OCRWM

MODEL COVER SHEET

1. QA: QA

Page 1 of 121

2. Type of Mathematical Model

Process Model

Abstraction Model

System Model

Describe Intended Use of Model

The purpose of this model report is to provide documentation of a conceptual and mathematical model (ASHPLUME) for atmospheric dispersal and deposition of tephra from a potential volcanic eruption at Yucca Mountain, Nevada.

3. Title

Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada

4. DI (including Rev. No. and Change No., if applicable):

MDL-MGR-GS-000002, REV 00

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ACRONYMS AND ABBREVIATIONS

ACM	alternative conceptual model
BDCF	biosphere dose conversion factor
BSC	Bechtel SAIC Company
cm	centimeter
CDF	cumulative distribution function
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
DE	Disruptive Events
DIRS	Document Input Reference System
DLL	Dynamic Linked Library
DOE	U.S. Department of Energy
DTN	data tracking number
FEPs	features, events, and processes
FY	fiscal year
g	gram
IA	igneous activity
kg	kilogram
km	kilometer
kPa	kilopascal
KTI	key technical issue
m	meter
mb	millibar
mm	millimeter
N/A	not applicable
NOAA	National Oceanic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission
OCRWM	Office of Civilian Radioactive Waste Management
PDF	probability distribution function
PVHA	Probabilistic Volcanic Hazard Analysis
QA	quality assurance
QARD	Quality Assurance Requirements and Description
RAI	request for additional information
RMEI	reasonably maximally exposed individual

ACRONYMS AND ABBREVIATIONS (Continued)

s	second
SCM	Software Configuration Management
STN	software tracking number
TDMS	Technical Data Management System
TSPA	Total System Performance Assessment
TSPA-LA	Total System Performance Assessment for the License Application
TSPA-SR	Total System Performance Assessment for the Site Recommendation
TWP	technical work plan
V	version
YMP	Yucca Mountain Project
YMR	Yucca Mountain region
YMRP	Yucca Mountain Review Plan
2-D	two dimensional
μm	micrometer

1. PURPOSE

The purpose of this model report is to provide documentation of the conceptual and mathematical model (ASHPLUME) for atmospheric dispersal and subsequent deposition of ash on the land surface from a potential volcanic eruption at Yucca Mountain, Nevada. This report also documents the ash (tephra) redistribution conceptual model. The ASHPLUME conceptual model accounts for incorporation and entrainment of waste fuel particles associated with a hypothetical volcanic eruption through the Yucca Mountain repository and downwind transport of contaminated tephra. The ASHPLUME mathematical model describes the conceptual model in mathematical terms to allow for prediction of radioactive waste/ash deposition on the ground surface given that the hypothetical eruptive event occurs. This model report also describes the conceptual model for tephra redistribution from a basaltic cinder cone. Sensitivity analyses and model validation activities for the ash dispersal and redistribution models are also presented. Analyses documented in this model report will improve and clarify the previous documentation of the ASHPLUME mathematical model and its application to the Total System Performance Assessment (TSPA) for the License Application (TSPA-LA) igneous scenarios. This model report also documents the redistribution model product outputs based on analyses to support the conceptual model.

The ASHPLUME mathematical model is implemented for TSPA calculations by the computer code ASHPLUME_DLL_LA Version (V) 2.0 (BSC 2003, software tracking number (STN): 11117-2.0-00 [166571], hereafter referred to as ASHPLUME_DLL_LA in this document). The ASHPLUME_DLL_LA computer code is a component of the TSPA model of the nuclear waste repository at Yucca Mountain. The TSPA model is used to evaluate the performance of the geologic repository in protecting humans and the environment from the risk associated with exposure to spent nuclear fuel and high-level radioactive waste. Within the TSPA, the atmospheric dispersal and deposition of tephra model implemented in the ASHPLUME code is used to predict the ground-level concentration or areal density (g/cm^2) of ash and waste after a violent Strombolian eruption that intersects the repository. The waste concentration is then combined with biosphere dose conversion factors (BDCFs) to calculate a radioactive dose to a reasonably maximally exposed individual (RMEI). The ash redistribution conceptual model describes the sedimentary processes acting on the tephra sheet after deposition. The concentrations of contaminated ash from sedimentary processes that could redistribute contaminated ash at the RMEI location (18 km south of the repository (40 CFR Part 197 [155216])) are calculated for different ash-fall deposition realizations. The model is based on several site-specific investigations, including analog studies of ash redistribution and erosional and depositional processes inferred from an analysis of cesium- (Cs) 137 data (BSC 2003 [166407]).

1.1 SCOPE OF WORK

The scope of this report is limited to descriptions of models for atmospheric dispersal of contaminated tephra after a violent Strombolian eruption of the type that could occur in the Yucca Mountain region (YMR) (BSC 2003 [166407], Section 6.3) and for redistribution of the contaminated tephra after the volcanic eruption. If such an eruption were to intersect the repository, the possibility exists for wastes to become entrained in the eruptive mixture and be transported via the same mechanisms as the ash plume. Although other eruption types that

include nonviolent as well as violent phases exist, the violent Strombolian eruption has the greatest potential to erupt ash and waste particles higher into the atmosphere, thus increasing the potential distance of dispersal (BSC 2003 [166407]).

Figure 1 is a schematic representation of a possible future volcanic eruption at Yucca Mountain, showing transport of radioactive waste in an ash plume. In Figure 1, the scope of the ASHPLUME conceptual model includes only the eruptive ash plume, convective/dispersive transport of contaminated ash particles downwind, and deposition on the ground surface. The ASHPLUME mathematical model may be used to evaluate ash and waste concentration (areal density) at any one point or multiple points on the surface relative to the volcanic vent. The ash redistribution conceptual model is used to describe the erosion and subsequent deposition of contaminated ash. The north-south orientation and 18-km distance shown in Figure 1 are for illustration purposes only.

For illustration purposes only
Source: Modified from CRWMS M&O (2000 [153246], Figure 3.10-5)

Figure 1. Schematic Representation of a Volcanic Eruption at Yucca Mountain, Showing Transport of Radioactive Waste in an Ash Plume

1.2 BACKGROUND

The following sections discuss both the ash dispersal model used for past Yucca Mountain TSPA analyses and the ash redistribution conceptual model and present the objectives of this report as defined by the *Technical Work Plan: Igneous Activity Assessment for Disruptive Events*, TWP-WIS-MD-000007 REV 04 (BSC 2003 [166289]) for this activity.

1.2.1 Previous Use and Documentation

The ASHPLUME V 1.0 computer code (Jarzemba et al. 1997 [100987]) implements the mathematical model of atmospheric dispersal and deposition of tephra of Suzuki (1983 [100489]) for estimation of the areal density of tephra deposits on the surface of the Earth following a volcanic eruption. The code includes estimation of the areal density of spent fuel particles incorporated into tephra particles due to a volcanic event that intersects the repository.

For the Total System Performance Assessment for the Site Recommendation (TSPA-SR) (CRWMS M&O 2000 [153246]), the original Jarzemba et al. (1997 [100987]) ASHPLUME V 1.0 code was modified to incorporate eruptive parameters developed from natural analog volcanoes that would be representative of any future volcanic event in the YMR. This modified version of the code, known as ASHPLUME V 1.4LV-dll (CRWMS M&O 2000, STN: 10022-1.4LV-dll-00 [154748], hereafter referred to as ASHPLUME V 1.4LV-dll in this document), was used as a component of the TSPA-SR model and was incorporated as a dynamically linked library (DLL) directly within the TSPA-SR model. For current work, it is proposed to use ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) for calculations within the TSPA-LA. As described below, ASHPLUME_DLL_LA V 2.0 is essentially the same as previous versions of the code but employs a modified set of input parameters that are based on those data analyzed within the revision to the scientific analysis report *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002, (BSC 2003 [166407]).

The main difference between ASHPLUME V 1.4LV (BSC 2002, STN: 10022-1.4LV-02 [161296], hereafter referred to as ASHPLUME V 1.4LV in this document) and ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) lies in the formulation of eruption column height. ASHPLUME V 1.4LV uses an empirical relationship between volume and column height that was determined to be less accurate than the use of eruptive power to calculate mass discharge rate and, subsequently, column height (as is implemented in ASHPLUME_DLL_LA V 2.0). This new version of the code (ASHPLUME_DLL_LA V 2.0) is more consistent with the state of practice among volcanologists. A form of ASHPLUME V 2.0 compiled for use on the Windows NT 4.0 platform was used for the model validation and sensitivity studies presented in Section 7; this form of the code differs insignificantly from ASHPLUME_DLL_LA V 2.0, which has been compiled to run on the Windows 2000 platform for TSPA. The change in the code from V 1.4 to V 2.0 produces slightly higher calculated column heights than in ASHPLUME V 1.4LV (CRWMS M&O 2000 [152998]), and, therefore, a new set of wind data collected at Desert Rock (near Mercury, Nevada) (National Oceanic and Atmospheric Administration {NOAA} 1995 [154435]) was used to calculate wind speed and direction up to a height of 13 km. This data set replaces the Nevada Test Site (NTS) data (Quiring 1968 [119317]) that were used for the TSPA-SR (CRWMS M&O 2000 [153246]).

Parameterization for the atmospheric dispersal model used in all ASHPLUME versions was documented in BSC (2001 [157876], Section 6.1.2). A comparison of tephra deposit thicknesses, which was simulated using ASHPLUME V 1.4LV (STN: 10022-1.4LV-02 [161296]) and ASHPLUME V 2.0 (CRWMS M&O 2001, STN: 10022-2.0-00 [152844], hereafter referred to as ASHPLUME V 2.0 in this document), with actual tephra deposit thicknesses from the 1995 eruptive event at the Cerro Negro volcano in Nicaragua was documented in CRWMS M&O (2000 [152998]). The purpose of this model report is to

consolidate and update documentation of the ASHPLUME conceptual and mathematical models, including parameterization and validation for ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]).

It should be noted that the ash redistribution conceptual model is new and was not used in the TSPA-SR; however, output from analyses supporting this model will be used in the TSPA-LA.

1.2.2 Technical Work Plan

This model report is governed by the *Technical Work Plan: Igneous Activity Assessment for Disruptive Events*, TWP-WIS-MD-000007 REV 04 (BSC 2003 [166289]), Work Package ADEM03. The technical work plan (TWP) specifies the activities to be carried out in consolidating and updating the documentation of the ASHPLUME conceptual and mathematical models. Specifically, the TWP calls for the following activities.

- Provide documentation of the atmospheric dispersal and tephra distribution conceptual model and the mathematical model employed by ASHPLUME to implement the conceptual model.
- Compare the ASHPLUME mathematical model with other ash/waste dispersal models found in the literature.
- Develop an improved technical basis for ASHPLUME model parameter values and distributions.
- Validate the ASHPLUME mathematical model and the ash redistribution conceptual model according to the model validation plan listed in Appendix C of the TWP.
- To the extent possible, use natural analogs similar to that of the Lathrop Wells volcanic center to corroborate outputs from the ASHPLUME mathematical model and the ash redistribution conceptual model. Use the analogs to calibrate the model's application to the Yucca Mountain region.
- Determine whether the currently used values or distribution of values for model parameters are appropriate as inputs to the ASHPLUME mathematical model, and develop updated parameter values/distributions as appropriate.
- Conduct sensitivity analyses to determine the relative importance of specific parameters to the calculation of ash/waste distribution.
- Assess the impact to erupted ash/waste deposition at the RMEI location due to the conceptualization of magma/waste form interaction (i.e., the ash/waste particle incorporation ratio).
- Develop a conceptual model for ash/sediment redistribution in the Yucca Mountain region based on field work completed and documented in the analysis report *Characterize Eruptive Processes at Yucca Mountain, Nevada*, REV 01 (BSC 2003 [166407]).

- Abstract the conceptual model to provide input to the TSPA model. This abstraction of the conceptual model will support the TSPA-LA analysis of the accretion/erosion processes to improve/reassess parameter distribution for the source term connected to ash/sediment redistribution.
- Develop a mathematical model of the Fortymile Wash drainage basin to represent erosional and depositional processes as they would relate to ash redistribution from a tephra sheet being located within that drainage system.
- Compare the models developed in this report with alternative models.

The ASHPLUME code was not used to quantitatively assess the sensitivity of the erupted ash/waste distributions due to the conceptualization of the magma/waste form interaction and the ash/waste particle incorporation ratio. However, these effects are assessed in the assumptions and model conceptualization sections (Sections 5.1.2, 5.2.3, 6.3, and 6.5.1).

1.3 MODEL LIMITATIONS

A mathematical model is generally considered to be a mathematical description of a conceptual model that approximates the behavior of a system, process, or phenomenon with determinable limits of uncertainty. The ASHPLUME mathematical model is an approximation of the physical systems involved in the atmospheric dispersal and deposition of contaminated tephra (ash and waste particles) associated with a possible future volcanic eruption through the repository at Yucca Mountain. Limitations inherent in all mathematical representations of complex geologic processes include: (1) incomplete knowledge of details of a highly complex and heterogeneous natural process involving localized regions of the Earth's crust; (2) use of a mathematical representation that approximates, but does not specifically represent, every detail of the process; and (3) lack of comprehensive data describing every aspect of the complex, heterogeneous geologic natural process being represented. As a result of these limitations, the model provides predictive capability but does not provide an exact representation of the process.

