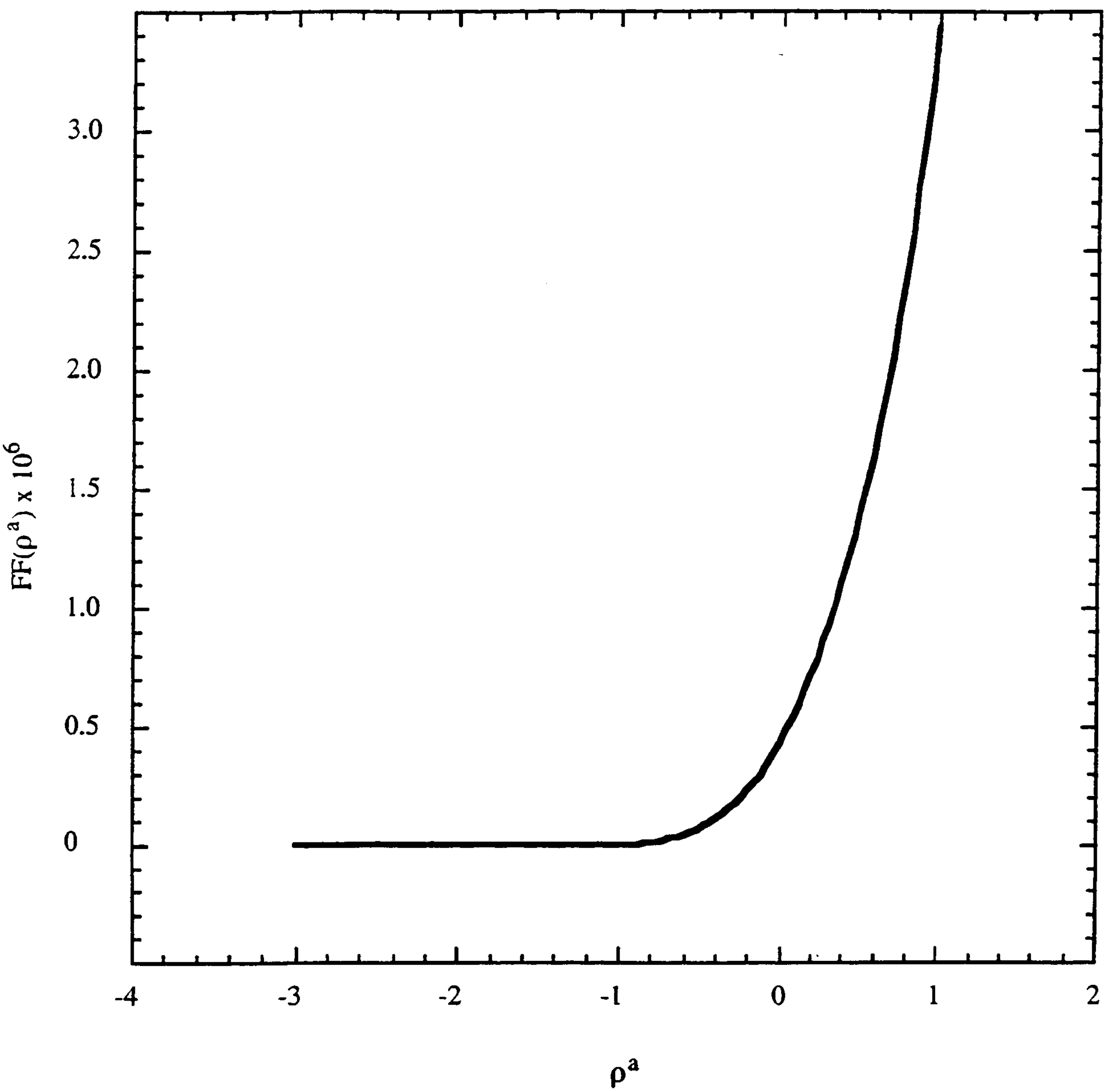


**Figure 5-4. Plot of normalized fuel fraction as function of $\rho^a$ for the single event realization shown in figure 5-3**

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# APPENDIX A

# EXAMPLE ASHPLUME CODE OUTPUT

```
iseed=          10
ASHPLUME Version 1.0
Example 1, User Input case with beta equal to 0.02
*********************************************************************
*                                                                   *
*                  realization number                    1          *
*                  wind speed (cm/s)             1000.0000          *
*                wind direction (deg)              -90.0000          *
*            mean particle diameter (cm)             0.1000          *
*                        log- std dev                0.4000          *
*                      column ht (km)               10.0000          *
*                  event duration (s)            0.3318E+06          *
*                        ash mass (g)            0.1000E+16          *
*                     event power (W)            0.2212E+13          *
*                                beta                0.0200          *
*             vent exit velocity (cm/s)          10000.0000          *
*               particle shape parameter             0.5000          *
*                  air density (g/cc)            0.1293E-02          *
*               air viscosity (g/cm-s)           0.1800E-03          *
*        eddy diff. constant (cm2/s5/2)            400.0000          *
*                    size cutoff (cm)               10.0000          *
*                  incorporation ratio               0.3000          *
*     fuel particle minimum log-diam                -2.0000          *
*      fuel particle median log-diam                -1.0000          *
*     fuel particle maximum log-diam                 0.0000          *
*          total fuel mass available (g)         0.1000E+08          *
*                                                                   *
*********************************************************************
```

| x (km) | y (km) | xash (g/cm^2) | xfuel (g/cm^2) |
|---|---|---|---|
| 0.000 | -1.000 | 0.1677E+05 | 0.2705E-03 |
| 0.000 | -2.000 | 0.7822E+04 | 0.1237E-03 |
| 0.000 | -3.000 | 0.4988E+04 | 0.7566E-04 |
| 0.000 | -4.000 | 0.3604E+04 | 0.5137E-04 |
| 0.000 | -5.000 | 0.2780E+04 | 0.3658E-04 |
| 0.000 | -6.000 | 0.2229E+04 | 0.2667E-04 |
| 0.000 | -7.000 | 0.1831E+04 | 0.1970E-04 |
| 0.000 | -8.000 | 0.1529E+04 | 0.1465E-04 |
| 0.000 | -9.000 | 0.1290E+04 | 0.1095E-04 |
| 0.000 | -10.000 | 0.1098E+04 | 0.8219E-05 |
| 0.000 | -11.000 | 0.9389E+03 | 0.6215E-05 |
| 0.000 | -12.000 | 0.8057E+03 | 0.4742E-05 |
| 0.000 | -13.000 | 0.6922E+03 | 0.3648E-05 |
| 0.000 | -14.000 | 0.5945E+03 | 0.2822E-05 |
| 0.000 | -15.000 | 0.5099E+03 | 0.2185E-05 |
| 0.000 | -16.000 | 0.4363E+03 | 0.1686E-05 |
| 0.000 | -17.000 | 0.3724E+03 | 0.1234E-05 |
| 0.000 | -18.000 | 0.3172E+03 | 0.9446E-06 |