The ASHPLUME model for Yucca Mountain is based on a model of Suzuki (1983 [100489]) that Jarzemba et al. (1997 [100987]) refined to represent violent Strombolian-type eruptions. Strombolian eruption involves ejection of magma into the atmosphere as a ballistic fountain of cm-sized scoria fragments from which μm - and mm-size ash is elutriated in a rising convective plume above the fountain. Whereas the fountain develops a cone of potentially contaminated scoria around the vent orifice, the convective plume provides a source for distal transport of potentially contaminated ash downwind over a wide area. Fallout of ash from the plume forms a ground layer that generally thins with distance from the vent and is subject to redistribution by wind and water erosion. The Strombolian-type eruption is considered to be the most typical of the type of eruption possible in the YMR (BSC 2003 [166407]). A Strombolian eruption includes violent phases as well as phases that are less violent, in which more effusive eruption dominates (BSC 2003 [166407], Section 6.3.3). With increasing violence of a Strombolian eruption, a larger fraction of the magma is fragmented to ash sizes, and a greater proportion of the magma contributes to the convective plume. The ASHPLUME model is limited to representation of the convective plume only and, thus, best models violent Strombolian eruptions.

The ASHPLUME model solves diffusive transport (by atmospheric turbulence and wind) of particles distributed in a column (plume) of a height determined by the heat flux (power) of the column source. The duration of this transport for individual particles is the fallout time for particles governed by their terminal fall velocity (a function of their specific size, density, and shape factor) and their rise velocity in the plume. One limitation of the model is that ASHPLUME assumes a linear decrease in the plume's rise velocity from its initial rise velocity at the vent to zero at the top of the plume, but a buoyancy-driven velocity profile is not calculated. In addition, the plume's initial rise velocity is not known and must be calculated as a function of the eruptive power and vent radius.

Another limitation of the ASHPLUME model is its ability to represent accurately the transport of ash particles of mean diameter less than approximately 15 micrometers (μm) (Jarzemba et al. 1997 [100987], Section 2.1). This cutoff in mean particle diameter is generally accepted to be the lower limit for the importance of gravitational settling. For particle sizes less than about 15 μm , atmospheric turbulence would tend to keep the particles aloft longer than would be predicted by the model. Because the typical mean diameter of ash particles after an eruption is generally much larger than 15 μm (see Section 6.5.2.4), the model described here is applicable to calculating the distribution of the majority of potential ash and radionuclide releases from a possible future eruption at Yucca Mountain.

The ASHPLUME mathematical model uses the simplification that wind speed is assumed to be constant throughout the atmospheric column. This assumption is discussed further in Section 5. This limitation is accommodated within the TSPA models by treating wind speed as an uncertain parameter. In addition, wind-speed data are taken from the upper altitudes reached by the ash plume where the majority of ash is dispersed from the eruptive column of a violent Strombolian eruption. The full range of wind speeds from near zero to the maximum winds observed at the higher altitudes is represented in the wind-speed distribution used in the TSPA-LA analyses. This stochastic treatment of wind speed produces a mean result in ash deposition that captures the uncertainty that exists in future wind speeds at all altitudes of the vertical eruptive column. Wind direction and wind speed are treated in a similar manner within the TSPA implementation of the dispersion model. The mathematical model limits wind direction to a single value for a given realization of the model. However, in the TSPA, wind direction is also treated stochastically so that the distribution of wind directions reflects the wind directions actually observed near the Yucca Mountain site.

The final limitation of the ASHPLUME model is its sensitivity to eruptive power and initial rise velocity, which are, in turn, functions of total erupted volume and duration. These parameters (power and initial rise velocity) are uncertain. A previous version of ASHPLUME (V 1.4LV-dll, STN 10022-1.4LV-dll-00 [154748]) calculated these parameters from the theoretical relationship of conduit radius to magma ascent velocity given by Wilson and Head (1981 [101034], p. 2977), and, in that version, the initial rise velocity was termed as the "eruption velocity at the vent." Because the actual eruption velocity at the vent in Strombolian eruptions is also a function of magma volatile content and the initial plume rise velocity is only weakly linked to eruption velocity, the previous relationship is not valid. The current version of ASHPLUME (ASHPLUME_DLL_LA V 2.0, (STN: 11117-2.0-00 [166571]) must assume a conservative condition in which all the magma is fragmented and enters the convective plume (violent Strombolian) such that the initial plume rise velocity can be derived using the relationship

between power, duration, and conduit diameter. This relationship is defined in Section 6.5.1, Equation 7, and the derivation of the initial rise velocity is discussed specifically in Section 6.5.2.10.

In spite of these limitations, the ASHPLUME model is considered to be appropriate, although conservative, for the analysis of the volcanic direct release scenario because the model includes those parameters that apply specifically to conditions of maximum entrainment of contaminated ash in an eruption column, dispersal of that ash downwind, and deposition of the ash at specified locations on the Earth's surface. The appropriateness of the model and the development of specific parameters are explained in detail in Section 6.

The conceptual model of tephra redistribution following a hypothetical eruption at Yucca Mountain does not have a mathematical basis. However, simple calculations were completed to provide an abstraction of that conceptual model for use in the TSPA-LA. The ash redistribution conceptual model describes surficial processes that modify and distribute tephra that has been deposited from a hypothetical volcanic eruption at Yucca Mountain. This model is described in Section 6.6. The abstraction of this model (Section 6.7) is considered to be adequate for inclusion in the TSPA model.

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2. QUALITY ASSURANCE

The modeling activities documented in this model report were performed with no variances to work described in the TWP (BSC 2003 [166289]). Development of this model report and the supporting activities have been determined to be subject to the Yucca Mountain Project (YMP) quality assurance (QA) program (BSC 2003 [166289], Section 8.1), Work Package ADEM03. Approved QA procedures identified in the TWP (BSC 2003 [166289], Section 4) have been used to conduct and document the activities described in this model report. The TWP also identifies the methods used to control the electronic management of data (BSC 2003 [166289], Section 8.4).

This report documents a conceptual and mathematical model of atmospheric dispersal and subsequent deposition of contaminated tephra from a potential volcanic eruption at Yucca Mountain and a conceptual model for subsequent redistribution of tephra by surficial processes. Therefore, it is classified in the *Q-List* (BSC 2003 [165179]) as Safety Category 1 because of its importance to waste isolation, as defined in AP-2.22Q, *Classification Analyses and Maintenance of the Q-List*. The results of this report are important to the demonstration of compliance with the post-closure performance objectives prescribed in 10 CFR 63.113 [156605]. This report contributes to the analysis and modeling data used to support performance assessment; the conclusions do not directly impact engineered features important to safety, as defined in AP-2.22Q.

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3. USE OF SOFTWARE

3.1 SOFTWARE TRACKED BY CONFIGURATION MANAGEMENT

The sequence of versions showing the evolution of the ASHPLUME software is provided in Table 1a. ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) was used for the calculation of initial ash/fuel concentrations, which are described in Section 6.7 of this model report. ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) is the version used in this model report for the validation activities in Section 7. Both versions were obtained from Software Configuration Management (SCM) and are appropriate for each application. Also, GoldSim V 8.01 SP1 (Golder Associates 2003, STN: 10344-8.01SP1-00 [166572], hereafter referred to as GoldSim V 8.01 SP1 in this document) was used (Table 1b) to estimate the mean concentrations of radioactive waste in the tephra sheet at 18 km from a hypothetical vent (Section 6.7.1 and Attachment IV). These qualified codes were used only within the range of validation as required by AP-SI.1Q, *Software Management*.

Table 1a. ASHPLUME Computer Software

Software Title/Version (V)	Software Tracking Number (STN)	Code Usage	Computer: Type, Platform, and Location
ASHPLUME V 1.0	* N/A	Not used in this model report. This is the original Jarzemba et al. (1997 [100987]) version of the ASHPLUME code.	Multi-platform Unix operating systems
ASHPLUME V 1.3	* N/A	Not used in this model report. This version was used for initial scoping calculations for the TSPA-Viability Assessment (CRWMS M&O 1998 [100369], Section 10.4.2.7).	Multi-platform Unix operating systems
ASHPLUME V 1.4LV-dll	10022-1.4LV-dll-00	Not used in this model report. This version of the software was a component of the TSPA-SR model.	PC, Windows NT TSPA computing cluster – BSC Summerlin facilities, Las Vegas, NV
ASHPLUME V 1.4LV	10022-1.4LV-00	Not used in this model report. This implementation of V 1.4LV is designed to run on the SUN platform under a Unix operating system.	Sun Unix
ASHPLUME V 1.4LV	10022-1.4LV-02	Not used in this model report. This implementation of V 1.4LV is designed to run on the PC Windows platform.	PC, Windows 2000/NT, 4.0/98 Framatome-ANP Austin, TX
ASHPLUME V 2.0	10022-2.0-00	This version is used in validation studies as described in Section 7.3.1 of this report.	PC, Windows NT 4.0
ASHPLUME_DLL_LA V 2.0	11117-2.0-00	This version is used for TSPA-LA calculations and calculation of initial ash/fuel areal concentrations for the ash redistribution conceptual model described in Section 6.7. Parameterization developed in this model report will directly feed this version of the software for TSPA-LA usage.	PC, Windows 2000

NOTE: * Early versions of the code; not subject to baseline requirements.

Table 1b. Other Software Used in This Model Report

Software Title/Version (V)	Software Tracking Number (STN)	Code Usage	Computer: Type, Platform, and Location
GoldSim V 8.01 Service Pack 1	10344-8.01SP1-00	In conjunction with ASHPLUME_DLL_LA V 2.0, this software was used for probabilistic simulations (Section 6.7.1 and Attachment IV).	PC, Windows 2000

3.2 EXEMPT SOFTWARE

Commercial, off-the-shelf software used in support of this model report is listed in Table 2. This software is exempt from the requirements of AP-SI.1Q, *Software Management*.

Table 2. Exempt Software

Software Name and Version (V)	Description	Computer and Platform Identification
Microsoft Excel, 2000	The commercial software, Microsoft Excel 2000, was used for plotting graphs and statistical calculations. Only built-in standard functions in this software were used. No software routines or macros were used with this software to prepare this report.	PC, Windows 2000/NT
Microsoft Access, 2000	The commercial software, Microsoft Access 2000, was used for unit conversions and data segregation. Only built-in standard query functions in this software were used. No software routines or macros were used with this software to prepare this report.	PC, Windows 2000

4. INPUTS

4.1 DATA, PARAMETERS, AND OTHER MODEL INPUTS

This section discusses data, parameters, and inputs to the modeling activities that are documented in this report.

4.1.1 Data

Data sources providing input for the development of parameters used as input to the ASHPLUME model documented in this report are listed in Table 3. These data are used to develop primary model inputs as described in Section 6.5.2. Ash physical characteristics required as inputs to the ASHPLUME model are developed in the scientific analysis report, *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002 REV 01 (BSC 2003 [166407]). The latter report provides information about natural volcanic systems and the parameters that can be used to model their behavior and is appropriate for use as input to the ash dispersion model documented in this report.

The wind speed cumulative distribution functions (CDFs) and wind direction probability distribution functions (PDFs) appropriate for use in modeling a potential future volcanic eruption in the YMR are developed in this model report from data provided in NOAA (1995 [154435]). The development of the CDFs and PDFs from the raw climatological data is described in Sections 6.5.2.7 and 6.5.2.8.

The waste-particle-size distribution used as input to this model report is provided in the report, *Miscellaneous Waste-Form FEPs*, ANL-WIS-MD-000009 (CRWMS M&O 2001 [153938]).

Air physical characteristics are taken from the *CRC Handbook of Chemistry and Physics* (Lide 1994 [147834]).

Data sources providing input for the development of parameters used in the ash redistribution conceptual model documented in this report are identified in Table 4. These data provide the technical basis for the bounding model described in Section 6.7.2.

The qualification status of the input sources is provided in the Technical Data Management System (TDMS) and listed in the Document Input Reference System (DIRS) database.