| | | | |
|---|---|---|---|
| 0.000 | -21.000 | 0.1939E+03 | 0.4189E-06 |
| 0.000 | -22.000 | 0.1639E+03 | 0.3142E-06 |
| 0.000 | -23.000 | 0.1382E+03 | 0.2360E-06 |
| 0.000 | -24.000 | 0.1160E+03 | 0.1776E-06 |
| 0.000 | -25.000 | 0.9709E+02 | 0.1337E-06 |
| 0.000 | -26.000 | 0.8254E+02 | 0.1004E-06 |
| 0.000 | -27.000 | 0.6884E+02 | 0.7499E-07 |
| 0.000 | -28.000 | 0.5738E+02 | 0.5553E-07 |
| 0.000 | -29.000 | 0.4785E+02 | 0.4065E-07 |
| 0.000 | -30.000 | 0.3995E+02 | 0.2937E-07 |
| 0.000 | -31.000 | 0.3344E+02 | 0.2091E-07 |
| 0.000 | -32.000 | 0.2808E+02 | 0.1467E-07 |
| 0.000 | -33.000 | 0.2368E+02 | 0.1014E-07 |
| 0.000 | -34.000 | 0.2006E+02 | 0.6920E-08 |
| 0.000 | -35.000 | 0.1709E+02 | 0.4570E-08 |
| 0.000 | -36.000 | 0.1463E+02 | 0.3157E-08 |
| 0.000 | -37.000 | 0.1272E+02 | 0.2178E-08 |
| 0.000 | -38.000 | 0.1132E+02 | 0.1504E-08 |
| 0.000 | -39.000 | 0.1016E+02 | 0.1040E-08 |
| 0.000 | -40.000 | 0.9167E+01 | 0.7212E-09 |
| 0.000 | -41.000 | 0.8310E+01 | 0.5018E-09 |
| 0.000 | -42.000 | 0.6381E+01 | 0.3539E-09 |
| 0.000 | -43.000 | 0.5642E+01 | 0.2476E-09 |
| 0.000 | -44.000 | 0.5007E+01 | 0.1734E-09 |
| 0.000 | -45.000 | 0.4566E+01 | 0.1215E-09 |
| 0.000 | -46.000 | 0.4094E+01 | 0.8503E-10 |
| 0.000 | -47.000 | 0.3682E+01 | 0.5945E-10 |
| 0.000 | -48.000 | 0.3321E+01 | 0.4147E-10 |
| 0.000 | -49.000 | 0.3004E+01 | 0.2885E-10 |
| 0.000 | -50.000 | 0.2724E+01 | 0.2000E-10 |

The following *ashplume.in* file was used for calculating the above results.

```
Example 1, User Input case with beta equal to 0.02
0.d0  0.d0               ! xmin, xmax in km
-1.d0  -50.d0            ! ymin, ymax in km
1                        ! numptsx
50                       ! numptsy
4.80d0 6.86d0            ! tlogmin, tlogmax- logs of t in sec
9.41   11.55             ! powlogmin, powlogmax- logs of P in W
-2.0d0 -0.3d0            ! betalogmin, betalogmax-logs
-2.0d0 -1.0d0      1.0d0! dmeanmin, dmeanmed, dmeanmax-logs of d in cm
0.1d0  1.0d0             ! dsigmamin, dsigmamax
0.8    2.5               ! ashdenmin, ashdenmax in g/cm3
-2.d0  -1.d0             ! ashrholow, ashrhohi
0.5d0                    ! fshape
0.001293d0  1.8d-04      ! airden in g/cm3, airvis in g/cm-s
400.d0                   ! c in cm2/s to the 5/2
10.d0                    ! dmax in cm
0.01d0 0.1d0 1.d0        ! fdmin, fdmean, fdmax al in cm
0.001d0                  ! hmin in km
1.d-10d0                 ! acutoff in g/cm2
0.3d0                    ! rhocut-incorporation ratio
1.d7                     ! Uran- total mass of fuel in g
```

# APPENDIX B

# EXAMPLE PARTICULATE SIZE INFORMATION

File "ashhxp005yp010v0001". Note that the output variable is truncated to zero if it is less than the parameter acutoff located in the input file.

| rho | ash mass (g) |
|---|---|
| -4.96555 | 0.00000E+00 |
| -4.75984 | 0.00000E+00 |
| -4.55413 | 0.00000E+00 |
| -4.34842 | 0.00000E+00 |
| -4.14271 | 0.00000E+00 |
| -3.93700 | 0.00000E+00 |
| -3.73130 | 0.00000E+00 |
| -3.52559 | 0.00000E+00 |
| -3.31988 | 0.00000E+00 |
| -3.11417 | 0.00000E+00 |
| -2.90846 | 0.00000E+00 |
| -2.70275 | 0.00000E+00 |
| -2.49704 | 0.00000E+00 |
| -2.29134 | 0.00000E+00 |
| -2.08563 | 0.00000E+00 |
| -1.87992 | 0.00000E+00 |
| -1.67421 | 0.00000E+00 |
| -1.46850 | 0.16892E-02 |
| -1.26279 | 0.30730E-01 |
| -1.05708 | 0.13945E+00 |
| -0.85138 | 0.10622E+01 |
| -0.64567 | 0.63459E+01 |
| -0.43996 | 0.20275E+02 |
| -0.23425 | 0.32711E+02 |
| -0.02854 | 0.12896E+02 |
| 0.17717 | 0.31038E+00 |
| 0.38287 | 0.00000E+00 |
| 0.58858 | 0.00000E+00 |
| 0.79429 | 0.00000E+00 |
| 1.00000 | 0.00000E+00 |