Table 3. Primary Data Supporting the Development of Input Parameter Values for the ASHPLUME Model

Data Description	Source	Data Tracking Number (DTN)
Eruptive volume and eruptive duration for the Lathrop Wells cinder cone	BSC (2003 [166407], Table 38)	LA0311DK831811.001 [166301]
Ash settled density (“tephra deposit density”)	BSC (2003 [166407], Table 38)	LA0311DK831811.001 [166301]
Basaltic magma density	BSC (2003 [166407], Table 38)	LA0311DK831811.001 [166301]
Conduit diameter (eruptive vent diameter)	BSC (2003 [166407], Table 38)	LA0311DK831811.001 [166301]
Clast characteristics (ash particle shape factor)	BSC (2003 [166407], Table 38)	LA0311DK831811.001 [166301]
Specific heat capacity of magma	Bacon (1977 [165512]); Drury (1987 [156447])	Technical Information
Median number of waste packages calculated to be hit by a magmatic conduit	BSC (2003 [161851])	SN0311T0503303.003 [166297]
Wind speed and wind direction	NOAA (1995 [154435])	Technical Information
Waste particle size	CRWMS M&O (2001 [153938])	LL001104412241.019 [155224]
Air physical characteristics (air viscosity and air density)	Lide (1994 [147834])	Technical Information
Incorporation ratio	Jarzemba et al. (1997 [100987])	Technical Information
Eddy diffusivity	Suzuki (1983 [100489]); Jarzemba et. al. (1997 [100987])	Technical Information
Eruptive mass flux	Detournay et al. (2003 [162914])	Technical Information

Table 4. Site-Specific Data Supporting the Ash Redistribution Conceptual Model

Data Description	Source	Data Tracking Number (DTN)
Ash weight percentages in samples of drainage channels near the Lathrop Wells cone	Harrington (2003 [164775])	LA0310CH831811.001 [164852]
Cesium-137 values for the Fortymile Wash alluvial fan	Harrington (2003 [164775])	LA0308CH831811.002 [164853]

4.1.2 Parameters and Parameter Uncertainty

The TSPA model, of which ASHPLUME is a component, uses Monte Carlo simulation as a method for mapping uncertainty in model parameters and future system states, expressed as probability distributions, into predictions of model output (CRWMS M&O 2000 [153246], Section 2.2.4). Large uncertainties exist in ASHPLUME model input parameters due to the uncertainty of future atmospheric conditions at the time of the hypothetical eruption and uncertainty in the characterization of the physical attributes of a future eruption. ASHPLUME model parameters that contain uncertainty and may significantly affect the outcome of TSPA calculations are developed in this model report as probability distributions for compatibility with the Monte Carlo methods used in the TSPA model.

Development of parameters used in the ASHPLUME model is documented in Section 6.5.2 of this report. Sampled parameters used in the ash redistribution conceptual model are documented in Section 6.7.2 of this report.

The erosion rates developed in this report and used in the ash redistribution conceptual model are based on a 50+ year record of Cs-137 (by-products of hydrogen bomb surface tests in the Pacific); therefore, considerable uncertainty is associated with the use of these rates for long-term (i.e., 10,000 yr) erosion of the Fortymile Wash alluvial fan. Future climate variability may affect the rates of erosion. Although considerable uncertainty is associated with the long-term erosion rates, the product range provided is considered reasonable for the regulatory time frame. As long as climate variations remain within projected limits, erosion rates are expected to remain nearly the same as current rates.

4.2 CRITERIA

The general requirements to be satisfied by the TSPA are stated in 10 CFR 63.114 [156605]. Technical requirements to be satisfied by the TSPA are identified in the *Yucca Mountain Project Requirements Document* (Canori and Leitner 2003 [161770]). The acceptance criteria that will be used by the Nuclear Regulatory Commission (NRC) to determine whether the technical requirements have been met are identified in the *Yucca Mountain Review Plan* (YMRP; NRC 2003 [163274]). The pertinent requirements and criteria for this report are summarized in Table 5.

Table 5. Project Requirements for This Model Report

Requirement Number*	Requirement Title*	10 CFR 63 Link	YMRP Acceptance Criteria [†]
PDR-002/T-015	Requirements for Performance Assessment	10 CFR 63.114	2.2.1.3.11.3, criteria 1 through 5

NOTE: * from Canori and Leitner (2003 [161770])

[†] from NRC (2003 [163274], Section 2.2.1.3.11.3).

The Yucca Mountain Review Plan (NUREG-1804, NRC 2003 [163274]) associates the integrated subissue of airborne transport of radionuclides with the requirements listed in 10 CFR 63.114 (10 CFR 63 [156605], (a)-(c) and (e)-(g)). NUREG-1804 (NRC 2003 [163274], Section

2.2.1.3.11.3) describes the acceptance criteria that the NRC will use to evaluate the adequacy of information addressing the airborne transport of radionuclides in the license application.

Acceptance Criterion 1: System Description and Model Integration Are Adequate

1. Total system performance assessment adequately incorporates important design features, physical phenomena, and couplings, and uses consistent and appropriate assumptions throughout the airborne transport of radionuclides abstraction process.
2. Models used to assess airborne transport of radionuclides are consistent with physical processes generally interpreted from igneous features in the Yucca Mountain region and/or observed at active igneous systems.
3. Models account for changes in igneous processes that may occur from interactions with engineered repository systems.
4. Guidance in NUREG-1297 and NUREG-1298 (Altman et al. 1988 [103597]; Altman et al. 1988 [103750]), or in other acceptable approaches for peer review and data qualification is followed.

Acceptance Criterion 2: Data Are Sufficient for Model Justification

1. Parameter values used in the license application to evaluate airborne transport of radionuclides are sufficient and adequately justified. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.
2. Data used to model processes affecting airborne transport of radionuclides are derived from appropriate techniques. These techniques may include site-specific field measurements, natural analog investigations, and laboratory experiments.
3. Sufficient data are available to integrate features, events, and processes, relevant to airborne transport of radionuclides into process-level models, including site-specific determination of appropriate interrelationships and parameter correlations.
4. Where sufficient data do not exist, the definition of parameter values and associated conceptual models is based on appropriate use of expert elicitation conducted, in accordance with NUREG-1563 (Kotra et al. 1996 [100909]). If other approaches are used, the U.S. Department of Energy adequately justifies their use.

Acceptance Criterion 3: Data Uncertainty is Characterized and Propagated through the Model Abstraction

1. Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an under-representation of the risk estimate.

2. Parameter uncertainty accounts quantitatively for the uncertainty in parameter values derived from site data and the available literature (i.e., data precision), and the uncertainty introduced by model abstraction (i.e., data accuracy).
3. Where sufficient data do not exist, the definition of parameter values and associated uncertainty is based on appropriate use of expert elicitation conducted in accordance with NUREG-1563 (Kotra et al. 1996 [100909]). If other approaches are used, the U.S. Department of Energy adequately justifies their use.

Acceptance Criterion 4: Model Uncertainty is Characterized and Propagated through the Model Abstraction

1. Alternative modeling approaches to airborne transport of radionuclides are considered and are consistent with the available data and current scientific understandings, and the results and limitations are appropriately considered in the abstraction.
2. Uncertainties in abstracted models are adequately defined and documented, and effects of these uncertainties are assessed in the total system performance assessment.
3. Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under representation of the risk estimate.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

1. Models implemented in the airborne transport of radionuclides abstraction provide results consistent with output from detailed process-level models and/or empirical observations (laboratory and field testings and/or natural analogs).
2. Inconsistencies between abstracted models and comparative data are documented, explained, and quantified. The resulting uncertainty is accounted for in the model results.

The Yucca Mountain Review Plan (NUREG-1804, NRC 2003 [163274] associates the integrated subissue of redistribution of radionuclides in soil with the requirements listed in 10 CFR 63.114(1)(a)-(c), (e)-(g), and 63.305 as they relate to the redistribution of radionuclides in soil abstraction. NUREG-1804 (NRC 2003 [163274], Section 2.2.1.3.13.3) describes the acceptance criteria that the NRC will use to evaluate the adequacy of information addressing redistribution of radionuclides in soil in the license application.

Acceptance Criterion 1: System Description and Model Integration Are Adequate

1. Total system performance assessment adequately incorporates important features, physical phenomena and couplings between different models, and uses consistent and appropriate assumptions throughout the abstraction of redistribution of radionuclides in the soil abstraction process.

2. The total system performance assessment model abstraction identified and describes aspects of redistribution of radionuclides in soil that are important to repository performance, including the technical bases for these descriptions. For example, the abstraction should include modeling of the deposition of contaminated material in the soil and the determination of the depth distribution of the deposited radionuclides.
3. Relevant site features, events, and processes have been appropriately modeled in the abstraction of redistribution of radionuclides, from surface processes, and sufficient technical bases are provided.
4. Guidance in NUREG-1297 and NUREG-1298 (Altman et al. 1988 [103597]; Altman et al. 1988 [103750]), or other acceptable approaches for peer reviews is followed.

Acceptance Criterion 2: Data Are Sufficient for Model Justification

1. Behavioral, hydrological, and geochemical values used in the license application are adequately justified (e.g., irrigation and precipitation rates, erosion rates, radionuclide solubility values, etc.). Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.
2. Sufficient data (e.g., field laboratory, and natural analog data are available to adequately define relevant parameters and conceptual models necessary for developing the abstraction of redistribution of radionuclides in soil in the total system performance assessment.

Acceptance Criterion 3: Data Uncertainty Is Characterized and Propagated Through the Model Abstraction

1. Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are consistent with the characteristics of the reasonably maximally exposed individual in 10 CFR Part 63 [156605].
2. The technical bases for the parameter values and ranges in the total system performance assessment abstraction are consistent with data from the Yucca Mountain region [e.g., Amargosa Valley survey (Cannon Center for Survey Research, 1997)], studies of surface processes in the Fortymile Wash drainage basin: applicable laboratory testings: or other valid sources of data. For example, soil types, crop types, plow depths, and irrigation rates should be consistent with current farming practices, and data on the airborne particulate concentration should be based on the resuspension of appropriate material in a climate and level of disturbance similar to that which is expected to be found at the location of the reasonably maximally exposed individual, during the compliance time period.
3. Uncertainty is adequately represented in parameters for conceptual models, process models, and alternative conceptual models considered in developing the total system performance assessment abstraction of redistribution of radionuclides in soil, either

through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the total system performance assessment.

4. Parameters or models that most influence repository performance based on the performance measure and time period of compliance, specified in 10 CFR Part 63 [156605], are identified.
5. Where sufficient data do not exist, the definition of parameter values and conceptual models on appropriate uses of other sources, such as expert elicitation, are conducted in accordance with appropriate guidance, such as NUREG-1563 (Kotra et al. 1996 [100909]).

Acceptance Criterion 4: Model Uncertainty is Characterized and Propagated Through the Model Abstraction

1. Alternative modeling approaches of features, events, and processes are considered and are consistent with available data, and current scientific understanding, and the results and limitations are appropriately considered in the abstraction.
2. Sufficient evidence is provided that alternative conceptual models of features, events, and processes have been considered; that the preferred models (if any) are consistent with available data (e.g., field, laboratory, and natural analog) and current scientific understanding; and that the effect on total system performance assessment of uncertainties from these alternative conceptual models has been evaluated.
3. Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

Acceptance Criterion 5: Model Abstraction Output Is Supported by Objective Comparisons

1. Models implemented in the abstraction provide results consistent with output from detailed process-level models and/or empirical observations (e.g., laboratory testing, field measurements, and/or natural analogs).

Additional information about how this report addresses these acceptance criteria and locations of relevant discussions in this report are provided in Attachment I.

4.3 CODES AND STANDARDS

No other standards or code requirements other than those referenced in Section 4.2 apply to this model report.

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5. ASSUMPTIONS

This section describes the assumptions applicable to the use of the ASHPLUME model. Each assumption listed is followed by a rationale for use, confirmation status, and a disposition in this report. Assumptions are grouped within this section according to whether they apply to the conceptual or mathematical model or to the model parameters. Assumptions made in source documents are not discussed in this report.

5.1 MODEL ASSUMPTIONS

5.1.1 ASHPLUME Representation of the Conceptual Model

Assumption: The ASHPLUME model assumes that volcanic eruptions in the YMR are violent Strombolian for the entire duration of the explosive phase. Erupted magma is presumed to be fragmented and dispersed in the convective plume for the entire duration of the eruption. This assumption is conservative in that it maximizes the potential for ash and waste dispersal during Strombolian activity. (Note that violent Strombolian does not reach the dispersive potential of more violent types of events that are not associated with the YMR, such as Vulcanian/Surtseyan [hydrovolcanic] eruptions or eruptive phases.) The validity of this assumption received support from the Igneous Consequences Peer Review Panel (Detournay et al. 2003 [162914], Section 4.2).

Rationale: This assumption is considered to be conservative because Strombolian activity is characterized by dominantly ballistic fountaining of magmatic ejecta within 1 km of the vent with a minor component of convective plume development (BSC 2003 [166407], Section 6.3.5.2). In contrast, the ASHPLUME model represents the most violent type of Strombolian activity, in which the near-vent ballistic component is negligible and tephra dispersal in a wind-blown convective plume dominates, according to the conceptual model (Jarzemba et al. 1997 [100987], p. 2-1). Clearly, this assumption maximizes the dispersal for contaminants for Strombolian activity. Uncertainties associated with the nature of violent Strombolian eruptive phases are their duration (the length of time the volcanic eruption is occurring), eruption power (the heat flux carried by the tephra), and the initial velocity of tephra entering the plume (BSC 2003 [166407], Section 6.3.3.4). These uncertainties are included in the model through the development of distribution functions for these parameters that characterize uncertainties. For historic eruptions, the uncertainties can be bounded by measurements of the volume of erupted material; such measurements for YMR analogs are used to provide realistic bounds on input parameters (Section 6.5.2).

Confirmation Status: It is conservative to assume that an eruptive event can be modeled as being in the violent Strombolian phase during the entire period of eruption because typical eruptions include only a minor component, if any, of violent Strombolian activity. Most of a typical eruption is less energetic. No further confirmation is required.

Where Used: This assumption is used in Section 6.3 to support the conceptual model for the volcanic eruption release.

5.1.2 Waste-Particle Values Below the Incorporation Ratio

Assumption: The mathematical formulation of the ASHPULME model makes the simplifying assumption that all waste particles with diameters less than a certain fraction of the diameter of ash particles, determined by the incorporation ratio (Section 6.5), are attached to ash particles for transport. The model also contains the assumption that any waste particles too large for incorporation are not transported downwind.

Rationale: There is no physical basis for this mathematical construct, but the assumption is consistent with the conceptualization that all waste material in canisters intersected by an eruptive conduit is incorporated into the magma (and, subsequently, into the eruption column). This mathematical formulation is required to transport an ash particle corrected for the density of the waste particle. It is reasonable to assume that small ash particles cannot host large fuel particles for transport. A limiting factor must be introduced into the mathematical model to represent a reasonable waste/ash fraction. In this mathematical simplification, waste-particle size distributions and ash-particle size distributions are appropriately paired to ensure a reasonable fraction of waste is transported in the eruption.

Confirmation Status: This assumption is consistent with the conceptual model of ash/waste interaction and is not identified as requiring further work for confirmation.

Where Used: This assumption is used in Section 6.5 in the development of the ASHPULME mathematical model.

5.1.3 Tephra Sheet Distribution for Ash Redistribution Model

Assumption: Two scenarios for tephra sheet distribution and orientation are identified to represent end members of the range.

Rationale: The possible orientation of tephra sheets from a basaltic volcanic eruption centered on Yucca Mountain suggests that the two end members are: Scenario 1, in which the tephra sheet covers the location of the RMEI, and Scenario 2, in which the tephra sheet is located within the Fortymile Wash drainage basin upstream from the RMEI location. The properties of the Scenario 1 tephra sheet at the RMEI location are consistent with the waste concentrations and ash thicknesses calculated from ASHPULME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) and presented in Table 10 of Section 6.7.1. Properties of a Scenario 2 tephra sheet located in the Fortymile Wash drainage basin assume that available ash from the eruption, other than that forming the cinder cone, is deposited within the drainage basin and is available for redistribution primarily by fluvial processes. The two scenarios are the basis for product outputs from the redistribution conceptual model for the TSPA. Other possible scenarios (e.g., where tephra are deposited west of Yucca Mountain) would result in exposure to a RMEI less than that of the two scenarios outlined above.

Confirmation Status: The two end members define the range of reasonable scenarios in that ash deposited to the northeast is consistent with prevailing wind direction and is the most likely direction of any ash plume in a hypothetical eruption in the vicinity of Yucca Mountain including one located at Yucca Mountain. The deposition of ash to the south directly on the location of the RMEI would be the exceptional case as a southerly wind direction is uncommon.

The ash redistribution conceptual model is supported by field and laboratory investigations and is believed to be representative of the processes currently occurring and expected to occur in the future regulatory period. No further confirmation studies are necessary for this model; however, given the limited availability of information on erosion rates and dilution rates, additional analog studies to address the uncertainties associated with the inputs to the conceptual model are warranted.

Where Used: This assumption is used in Section 6.6.1 of this report to support the ash redistribution conceptual model.

5.2 PARAMETER ASSUMPTIONS

5.2.1 Future Wind Speed and Direction

Assumption: Data characterizing variability in wind speed and wind direction under present climatic conditions in the YMR are provided by NOAA (1995 [154435]) data from the Desert Rock station near Mercury, Nevada, which are assumed to be acceptable approximations of variability in wind speed and direction for future wind conditions. Conceptually, this assumption corresponds to an assumption that climatic change will not significantly affect wind speed and direction. The magnitude of short-term variability in wind speed and direction, which is included in the data that characterize present wind conditions, is presumed to be significantly greater than long-term variability introduced by potential future climatic changes.

Rationale: Justification for future wind conditions in future climates is based on the observation that the magnitude of short-term variability in meteorological phenomena is great compared to changes in long-term averages. Emphasis for relatively brief volcanic events is correctly placed on the short-term variability rather than on long-term averages in wind patterns.

Additional support for the reasonableness of this assumption comes from examination of published modeling studies of past climatic conditions that may be reasonable analogs for future climatic conditions at Yucca Mountain. Kutzbach et al. (1993 [119269], p. 60) have modeled global climates at 3,000-year intervals during the last 18,000 years, using general circulation models with available paleoclimatic information used to define boundary conditions. Resolution of the model is extremely coarse (grid blocks are 4.4 degrees latitude by 7.5 degrees longitude (Kutzbach et al. 1993 [119269], p. 60)), and results are not intended to be interpreted at local scales. However, model results (presented at a regional scale) provide qualitative information about modeled wind speeds and directions for the southwestern United States. Model results are provided for 18,000 years ago, at the end of the last major glaciation of northern North America; at 12,000, 9,000, and 6,000 years ago and also for present conditions. Climatic conditions at these times span the range of conditions that might reasonably occur during a future transition from the present climate to a glacial climate.

Modeled surface winds for the southwestern United States in winter and summer show a slightly stronger westerly component (away from the location of the RMEI south of the repository) 18,000 years ago than at present and are essentially unchanged from the present at 12,000, 9,000, and 6,000 years ago (Kutzbach et al. 1993 [119269], Figures 4.6 and 4.8). Modeled winter (January) winds at the 500-millibar (mb) pressure isobars (about 5.5-km altitude) blow strongly

from the west at all times and were somewhat stronger at 18,000 years ago than at present (Kutzbach et al. 1993 [119269], Figure 4.14). Modeled summer (July) winds at 500 mb are weaker and less consistent, blowing from the southwest and west at 18,000 and 12,000 years ago and at the present and from the northwest 9,000 and 6,000 years ago (Kutzbach et al. 1993 [119269], Figure 4.15).

The information relevant to the assumption discussed here is that significant changes in the Kutzbach et al. (1993 [119269]) modeled wind speeds and directions in the southwestern United States are not dramatic during the modeled transition from glacial to interglacial climates. The largest changes, occurring during full glacial conditions 18,000 years ago, appear qualitatively to correspond to a decrease in the relative frequency of winds blowing toward the RMEI location south of Yucca Mountain. Therefore, these changes are reasonably and conservatively neglected, and variability in present wind conditions is assumed to characterize variability adequately in future conditions.

Confirmation Status: No testing or modeling activities are planned to provide further confirmation of this assumption.

Where Used: This assumption is used to justify the distributions of future wind speed and direction that are recommended for use in the TSPA-LA analyses. The recommended wind direction and wind speed distribution functions are discussed in Section 6.5. Functionally, the assumption means that individual values of wind speed and direction can be sampled for time zero from distributions based on present data, and the same values can then be used for all time steps for each realization.

5.2.2 Wind Speed and Direction Remain Constant During an Eruptive Event

Assumption: Wind speed and direction are assumed to be constant during an eruptive event.

Rationale: This assumption prevents short-term variations in wind speed and direction from spreading the ash plume over a broader area and results in both a maximum quantity and maximum concentrations of waste at the center line of the plume. This is a reasonable simplification, given the relatively short duration of violent eruptive events, and is conservative because it tends to overestimate the maximum waste concentrations that might reach the RMEI location.

Confirmation Status: No testing or modeling activities are planned to provide further confirmation of this assumption.

Where Used: This assumption is used in Section 6.5.

5.2.3 ASHPLUME Utilization of Wind Speed and Direction

Assumption: The ASHPLUME model assumes that the wind speed and direction that dictate tephra dispersal are those that occur at the top of the plume.

Rationale: Wind speed and wind direction vary with altitude above the ground, and, thus, tephra dispersed from the plume at different altitudes follows trajectories governed by altitude-

dependent wind vectors. The column diffusion constant (β) determines which locations in the column contribute the most tephra dispersal. This constant was presumed to be a log-uniform distribution from 0.01 to 0.5 (Jarzemba et al. 1997 [100987], p. 4-1) without justification (for the distribution type) other than it spans more than one order of magnitude. Because violent Strombolian eruptions typically form an anvil-shaped plume, most particles must rise to near the plume top before dispersal down wind. This suggests that large values of β are common such that the distribution is likely uniform, as is implemented in this report. With a uniform distribution of beta between 0.01 and 0.5, the majority (about 80%) of violent Strombolian eruptions are modeled with β greater or equal to 0.1, a level at and above which Suzuki (1983 [100489], Figure 6) showed dominant dispersal from the upper half of the column. Hence, the wind speed and direction near the top of the plume are appropriate and maximize dispersal for modeled eruptions.

Confirmation Status: This assumption is considered to be reasonable and consistent with the intended use of the ASHPLUME model. No further confirmation is needed.

Where Used: This assumption is used in Section 6.5.

5.2.4 Waste-Particle Size

Assumption: For the purpose of estimating waste-particle diameters in the eruptive environment, all waste is assumed to be pulverized unaltered commercial spent fuel. The usage of the terms “spent fuel” and “fuel form” in this model report connote the more general meaning of radionuclide mass or concentration for the purposes of modeling in the TSPA.

Rationale: This assumption is considered reasonable for analyses of the 10,000-year post-closure performance period as specified in 10 CFR 63 [156605].

CRWMS M&O (2001 [153938], Table I-2) suggests a distribution for particle diameters of 0.0001 cm to 0.05 cm with a mean of 0.002 cm based on an examination of waste fuel particles resulting from crushing and grinding for corrosion studies that were conducted at the Argonne National Laboratory (ANL). The mean particle size of 0.002 cm is provided in DTN: LL001104412241.019 [155224]. The limiting values are assumptions supported in CRWMS M&O (2001 [153938], Section I.2.3) by noting that “...it is likely that 80 to 90 percent of the fuel particles will fall within the range...”. Given the conceptualization that waste particles are transported by combining with ash particles of larger sizes (see Assumption 5.1.2), the assumption to treat all waste as unaltered commercial spent fuel is conservative but reasonable. The unaltered glass waste forms are likely to have particle diameters comparable to those of the ash particles, which are larger than the values used for spent fuel. The assumption that the waste form is unaltered prior to being disturbed in a volcanic event is reasonable for analyses of the 10,000-year post-closure performance period, given the relatively small number of waste packages expected to fail under nominal conditions during that period and the expected stability of the waste form within the undisturbed waste packages.

Experimental evidence is lacking for processes capable of fragmenting spent nuclear fuel in a volcanic eruption. Consequently, the model assumes that fuel in the affected waste packages is available for entrainment in the ash plume as finely-divided particles with diameters in the range

of 0.0001 to 0.05 cm. This is conservative because other investigators have suggested coarser distributions could be defended (Codell 2003 [165503], Figure 1); however, such an approach would minimize transport distances and consequences of an eruptive ash plume. Furthermore, Codell (2003 [165503], Section IIE) indicates that time scales for magma/waste and atmospheric transport are too short to support significant oxidation of waste. Therefore, alteration of waste particles does not occur, and waste-particle sizes remain constant after the initial magma/waste interaction.

Confirmation Status: This assumption is considered reasonable for analyses of 10,000-year performance, as described above, and no further confirmation activities are planned.

Where Used: This assumption is used in Section 6.5 in describing the waste-particle size distribution.

5.2.5 Initial Rise Velocity

Assumption: The ASHPLUME model stipulates that the convective rise velocity of tephra particles linearly decreases from the initial rise velocity at the base of the plume to zero at the top of the plume. The initial rise velocity of tephra particles in the plume is assumed to be the minimum velocity required to provide the plume the modeled thermal power. Because the upward velocity profile of buoyant plumes generally decreases with height to zero at their tops where neutral buoyancy is a complex relationship of plume and atmospheric density profiles and the rate of air entrainment and heating, this assumption represents the model-equivalent of the modeled plume's vertical velocity profile. In order for model-equivalence to give a reasonable numerical approximation, the initial rise velocity is assumed to be constrained to values that are compatible with the plume height and, thus, eruption power.

Rationale: ASHPLUME models a column (plume) instantaneously loaded with particles moving at some upward velocity. The height of the column determined by ASHPLUME is fixed by the power (heat flux) provided by erupting magma. The heat flux is directly proportional to the mass flux of magma from the vent, which, for continuity, is determined by the vent area, magma bulk density, and vent velocity. For any given vent area, minimum vent velocity occurs when the magma bulk density is at its maximum value; maximum vent velocity occurs when magma bulk density is at its minimum value. The latter case of minimum magma bulk density arises when magma volatile components are fully expanded to atmospheric pressure. Realistic vent velocities fall between these two extremes. Before the magma and gas mixture enters the plume, it rapidly decelerates by its interaction with the atmosphere and gravitational forces in a region known as the gas-thrust region. Because the gas-thrust region height is generally less than 10% of the total eruptive column height, a convective plume model such as ASHPLUME is justified (Wilson et al. 1978 [162859], p. 1830). The ASHPLUME model must account for gas expansion and air entrainment as well as the deceleration of tephra in the gas-thrust region while maintaining continuity in order for the column height to eruptive power relationship to hold. Implicit in the convective plume model is that (1) height is solely determined by the convection produced by the supplied thermal power and that (2) the contribution to the plume height by the momentum of gas-thrust region is negligible. This approximation stipulates that the velocity of tephra entering the plume must only be that required to deliver the required power. Thus, for eruptions involving gas expansion, the plume base area must be greater than the vent area by a

factor equal to the amount of gas expansion. For plumes of circular cross section, the radius increases by the square root of the gas expansion. As an example, consider a mixture of gas and tephra issuing from a vent of 1-m radius for which the mixture expands by a factor of 200. The resulting plume would have a radius of ~14 m, and its initial velocity would be the minimum vent velocity. While arguments for a higher velocity clearly can be made, they would not be consistent with the assumption of buoyant plume theory. Also, higher velocities would be even less desirable, considering that they are also applied to the top of the plume where tephra no longer have much upward velocity.