EOF

File "fuelxp005yp010v0001"

| rho-f | fuel mass (g) |
|---|---|
| -2.3000 | 0.00000E+00 |
| -2.2310 | 0.45824E-05 |
| -2.1621 | 0.93579E-05 |
| -2.0931 | 0.14292E-04 |
| -2.0241 | 0.19093E-04 |
| -1.9552 | 0.24090E-04 |
| -1.8862 | 0.29974E-04 |
| -1.8172 | 0.36698E-04 |
| -1.7483 | 0.42405E-04 |

| | |
|---|---|
| -1.6793 | 0.47480E-04 |
| -1.6103 | 0.53094E-04 |
| -1.5414 | 0.59950E-04 |
| -1.4724 | 0.66931E-04 |
| -1.4034 | 0.76668E-04 |
| -1.3345 | 0.82676E-04 |
| -1.2655 | 0.83572E-04 |
| -1.1966 | 0.77597E-04 |
| -1.1276 | 0.71294E-04 |
| -1.0586 | 0.60293E-04 |
| -0.9897 | 0.50779E-04 |
| -0.9207 | 0.41205E-04 |
| -0.8517 | 0.28658E-04 |
| -0.7828 | 0.18083E-04 |
| -0.7138 | 0.10372E-04 |
| -0.6448 | 0.52472E-05 |
| -0.5759 | 0.22368E-05 |
| -0.5069 | 0.63134E-06 |
| -0.4379 | 0.70238E-07 |
| -0.3690 | 0.14698E-07 |
| -0.3000 | 0.00000E+00 |
| -0.2310 | 0.00000E+00 |

# APPENDIX C

# Software Requirements Description For ASHPLUME Consequence Module

1. **Functions to be performed:** The ASHPLUME consequence module is being developed to determine the concentration of spent fuel (in grams of spent fuel per $cm^2$) at points on the surface of the earth after an extrusive volcanic event penetrates the repository and exhumes spent fuel. This module is expected to be used in NRC IPA. Using published data for wind velocity at the YM site and the pertinent volcanic parameters of events similar to those that could be expected at YM in the future, The ASHPLUME consequence module simulates the transport of contaminated particles (composed of spent fuel and ash) to surface points downwind. The spent fuel concentration will be used to calculate the dose to members of the local population after the event has deposited the contaminated isopachs.

2. **Description of Technical Basis and Computational Approach:** The technical basis and computational approach for this module is described in:

   Jarzemba, M.S. 1996. *Stochastic Radionuclide Distributions After a Basaltic Eruption for Performance Assessments of Yucca Mountain.* Journal article submitted to Nuclear Technology.

3. **Initial Plan for Data Flow and User Interfaces:** The code will be designed to accept input data for parameter values and distributions from a file and will write the results of the calculations to an output file.

4. **Programming Language:** FORTRAN 77

5. **Hardware Platform:** Macintosh 8100/100 or UNIX workstations

6. **Graphics Output Devices:** None

7. **Pre- and Post- Processors:** The VOLCANO TPA consequence module may be used to generate the amount of waste to be distributed via this module. The results of the calculations will be used by the TPA consequence modules ASHREMOVE and DCAGS.

8. **Mathematical Model, Control Flow, Data Flow, Control Logic and Data Structure:** Unknown at this time.

CNWRA 97-004

ASHPLUME VERSION 1.0 – A CODE FOR CONTAMINATED ASH DISPERSAL AND DEPOSITION

TECHNICAL DESCRIPTION AND USER'S GUIDE