Confirmation Status: This assumption is considered reasonable and consistent with the intended use of the ASHPLUME model. No further confirmation is needed.

Where Used: This assumption is used in Section 6.5.

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6. MODEL DISCUSSION

The potential consequences of an igneous event intersecting the repository (BSC 2003 [163769]) require consideration of both the eruption and deposition of pyroclastic material and redistribution of that pyroclastic material after initial deposition. This section presents the objectives, technical bases, and applications of the two models that represent the eruption, deposition, and redistribution of volcanic ash. Section 6.1 presents the modeling objectives. Section 6.2 presents the applicable features, events, and processes addressed by the models. Sections 6.3 to 6.5 provide the technical basis for the eruptive transport and deposition of waste-contaminated ash from a hypothetical volcanic eruption through a repository at Yucca Mountain. Sections 6.6 and 6.7 provide the technical basis for and application of the redistribution of waste-contaminated volcanic ash through sedimentary processes.

6.1 MODELING OBJECTIVES

Two models have been developed to represent the dispersal, deposition, and redistribution processes for volcanic ash contaminated with radioactive waste from a hypothetical eruption through the repository at Yucca Mountain. The overall objectives of these two models are to:

- Represent the processes and the associated potential consequences related to deposition and redistribution of contaminated ash at and near the RMEI location.
- Provide representative abstractions of the models with bounding conditions for inclusion in the TSPA model.

6.1.1 Objectives of the ASHPLUME Model

The ASHPLUME conceptual model provides the basis, supported by analog descriptions, for the applicability of using the ASHPLUME code to model volcanic ash and waste dispersal during a hypothetical future volcanic eruption through the repository. Development of the model uses the Eruptive Processes Conceptual Model (BSC 2003 [166407], Section 6) and is based on comparison of the expected scenario characteristics with the physical processes modeled by ASHPLUME.

The ASHPLUME model implements the conceptual and mathematical model of Suzuki (1983 [100489]) for estimation of the areal density of tephra (ash) deposits on the surface of the earth following a violent Strombolian-type volcanic eruption. The computer code, developed by Jarzempa et al. (1997 [100987]) from the Suzuki mathematical model, includes estimation of the areal density on the Earth's surface of spent fuel particles incorporated into ash particles due to an eruption that intersects the repository at Yucca Mountain. Areal densities can be converted to deposit thickness by dividing the areal density by the value of settled (deposit) density (typically 1.0 g/cm^3 (BSC 2003 [166407], Table 38)).

ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) includes a DLL (dynamic link library) module for use as a component of the TSPA GoldSim model to assess risk to the RMEI from exposure to contaminated ash from possible volcanic activity at the Yucca Mountain site. The results of the ASHPLUME model calculations (tephra and waste areal densities) are used by the TSPA-LA model in conjunction with BDCFs to calculate dose to the RMEI. (For compliance demonstration purposes for disruptive scenarios, the TSPA-LA assumes that the dose

occurs to an individual who has the same characteristics as the RMEI.) ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) also includes an executable module for stand-alone use, which is applied to making calculations shown in Section 7 of this report. The stand-alone version calls the DLL module for making the calculations and serves only to format user input parameters for the DLL. Thus, the following discussions in this report apply equally to both stand-alone and DLL implementations of ASHPLUME V 2.0.

6.1.2 Objectives of the Ash Redistribution Conceptual Model

The consequences of a volcanic eruption include consideration of the potential increase in dose at the location of the RMEI from the transport of radioactive-waste-contaminated ash through sedimentary processes. This potential consequence is described in greater detail in Section 6.2 as a specific disruptive events (DE) feature, event, and process (FEP 1.2.04.07.0C). The ash redistribution conceptual model presents the basis for the ash redistribution abstraction, which is a component of the TSPA model. The objective of the ash redistribution conceptual model is to describe the range of conditions that allow for the transport of waste-contaminated volcanic ash to the location of the RMEI by sedimentary processes that include both eolian and alluvial transport mechanisms. The ash redistribution conceptual model also addresses the conditions for the concentration of radionuclides from the transport of waste-contaminated ash at the location of the RMEI.

6.2 FEATURES, EVENTS, AND PROCESSES INCLUDED IN THE MODEL

The development of a comprehensive list of FEPs potentially relevant to post-closure performance of the Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. The approach for developing an initial list of FEPs in support of the TSPA-SR (CRWMS M&O 2000 [153246]) was documented in Freeze et al. (2001 [154365]). The initial FEPs list contained 328 FEPs, of which 176 were included in TSPA-SR models (CRWMS M&O 2000 [153246], Tables B-9 through B-17). To support the TSPA-LA, the FEPs list was re-evaluated in accordance with *The Enhanced Plan for Features, Events, and Processes (FEPs) at Yucca Mountain* (BSC 2002 [158966], Section 3.2).

Tables 2 and 3 of the TWP for igneous activity assessment (BSC 2003 [166289]) provide a listing of both included and excluded FEPs for each of the DE scientific analysis reports and model reports. One FEP that was listed as included in the TWP, Igneous Activity, was deleted during the FEPs review for the TSPA-LA that was conducted as part of the Enhanced FEPs Plan. The description of the FEP was found to be entirely redundant with more specific igneous related FEPs. A new FEP, 1.2.04.07.0C, Ash Redistribution, was added to the FEP list as a result of the FEPs review. Disposition and discussion of the FEP is presented in this report and in the revision to the scientific analysis report *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002 (BSC 2003 [166407]).

Table 6 provides a list of FEPs that are included in the TSPA-LA model described in this model report and indicates their disposition. For each of the included FEPs listed in the table, the implementation in TSPA-LA is described in this model document. Details of the implementation are summarized, including specific reference to sections within this document. However, this report describes the model used to include the FEPs listed in Table 6.

Table 6. Included FEPs for This Model Report and Their Disposition in TSPA-LA

TSPA-LA FEP Number, Name, and Description	Section Where Disposition is Described	Summary of TSPA-LA Disposition
<p>1.2.04.06.0A Eruptive Conduit to Surface Intersects Repository</p> <p><i>As a result of an igneous intrusion, one or more volcanic vents forms at land surface. The conduit(s) supplying the vent(s) pass(es) through the repository, interacting with and entraining waste.</i></p> <p>The name of this FEP was changed to "Eruptive Conduit to Surface Intersects Repository," and the FEP description was revised to focus on conduit development and waste entrainment, rather than scoria cone development.</p>	<p>Section 6.5.2</p>	<p>The scientific analysis report, <i>Characterize Eruptive Processes at Yucca Mountain, Nevada</i>, ANL-MGR-GS-000002 (BSC 2003 [166407]) provides a technical basis for inclusion of the FEP in the TSPA-LA. The report (BSC 2003 [166407]) includes the results of field investigations dealing with physical volcanology and describes the conceptual models for eruptive processes including conduit formation. This information is used to develop parameter-value distributions appropriate for evaluation of the related FEPs and analysis of the consequences of volcanic eruptions through a repository at Yucca Mountain, Nevada. In particular, the BSC (2003 [166407]) report addresses the following aspects of the FEP:</p> <ul style="list-style-type: none"> • The geometry of volcanic feeder systems, which is of primary importance in predicting how much of a repository would be affected by an eruption. • The physical and chemical properties of the magmas, which influence both eruptive styles and mechanisms for interaction with waste packages. • Eruptive processes, including the ascent velocity of magma at depth, the onset of bubble nucleation and growth in the rising magmas, magma fragmentation, and velocity of the resulting gas-particle mixture. <p>The parameters related to this FEP that are developed in the eruptive processes report (BSC 2003 [166407], Table 37) include the following output distributions:</p> <ul style="list-style-type: none"> • Conduit diameter • Eruptive power • Eruption volume • Eruption duration. <p>The results documented in BSC (2003 [166407]) do not directly feed the TSPA-LA model. Rather, the results provide inputs for the reports identified below. Because the outputs of the identified reports are used either implicitly or explicitly in the TSPA-LA model and the outputs of the listed reports are dependent on the underlying inputs documented in this analysis report, the underlying inputs and related FEPs are considered to be implicitly included in the TSPA-LA model.</p> <p>The scientific analysis report, <i>Number of Waste Packages Hit by Igneous Intrusion</i>, ANL-MGR-GS-000003 REV 00 (BSC 2003 [161851], Sections 6 and 7), provides parameters to the TSPA-LA that address this FEP. The analysis (BSC 2003 [161851]) uses the outputs from the revisions of the reports, <i>Characterize Framework for Igneous Activity at Yucca Mountain, Nevada</i> (BSC 2003 [163769]) and <i>Characterize Eruptive Processes at Yucca Mountain, Nevada</i> (BSC 2003 [166407]), and repository design information to calculate the number of waste packages exposed to defined magmatic-related environments. The analysis uses spreadsheet calculation operations to evaluate geometric relationships between conduit geometry and the number of waste packages impacted by conduits. The types of information used include:</p>

Table 6 (Continued). Included FEPs for This Model Report and Their Disposition in TSPA-LA

TSPA-LA FEP Number, Name, and Description	Section Where Disposition is Described	Summary of TSPA-LA Disposition
		<ul style="list-style-type: none"> Repository design information (repository area, drift diameter, drift spacing, waste package length, and waste package spacing). Igneous event probability. Probabilities and parameters associated with conduits occurring within the repository (conditional probability that more than one conduit will occur within the repository footprint and conduit diameter distributions). Conduit diameter. <p>For the volcanic-eruption modeling case, the analysis report (BSC 2003 161851J) provides a CDF for number of waste packages hit by an eruptive conduit. The CDF is based on a relation between the resulting conduit areas and the fraction of the repository area occupied by waste packages. This relation was used in conjunction with a joint distribution incorporating variabilities in eruptive conduit diameters and in the number of eruptive conduits that could intersect the repository to calculate the resulting CDF. The CDF is used directly by the TSPA-LA for the volcanic-eruption modeling case featuring the development of a volcano within the repository footprint with one or more conduits that intersect waste packages. Because the CDF is dependent on the underlying inputs, these inputs and related FEPs are considered to be included implicitly in the TSPA-LA model. The modeling of the eruptive event is outlined in this model report. The TSPA-LA model, using ASHPLUME, estimates radionuclide concentrations in contaminated ash falling at the location of the RMEI, approximately 18 km south of the repository. For the volcanic-eruption modeling case, the TSPA-LA presumes that a hypothetical violent Strombolian eruption occurs through a section of the repository, entraining radionuclide-bearing wastes in the ash plume that disperses down wind, and deposits contaminated ash on the ground surface.</p> <p>Once entrained and erupted, atmospheric transport of ash and radionuclides is modeled directly in the TSPA-LA using the software code ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571J]) as identified and discussed in Section 8 of this report. Sections 6.5.1 and 6.5.2 of this report describe the mathematical model and parameter inputs, respectively, that are used to calculate ash-and-waste dispersal in the wind. The TSPA LA model stochastically samples the number of waste packages hit and the parameters used as input in each single ASHPLUME realization. Table 8 of this report addresses the eruptive characteristics processes in the form of the following inputs:</p> <ul style="list-style-type: none"> Mean ash particle diameter Ash particle diameter standard deviation for particle-size distribution Ash particle shape factor Ash particle density at minimum, and a maximum, particle size Log ash particle size for ash particle Eruptive power, eruption duration, and initial rise velocity. <p>The ASHPLUME model is executed from within the TSPA-LA GoldSim model, and ASHPLUME results are produced therein. Consequently, the processes defined by the ASHPLUME mathematical model are considered to be included explicitly in the TSPA-LA.</p>

Table 6 (Continued). Included FEPs for This Model Report and Their Disposition in TSPA-LA

TSPA-LA FEP Number, Name, and Description	Section Where Disposition is Described	Summary of TSPA-LA Disposition
<p>1.2.04.07.0A Ashfall</p> <p><i>Finely-divided waste particles are carried up a volcanic vent and deposited at land surface from an ash cloud.</i></p>	<p>Section 6.5</p>	<p>The scientific analysis report, <i>Characterize Eruptive Processes at Yucca Mountain, Nevada, ANL-MGR-GS-000002</i> (BSC 2003 [166407]) provides the technical basis for inclusion of the FEP in the TSPA-LA. Properties of basaltic eruptions described in BSC (2003 [166407]) are based on the observed characteristics of past basaltic eruptions in the YMR and other analogous eruptions. This report (BSC 2003 [166407]) includes the results of field investigations dealing with physical volcanology and with ash and tephra redistribution and includes the conceptual models for eruptive processes and for ash and tephra redistribution. This information is used to develop parameter value distributions appropriate for analysis of the consequences of volcanic eruptions through a repository at Yucca Mountain, Nevada. In particular, the eruptive processes report (BSC 2003 [166407]) addresses the following aspects of the related FEP:</p> <ul style="list-style-type: none"> • The duration of eruptions, their power output, and mass discharge rates • The bulk grain size produced by relevant explosive eruptions and grain shapes. <p>The parameters developed in the eruptive processes report (BSC 2003 [166407], Table 37) related to this FEP include the following:</p> <ul style="list-style-type: none"> • Eruptive power • Eruption duration for formation of an entire volcano • Duration of a single explosive phase constituting a violent Strombolian eruptive phase • Eruption volume • Mean particle size erupted during violent Strombolian phases • Standard deviation of particle-size distribution for a given mean • Clast characteristics • Density of erupted particles • Tephra deposit density. <p>The results of the analysis report (BSC 2003 [166407]) do not feed directly to the TSPA-LA model. Rather, these results provide input for the ASHPLUME model run within the TSPA-LA. Because both the outputs of the BSC (2003 [166407]) scientific analysis report are used either implicitly or explicitly in the TSPA-LA model and the outputs of the ASHPLUME model are dependent on the underlying inputs documented in this model report, the underlying inputs and related FEPs are considered to be included implicitly in the TSPA-LA model. The output from the eruptive processes report (BSC 2003 [166407], Table 38) is used in this model report (Table 8) as input for developing the following parameters:</p>

Table 6 (Continued). Included FEPs for This Model Report and Their Disposition in TSPA-LA

TSPA-LA FEP Number, Name, and Description	Section Where Disposition is Described	Summary of TSPA-LA Disposition
		<ul style="list-style-type: none"> • Mean ash particle diameter • Ash particle diameter standard deviation for particle size distribution • Ash particle shape factor • Ash particle density at minimum, and a maximum, particle size • Log ash particle size for ash particle density at minimum, and at maximum, particle size • Eruptive power and eruption duration. <p>In addition, the following process parameters are described within this model report:</p> <ul style="list-style-type: none"> • Column diffusion constant, which affects the distribution of particles within the ash column. • Waste incorporation ratio, a mathematical construct used to transport a density-corrected "combined" ash and fuel particle. • Waste particle size (min, max, mode). • Wind speed and wind direction, based on site specific data collected over the appropriate range of ash column height. • Initial rise velocity of the plume. • Eddy diffusivity constant, with the simplification made that particle diffusion time equals particle fall time). <p>Once entrained and erupted, atmospheric transport of ash and radionuclides is modeled directly in the TSPA-LA using the software code ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) as identified and discussed in Section 8 of this model report. The TSPA-LA model estimates radionuclide concentrations in contaminated ash falling at the location of the RMEI, approximately 18 km south of the repository. For the volcanic-eruption modeling case, the TSPA-LA presumes that a hypothetical violent Strombolian eruption occurs through a section of the repository, entraining radionuclide-bearing wastes in the ash plume that disperses downwind, and deposits contaminated ash on the ground surface. Sections 6.5.1 and 6.5.2 of this report describe the mathematical model and parameter inputs, respectively, used to calculate ash and waste dispersal in the wind. The ASHPLUME model is executed from within the TSPA-LA GoldSim model, and ASHPLUME results are produced therein. The TSPA LA model stochastically samples the number of waste packages hit and the parameters used as input in each single ASHPLUME realization. The ASHPLUME model specifically addresses the issues of incorporation of the waste into the volcanic ash, the extent of the ash plume into the atmosphere, the atmospheric transport of the ash and entrained waste, and the thickness of ash deposits in the vicinity of the RMEI. These aspects of the FEP are, therefore, considered to be included explicitly in the TSPA-LA model.</p>

Table 6 (Continued). Included FEPs for This Model Report and Their Disposition in TSPA-LA

TSPA-LA FEP Number, Name, and Description	Section Where Disposition is Described	Summary of TSPA-LA Disposition
<p>1.2.04.07.0C Ash Redistribution Via Soil and Sediment Transport</p> <p><i>Following deposition of contaminated ash on the surface (see FEP 1.2.04.07.0A Ashfall), ash deposits may be redistributed on the surface via aeolian and fluvial processes.</i></p> <p>(NOTE: New FEP created to address post-eruptive effects of ash fall with regard to mechanisms for contaminant transport.)</p>	<p>Sections 6.6, 6.7.2, 7.3</p>	<p>This model report describes and constrains the consideration of the FEP 1.2.04.07.0C, Ash Redistribution via Soil and Sediment Transport, and provides a technical basis for inclusion of the FEP in the TSPA-LA. In addition, this report includes the conceptual model description and model results for ash redistribution. Information from field investigations is used to develop values that constrain amounts of erosion, deposition, and dilution of ash and are appropriate for analysis of the consequences of volcanic eruptions through a repository at Yucca Mountain, Nevada. In particular, this report addresses the following aspects of the related FEP:</p> <ul style="list-style-type: none"> • The rate of erosion/deposition of sediments on the Fortymile Wash alluvial fan. <p>The parameters developed in this document related to this FEP include the following:</p> <ul style="list-style-type: none"> • Ash dilution rate • Site erosion/aggradation rate. <p>The parameters for the FEP 1.2.04.07.0C, Ash Redistribution Via Soil and Sediment Redistribution, developed in this report directly feed to the TSPA-LA model, and the FEP is, therefore, explicitly included.</p>

6.3 BASE-CASE ASHPLUME CONCEPTUAL MODEL

The ASHPLUME mathematical model is based on a two-dimensional (2-D) diffusion model in which only horizontal turbulent diffusion is considered. The movement of air in the atmosphere is random due to the many eddy currents that exist (Suzuki 1983 [100489]). The movement of particles within the air mass is also random for the same reason. Particles diffuse in the atmosphere in both vertical and horizontal directions, but because the scale of horizontal turbulence is much greater than the scale of the vertical turbulence (Suzuki 1983 [100489]), horizontal diffusion is the dominant factor in determining the width of a plume as it moves downwind. Therefore, the ASHPLUME model is based on a 2-D diffusion equation in which only horizontal turbulent diffusivity is considered.

The conceptual model for Strombolian eruption (Igneous Framework Conceptual Model) in the YMR is developed in the document *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* (BSC 2003 [163769], Section 6), including details of volcanic eruption characteristics (Eruptive Processes Conceptual Model and supporting parameters). The following description is a compilation of information from this source.

A description of the ASHPLUME conceptual model for the atmospheric dispersal and deposition of contaminated tephra begins with a magmatic dike rising through the Earth's crust and intersecting the proposed repository at Yucca Mountain (Figure 1). An eruptive conduit, or conduits, can form when a portion of the dike begins to widen and provides a preferential pathway to focus an eruption that penetrates the Earth's surface in a violent Strombolian eruption. If the conduit intersects one or more repository drifts, the canisters located partially or entirely within the conduit provide no further protection to the waste, which will become fragmented and entrained within the rising magma (BSC 2003 [165002]). This condition is inherent in the input parameter for amount of waste erupted and is given a technical basis in the *Number of Waste Packages Hit by Igneous Intrusion*, ANL-MGR-GS-000003 REV 00 (BSC 2003 [161851]) for the TSPA-SR (CRWMS M&O 2000 [153246], Section 3.10). This condition will be carried forward for the TSPA-LA (BSC 2002 [160313], p. B-8).

Existing data are limited regarding the expected state of the waste particles (e.g., grain size) resulting from a magmatic disruptive event and associated thermal, chemical, and physical processes (e.g., Codell 2003 [165503]). The model assumes that fine-grained waste particles are entrained into a mixture of tephra and gas, rather than mixing directly into the magma prior to fragmentation. As described in Section 6.5.1, the waste particle size distribution is paired with an appropriate ash size distribution and an incorporation ratio is used to account for the amount of waste fuel that is transported with the ash. For transport calculations, the paired ash and waste particles are modeled as density-corrected ash particles.

A Strombolian eruption is characterized by the eruption of a high-speed column of a gas-pyroclast-waste-particle mixture. The column consists of two regions. The lower region directly above the vent is called the gas-thrust region, and it behaves as a ballistic fountain of tephra moving under the influence of its eruption momentum. The upper region of the column is called the convective-thrust region, in which tephra rise by buoyant convective currents (Self and Walker 1994 [162831]). Strombolian eruptions typically vary in eruptive intensity as measured by the degree of magma fragmentation and eruption column height (BSC 2003 [166407], Section

6.3.5.1). When the eruptive intensity reaches a point where a dominant portion of the tephra is carried into the convective-thrust region, the eruption is said to be in a violent Strombolian phase (BSC 2003 [166407], Section 6.3.5.2). Hence, a violent Strombolian eruption is one that is dominated by a violent phase, and the atmospheric transport of the fragmented magma and gas mixture approximates a thermally buoyant plume.

As the eruptive mixture rises in the plume of a violent Strombolian eruption, it entrains and heats air, which, in turn, reduces the bulk density of the mixture, and the plume becomes buoyant and continues to rise as a plume (BSC 2003 [166407], Section 6.3.5.2). The plume rises to an altitude of neutral buoyancy compared to the surrounding atmosphere, in which it then spreads laterally as an anvil cloud and is transported down wind. Tephra particles fall out from both the vertical eruption column and from the anvil cloud according to their settling velocities. Such eruptions produce a fallout sheet of varying thickness extending from the volcanic vent (e.g., Section 7.3.3, Figure 11). The thickness of the deposit depends on factors such as particle density, eruptive parameters, wind speed and direction, and distance from the vent (Suzuki 1983 [100489]).

ASHPLUME is designed to model violent Strombolian eruption behavior as a thermally buoyant plume, calculating the atmospheric dispersal of tephra and its deposition on the ground. Furthermore, ASHPLUME calculates the entrainment of waste in the erupted plume by an “incorporation ratio,” which defines the minimum ash particle size needed to carry a given waste particle size in the plume (Section 6.5.1). By doing so, the fallout of tephra carries fuel particles to where they are deposited on the ground, forming a contaminated fallout deposit. The contaminated fallout has the potential to affect the food and water supplies of the RMEI by direct contamination or by later surface redistribution of fallout deposits, which could be carried to the RMEI location by a number of mechanisms (BSC 2003 [164186]). It is beyond the scope of this report to identify the mechanisms for human exposure due to the described eruptive model. The scope of this conceptual model begins with the intersection of waste by the magma and ends with the ash-waste mixture settling to the ground surface. The ASHPLUME conceptual and mathematical models are appropriate for estimating the ground-level concentration of waste fuel within the limitations discussed in Section 1.3. Outputs of the ASHPLUME model include prediction of ash/waste areal densities (g/cm^2) at prescribed points surrounding the volcanic vent.

The ground-surface concentration and redistribution of waste, combined with BDCFs, will be used as input to the TSPA model to calculate the dose at the RMEI location. The analysis documented in this model report will improve and clarify the previous documentation of the ASHPLUME model and its application to TSPA-LA igneous scenarios.

6.4 CONSIDERATION OF ALTERNATIVE CONCEPTUAL MODELS

The consideration of alternative conceptual models (ACMs) for each of the two models documented in this report is described in Sections 6.4.1 and 6.4.2. Note that the ash redistribution conceptual model is the first of its kind.

6.4.1 Consideration of Alternative Conceptual Models for Airborne Transport of Tephra

Several ACMs were considered to evaluate the violent Strombolian eruption and transport of the ash/waste mixture. The qualitative evaluations conducted are summarized in the following discussions.

6.4.1.1 Gaussian-Plume Model

Methods used previously to estimate radionuclide dispersal by volcanism (Wescott et al. 1995 [100476]) theorize that the ash cloud travels as 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's surface due to gravitational settling. Contaminant concentration in the plume follows a Gaussian distribution in the 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). However, a point-source approximation may not be appropriate for a volcanic eruption because a volcanic-eruption column is usually modeled as 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 could lead to predictions of a higher upper limit on the particle-size range for particles dispersed a significant distance downwind than would be the case in reality. The increased particle size would result in the distribution of a larger amount of waste farther downwind than would normally be expected after a basaltic eruption. Based on these factors, the Gaussian-plume ACM is excluded from further evaluation because the model does not adequately portray a volcanic eruption column and is not conservative in the distribution of contaminated ash.

6.4.1.2 PUFF

PUFF (Searcy et al. 1998 [101015]) was evaluated conceptually based on descriptions in the scientific literature. The PUFF model was developed primarily to predict airborne distribution of ash plumes to aid aircraft navigation near volcanic eruptions. The PUFF conceptual model does not include incorporation of contaminated particles with the ash plume or calculate ground-level concentrations due to settling. The PUFF model was excluded from further evaluation because of these limitations.

6.4.1.3 Gas-Thrust Code

Another ACM considered was the gas-thrust code that was proposed in the NRC's *Igneous Activity Issue Resolution Status Report* (IRSR) (Reamer 1999 [119693], Section 4.2.2.3). Use of the code would require either the development of an atmospheric transport and deposition model to couple to the gas-thrust code or a code would have to be developed to retrofit the gas-thrust code to an existing atmospheric transport model. The ash-dispersion controlling constant (beta) within the ASHPLUME code has an analogous effect to the gas-thrust code. The parameter beta has the effect of generating a vertical distribution of particles above the volcano. The gas-thrust

code is a variation on this concept and falls within the uncertainties associated with the input parameter values used in forming the beta distribution. The gas-thrust ACM was excluded from further evaluation because ASHPLUME, without modification, uses input parameters that incorporate the vertical distribution of particles above a volcano.

6.4.1.4 Alternative Igneous Source Term Model

The Alternative Igneous Source Term model was developed by Codell (2003 [165503]) as an extension of ASHPLUME to investigate the processes of waste fragmentation and incorporation into the tephra. Despite an in-depth review of thermal, chemical, and physical processes of waste degradation in the presence of magma, there are no reliable means to predict the grain size of incorporated waste, and Codell concludes that one should assume that all waste from damaged waste packages is incorporated homogeneously into the magma/pyroclast medium as a fine-grained material. Codell's (2003 [165503]) main improvement over ASHPLUME is the addition of a complex model for the mixing of ash and fuel particles. While ASHPLUME uses a fixed incorporation ratio to specify the mixing of fuel and ash by particle size, Codell's (2003 [165503]) alternative model allows for a range of fuel concentrations on a given ash particle, following the rule that the fraction of mass of fuel incorporated into ash is proportional to the mass of the ash. To accomplish this, the ACM bins the ash-particle-size distribution, develops symbolic "indicator particles" to represent the mass of ash in each bin, and then distributes the available mass of fuel to those indicator particles according to a probability function. Therefore, Codell's (2003 [165503]) particles range much more widely in density than those used in the current ASHPLUME model, which produces the possible existence of dense particles that would fall out of the column sooner than is predicted by the current model. However, Codell (2003 [165503]) found that the difference in results between ASHPLUME and the ACM was, on average, within a factor of two for fuel concentration and that ASHPLUME typically predicts higher concentrations, and is, therefore, more conservative. Codell (2003 [165503]) concludes that given other, larger, uncertainties in modeling volcanism, ASHPLUME is credible.

In summary, this alternative model explores aspects of waste incorporation into the magma and ash beyond the scope of previous work. However, despite the detailed analysis of concepts of waste/magma mixing and a complex approach to the mixing of waste and ash particles, the resulting predictions of waste concentration on the ground are not significantly different from the current model and may, therefore, be excluded from consideration.

6.4.2 Consideration of Alternative Conceptual Model for Ash Redistribution

The ash redistribution conceptual model is based on observations and laboratory data from field work in Fortymile Wash, on the Fortymile Wash alluvial fan, and from drainages near the Lathrop Wells cone. Specifically, the ash redistribution conceptual model is based on erosion rate data, soil profile data, and surficial processes information collected in the Yucca Mountain area, including sample locations in Fortymile Wash and surrounding the Lathrop Wells cone. The documentation of this ash redistribution conceptual model is the first of its kind. Therefore, there are no ACMs.

6.4.3 Summary of Alternative Conceptual Models

Table 7 summarizes the ACMs considered for use to evaluate the volcanic direct release scenario and the screening status of the alternative models. Based on the screening of the ACMs considered, the ASHPLUME model was determined to be the most appropriate model for use in TSPA-LA calculations of atmospheric dispersal and deposition of tephra due to a volcanic eruption through the repository.

Development of the ash redistribution conceptual model is based on analog data from sites at and near Yucca Mountain. The documentation of this model is the first of its kind; therefore, there are no ACMs.

Table 7. Alternative Conceptual Models Considered for Airborne Transport of Tephra

Alternative Conceptual Model	Key Assumptions	Screening Assessment and Basis
Gaussian Plume	Point source, Gaussian distribution of plume	Excluded—line source required, larger particles are not accurately accounted for in gravitational settling.
PUFF	Convection and dispersion of ash from a volcanic eruption	Excluded—model still in development, waste-fuel interaction not included, surface concentrations not available.
Gas-Thrust	Buoyancy of a vertical erupting column	Excluded—atmospheric transport not available, surface concentrations of waste and ash not available.
Alternative Igneous Source Term	ASHPLUME plus probability model for size of waste particles mixing with a given ash particle	Excluded—results of ACM not significantly different from those of ASHPLUME.

6.5 ASH DISPERSAL CONCEPTUAL MODEL DESCRIPTION

The model of atmospheric dispersal and deposition of tephra used in the TSPA-LA and implemented with the ASHPLUME mathematical model is based on a theoretical model for the dispersion of tephra developed by Suzuki (1983 [100489]). Jarzemba et al. (1997 [100987]) extended the mathematical model to include the incorporation of waste-fuel particles with tephra particles. This section presents the mathematical formulation of the Suzuki/Jarzemba dispersion model and discusses model inputs developed for use in the TSPA-LA.

6.5.1 Mathematical Description of the Base-Case Conceptual Model

The movement of air mass in the atmosphere is random within the scale of eddy motions in wind currents (Suzuki 1983 [100489]). Therefore, the dispersion of the ash-waste particles in the atmosphere is also random. Particles disperse in the atmosphere in both vertical and horizontal

directions. However, the scale of horizontal turbulence is much greater than the scale of vertical turbulence (Suzuki 1983 [100489]). Therefore, in the Suzuki (1983 [100489]) development of the mathematical model, particle diffusion is considered to be 2-D in the horizontal x - y plane. Particle movement in the third (vertical) direction is accounted for by settling velocity in the Suzuki model.

The underlying 2-D partial differential equation relating the change in concentration, C , at a point x - y (with x downwind) to wind velocity, u , and an eddy diffusivity constant, K , follows (Suzuki 1983 [100489]):

$$\frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial x} + \frac{\partial}{\partial x} \left(K \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(K \frac{\partial C}{\partial y} \right). \quad (\text{Eq. 1})$$

Because the x direction is assumed to be aligned with the wind, the y component of the convective term in Equation 1 is zero. By selecting an appropriate value for the diffusivity constant K , Equation 1 is appropriate for estimating the 2-D diffusion of particulate matter in the atmosphere downwind from a source of contamination. Suzuki (1983 [100489]) developed the mathematical model shown in Equation 1 for application to atmospheric dispersal of tephra by applying source conditions and settling velocities suitable for explosive volcanic eruptions that are unlikely, but possible, in the YMR and termed violent Strombolian. Jarzemba et al. (1997 [100987]) further developed the model to calculate the concentration of spent-fuel waste particles that become incorporated with ash particles in the case of a hypothetical volcanic eruption through the Yucca Mountain repository. A summary of the mathematical development in Suzuki (1983 [100489]) and Jarzemba et al. (1997 [100987]) of the ash-waste dispersal model follows.

To derive a solution to Equation 1 suitable for application to calculation of tephra dispersion in the atmosphere after a volcanic eruption, Suzuki (1983 [100489]) used the following boundary and initial conditions.

- Erupted material (the source boundary) consists of a finite mass of volcanic ash particles contaminated with waste particles.
- The source of tephra particles is described by the distribution of the diameter of the released particles, and the distribution has a single mode.
- Combined ash/waste particles have a probability to diffuse out of the eruption column during upward travel in the column.
- All particles fall at the terminal velocity and finally accumulate on the ground.

The solution to the mathematical model described in Equation 1 is provided by Suzuki (1983 [100489]) and can be summarized by the following equation that describes the areal density of accumulated ash on the Earth's surface after an eruption:

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

where

$X(x, y)$ = mass of ash per unit area accumulated at location (x, y) in g/cm^2

ρ = common logarithm of particle diameter d , where d is in cm

$\rho_{\min}$ = minimum value of ρ

$\rho_{\max}$ = maximum value of ρ

z = vertical distance of particle from ground surface in km

H = height of eruption column above vent in km

$x = x$ coordinate on the surface of the Earth oriented in the same direction as the prevailing wind in cm

$y = y$ coordinate on the surface of the Earth, oriented perpendicular to the direction of the prevailing wind in cm

Q = total quantity of erupted material in g

$p(z)$ = distribution function for particle diffusion out of the column within $\pm dz$ of height z

$f(\rho)$ = distribution function for log-diameter of particles within $\pm d\rho$ of ρ normalized per unit mass

C = constant relating eddy diffusivity and particle fall time in $\text{cm}^2/\text{s}^{5/2}$

t = particle fall time in s

t_s = particle diffusion time in eruption column in s

u = wind speed in cm/s.

The probability density distribution function for particle diffusion out of the eruption column $p(z)$ is given by (Suzuki 1983 [100489]):

$$p(z) = \frac{\beta W_0 Y e^{-Y}}{V_0 H \{1 - (1 + Y_0) e^{-Y_0}\}} \quad (\text{Eq. 3})$$

where

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

$$Y_0 = \frac{\beta W_0}{V_0}$$

β = a constant controlling diffusion of particles in the eruption column

W_0 = initial particle rise velocity in cm/s

V_0 = particle terminal velocity at mean sea level in cm/s

$W(z)$ = particle velocity as a function of height = $W_0 \left(1 - \frac{z}{H}\right)$ in cm/s.

According to Jarzemba et al. (1997 [100987]), the definitions of Y and Y_0 differ from those found in Suzuki (1983 [100489]), that is, $Y = \frac{\beta(W(z) - V_0)}{V_0}$ and $Y_0 = \frac{\beta(W_0 - V_0)}{V_0}$, for two reasons:

- The definitions in Suzuki (1983 [100489]) lead to negative values of $p(z)$ at heights approaching the top of the column, and
- $p(z)$ (Equation 3) integrated over all column heights does not equal one using the definitions of Y and Y_0 found in Suzuki (1983 [100489]).

The revised definitions provided in Jarzemba et al. (1997 [100987]) are used in this document.

The particle terminal velocity at mean sea level is given by (Suzuki 1983 [100489]):

$$V_0 = \frac{\psi_p g d^2}{9\eta_a F^{-0.32} + \sqrt{81\eta_a^2 F^{-0.64} + \frac{3}{2}\psi_p \psi_a g d^3 \sqrt{1.07 - F}}} \quad (\text{Eq. 4})$$

where

Ψ_a, Ψ_p = density of air and of particles, respectively in g/cm³

g = gravitational acceleration constant = 980 cm/s²

η_a = viscosity of air in g/cm-s

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

d = mean particle diameter in cm.

Jarzemba et al. (1997 [100987]) define particle density, Ψ_p in g/cm³, to be a function of the particle log-diameter, ρ_a in cm, as follows:

$$\begin{aligned} \Psi_p &= \Psi_p^{high} && \text{for } \rho_a < \rho_a^{low} \\ \Psi_p &= \Psi_p^{low} + (\Psi_p^{high} - \Psi_p^{low})(\rho_a^{high} - \rho_a)/(\rho_a^{high} - \rho_a^{low}) && \text{for } \rho_a^{low} < \rho_a < \rho_a^{high} \text{ (Eq. 5)} \\ \Psi_p &= \Psi_p^{low} && \text{for } \rho_a > \rho_a^{high} \end{aligned}$$

where Ψ_p^{high} , Ψ_p^{low} , ρ_a^{high} , and ρ_a^{low} are defined by user inputs.

The particle fall time (in s) is given by (Suzuki 1983 [100489]):

$$t = 0.752 \times 10^6 \left[\frac{1 - e^{-0.0625z}}{V_0} \right]^{0.926} \quad (\text{Eq. 6})$$

For a detailed derivation of Equations 2 through 6, the reader is referred to Suzuki (1983 [100489]).

The height of the eruption column or plume, H , used in Equation 2, follows buoyant plume theory applied to volcanic eruptions by Wilson et al. (1978 [162859]) and discussed in Jarzempa et al. (1997 [100987]). In ASHPLUME, height in km is given as:

$$H = 0.0082P^{0.25} \quad (\text{Eq. 7a})$$

where the eruption column power, P , in watts, is determined by the eruption mass flux and heat content:

$$P = \dot{Q}(C_p \Delta T E) \quad (\text{Eq. 7b})$$

The parameters in parentheses in Equation 7b represent the heat content and its efficiency in adding buoyancy; they are fixed by magma and tephra characteristics. The mass flux, $\dot{Q}$, can be evaluated by assuming a constant eruptive mass flux over the duration of the eruption, which is related to the erupted ash settled volume by

$$\dot{Q} = \frac{Q}{T_d} = \frac{V\psi_s}{T_d} = \psi_m W_0 \pi \left(\frac{d_c}{2} \right)^2 \quad (\text{Eq. 7c})$$

where

C_p = specific heat capacity of magma

ΔT = temperature difference between magma and ambient

E = efficiency factor of heat usage (1.0 for Equation 7b)

Q = total mass of erupted material

V = ash erupted volume

T_d = eruption duration

ψ_s = ash settled density

ψ_m = bulk density of erupting magma and gas mixture

d_c = effective conduit (vent) diameter.

In contrast to Equation 7a, Equations 7b and 7c are not presented using specific units; however, a consistent set of units must be used (e.g., SI or cgs). The ASHPLUME model input parameters of initial rise velocity, power, and duration are linked in Equations 7b and 7c and determine the plume height in Equation 7a; velocity also contributes to the probability density distribution function (Equation 3). Accordingly, the basis for selecting these parameters is further discussed

in Section 6.5.2. The value for the efficiency factor (E) is assumed to be 1.0 in this analysis, given the uncertainties in values for C_p and ΔT (Heiken et al. 2003 [166290], pp. 41 to 42).

In the Suzuki mathematical model (Suzuki 1983 [100489]), the volcanic ash mass is distributed log-normally with particle size:

$$f(\rho^a) = \frac{1}{\sqrt{2\pi}\sigma_d} \exp\left[-\frac{(\rho^a - \rho_{\text{mean}}^a)^2}{2\sigma_d^2}\right] \quad (\text{Eq. 8})$$

where

$f(\rho^a)$ = normalized (per unit mass) probability distribution for ash mass

ρ^a = log-diameter of ash particle size, with particle size in cm

ρ_{mean}^a = mean of log-diameter of ash particle size, with particle size in cm

σ_d = standard deviation of log particle size.

The TSPA analyses for Yucca Mountain require a prediction of spent fuel per unit area on the ground surface as a function of location relative to the volcanic vent (i.e., relative to the repository) after a hypothetical eruption through the repository. It is assumed (Section 5.1.3) that the transport mechanism for waste fuel particles is by attachment to ash particles larger than a certain relative size represented by an incorporation ratio.

The rationale for limiting the amount of fuel mass available for incorporation into a volcanic-ash particle 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, it is unlikely that a 1-cm fuel particle could 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 (ρ_c) of 1. Mathematically, the incorporation ratio is defined as (Jarzemba et al. 1997 [100987]):

$$\rho_c = \log_{10} \left[\frac{d_{\text{min}}^a}{d^f} \right] \quad (\text{Eq. 9})$$

where

d_{min}^a = minimum ash particle size needed for incorporation in cm

d^f = fuel particle size in cm.

Setting the incorporation ratio, ρ_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.

Fuel mass is defined in Jarzemba et al. (1997 [100987]) as following a log-triangular distribution function of the log-diameter of fuel particles (specifically, a log-triangular distribution for fuel mass within $\pm d\rho^f$ of ρ^f normalized per unit mass). The log-triangular distribution is defined in

Equation 10. It should be noted that an error in the Jarzemba et al. (1997 [100987]) presentation of the fuel particle size log-triangular distribution has been corrected here in Equation 10 by reversing the sign on the coefficient k_2 .

$$\begin{aligned}
 m(\rho^f) &= k_1(\rho^f - \rho_{\min}^f) && \text{for } \rho_{\min}^f < \rho^f \leq \rho_{\text{mode}}^f \\
 &= k_1(\rho_{\text{mode}}^f - \rho_{\min}^f) - k_2(\rho^f - \rho_{\text{mode}}^f) && \text{for } \rho_{\text{mode}}^f < \rho^f \leq \rho_{\max}^f \\
 &= 0 && \text{otherwise}
 \end{aligned} \tag{Eq. 10}$$

where

ρ^f = log-diameter of fuel particle size, with particle size in cm

$$k_1 = \frac{2}{(\rho_{\max}^f - \rho_{\min}^f)(\rho_{\text{mode}}^f - \rho_{\min}^f)}$$

$$k_2 = \frac{2}{(\rho_{\max}^f - \rho_{\min}^f)(\rho_{\max}^f - \rho_{\text{mode}}^f)}$$

$\rho_{\min}^f$ = minimum log-diameter of fuel particle size, with particle size in cm

$\rho_{\max}^f$ = maximum log-diameter of fuel particle size, with particle size in cm

ρ_{mode}^f = mode log-diameter of fuel particle size, with particle size in cm.

Jarzemba et al. (1997 [100987]) determined the fuel fraction (ratio of fuel mass to ash mass) as a function of ρ^a by considering that all fuel particles of size smaller than $(\rho^a - \rho_c)$ have the ability to be incorporated simultaneously into volcanic-ash particles of size ρ^a or larger. The fuel fraction as a function of ρ^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

$$FF(\rho^a) = \frac{U}{Q} \cdot \int_{\rho=-\infty}^{\rho=\rho^a} \frac{m(\rho - \rho_c)}{1 - F(\rho)} d\rho \tag{Eq. 11}$$

where

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

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

m = probability density function of fuel mass

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

Equation 11 assumes the resulting contaminated particles follow the same size distribution as the original volcanic ash particles. This assumption seems reasonable because the total mass of volcanic ash erupted will be much greater than the total mass of fuel available for incorporation. Introduction of a relatively small amount of fuel mass into the ash mass is unlikely to alter the size distribution of the ash. The mathematical and computational models do, however, adjust the density of ash particles to account for the incorporation of fuel. The particle density used in the

calculation of the terminal velocity of a particle is adjusted as a combined particle in the dispersion calculation. The combined-particle density is adjusted by a statement in the ASHPLUME code: $\text{ashden} = \text{ashden} \times [1 + \text{fuel fraction}]$. In this statement, “ashden” represents the ash particle density and “fuel fraction” represents the mass fraction of fuel in the combined particle. The integrand of Equation 2 is multiplied by $FF(\rho^a)$ and then recalculated to find the spent fuel density at the (x, y) location.

6.5.2 Base-Case Model Inputs

The values for input parameters to ASHPLUME are developed from observed, or primary, data from analog volcanoes. Self-consistent relationships among eruptive duration, eruptive volume, and vent radius are used in Equation 7c to derive values for initial rise velocity and mass flux (see Section 5.2.5 for further discussion). Mass flux is in turn used to derive eruptive power (a primary model input) in Equation 7b. Finally, eruptive height, calculated from power, is used to define the atmospheric height bin from which wind speed and direction are sampled. While values for mass flux (or power) and initial eruptive velocity could be chosen from published values, the model is kept self-consistent by the use of appropriate ranges in primary data for the YMR (e.g., eruptive volume, eruptive duration, and vent radius) developed in BSC (2003 [166407]). In addition, the relationships among the primary data provide upper and lower bounds on the distributions for derived input parameters (Heiken et al. 2003 [166290]); for instance, the minimum mass flux is derived from the minimum erupted volume and the maximum eruption duration. These values, combined with reasonable material properties data (ash settled density, magma density, magma specific heat, and temperature difference) provide a firm link between the model performance and primary data. The ash settled density, which is the bulk density of the ash that settles on the ground after an eruption, is provided in BSC (2003 [166407], Table 38) as 1.0 g/cm^3 . Magma density is also provided in BSC (2003 [166407], Table 38), and magma specific heat is provided in Bacon (1977 [165512]) and Drury (1987 [156447]).

Once the primary input parameter values have been developed (e.g., eruptive power and duration), they are used within the ASHPLUME code at run time to calculate values for column height (from power) and total mass of ash (from power and duration), among others, for use in transport calculations. Because these values are calculated using equivalent mathematical relationships, the results of the model are consistent with the primary data used to develop the input parameter values.

For the ASHPLUME_DLL_LA V 2.0 computer code (STN: 11117-2.0-00 [166571]) to calculate the concentration of ash and waste fuel on the ground surface according to Equation 2, parameter values must be provided for all of the unknown coefficients in the governing Equations 2 to 11 given above in Section 6.5.1. ASHPLUME_DLL_LA V 2.0 allows parameters that are distributions to be sampled outside of the ASHPLUME code (within the TSPA-LA GoldSim model). GoldSim then passes the sampled point values for each parameter into the ASHPLUME_DLL_LA V 2.0 code. Each realization simulates only one volcanic event at a time. The following sections discuss each of the parameters given in Table 8 in more detail and provide the technical basis for the parameter values and distributions.

Table 8. Inputs for the ASHPLUME Model

Coefficient (Equation Number)	Input Description	Point Value or Distribution	Data Source
x and y (Eq. 2)	Determined by wind direction	Wind direction is a distribution	Based on location of the RMEI
ψ_p^{high} (Eq. 5)	Ash particle density at minimum particle size	Point value	BSC (2003 [166407])
ψ_p^{low} (Eq. 5)	Ash particle density at maximum particle size	Point value	BSC (2003 [166407])
ρ_a^{high} (Eq. 5)	Log ash particle size at minimum ash density	Point value	BSC (2003 [166407])
ρ_a^{low} (Eq. 5)	Log ash particle size at maximum ash density	Point value	BSC (2003 [166407])
F (Eq. 4)	Ash particle shape factor	Point value	BSC (2003 [166407])
ψ_a (Eq. 4)	Air density	Point value	Lide (1994 [147834])
η_a (Eq. 4)	Air viscosity	Point value	Lide (1994 [147834])
C (Eq. 2)	Eddy diffusivity constant	Point value	Calculated from information in Suzuki (1983 [100489])
d_{max}	Maximum particle diameter for transport	Point value	Jarzemba et al. (1997 [100987])
ρ_{min}^f (Eq. 10)	Minimum waste particle size	Point value	CRWMS M&O (2001 [153938])
ρ_{mode}^f (Eq. 10)	Mode waste particle size	Point value	CRWMS M&O (2001 [153938])
ρ_{max}^f (Eq. 10)	Maximum waste particle size	Point value	CRWMS M&O (2001 [153938])
H_{min}	Minimum height of eruption column	Point value	Minimum practical value
<i>Ash Cutoff</i>	Threshold limit on ash accumulation	Point value	Minimum practical value
β (Eq. 3)	Column diffusion constant	Distribution	Jarzemba et al. (1997 [100987])
d (Eq. 4)	Mean ash particle diameter	Distribution	BSC (2003 [166407])
σ_d (Eq. 8)	Ash particle diameter standard deviation	Distribution	BSC (2003 [166407])
ρ_c (Eq. 9)	Waste incorporation ratio	Point value	Jarzemba et al. (1997 [100987])
U (Eq. 11)	Mass of waste to incorporate	Distribution determined by TSPA model	N/A
<i>Wind Direction</i>	Wind direction	Distribution	NOAA (1995 [154435])
u (Eq. 2)	Wind speed	Distribution	NOAA (1995 [154435])
W_o (Eq. 3)	Initial rise velocity	Distribution	See Section 6.5.2.10
P (Eqs. 7a and 7b)	Eruptive power	Distribution	See Section 6.5.2.1
T_d	Eruption duration	Distribution	BSC (2003 [166407])

6.5.2.1 Eruptive Power, P

Type: log uniform distribution
Value: $6.17 \times 10^8 - 5 \times 10^{12}$
Units: Watts

The range of eruptive power is a function of settled volumes and eruption duration as shown in Equations 7b and 7c. The range for the event eruptive volume to be expected in the YMR is defined in *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002 (BSC 2003 [166407]) as 0.004–0.08 km³. The range of eruption duration is discussed below in Section 6.5.2.2. By converting the lowest volume to mass, using the settled density (1.0 g/cm³; see Section 6.5.2), and dividing this mass by the longest duration to get eruptive mass flux, the lower limit of eruptive power is set by Equation 7b. In contrast, the upper limit of power is set to the value using the maximum mass flux recommendations of the Igneous Consequences Review Panel (Detournay et al. 2003 [162914], p. 18). This range in power is consistent with and slightly more conservative than the distribution for eruptive power developed in BSC (2003 [166407]).

6.5.2.2 Eruption Duration, T_d

Type: log-uniform distribution
Value: $8.64 \times 10^4 - 6.48 \times 10^6$
Units: seconds

The range of eruption durations and rationale for using this range of values is discussed in *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002 (BSC 2003 [166407], Table 38). The range of values spans times from 1 day to 75 days (the duration of a single explosive phase constituting a violent Strombolian eruptive phase). This parameter is used within ASHPLUME to calculate the total mass erupted, Q . The range in eruption duration is also used to bound the upper and lower limits on the distribution for eruptive power, P , using Equation 7c; for example, minimum mass flux is a function of minimum volume and maximum duration. The value for eruption duration in each model realization is determined by Equation 12 (Section 8) such that the total volume of the eruption remains within the bounds provided in BSC (2003 [166407], Table 38).

6.5.2.3 Column Diffusion Constant, β

Type: uniform distribution
Value: 0.01 - 0.5
Units: N/A

The column diffusion constant (β) is set at a uniform distribution with a minimum value of 0.01 and a maximum value of 0.5.

The column diffusion constant was discussed by Suzuki (1983 [100489], pp. 104 to 107). This parameter affects the distribution of particles vertically in the ash column and helps determine where particles exit the column. The erupted ash cloud is assumed (by Suzuki) to spread axially a distance of half the height. ASHPLUME takes a beta value and determines the vertical profile

of particle sizes in the erupted column that will then be transported down wind. Suzuki discussed beta values of 0.01, 0.1, and 0.5. The larger beta becomes, the more the particle distribution becomes skewed towards the top of the column. Therefore, a value of 0.5 generates a column particle distribution that contains very few particles in the lower 70 percent of the column, whereas a beta value of 0.01 gives an upwardly decreasing distribution that contains the most particles lower in the column. The beta parameter, in effect, is related to the buoyancy of particles in the eruptive column and determines how high most particles will travel before exiting the column. Suzuki (1983 [100489]) suggests that beta values of 0.5 or greater are possible but are not very likely to occur. Jarzempa et al. (1997 [100987], p. 4-1) uses a log-uniform distribution for beta that has a minimum value of 0.01 and a maximum value of 0.5. This range of values spans more than an order of magnitude and encompasses the range that is valid for the ASHPLUME model. However, in order to simulate the anvil cloud associated with a violent Strombolian eruption properly, samples from the range in beta should be focused toward the upper end of the range; therefore, a uniform (rather than log-uniform) distribution is recommended (Section 5.2.2).

6.5.2.4 Mean Ash Particle Diameter, d

Type: log-triangular distribution

Value: 0.001 - 0.01 - 0.1

Units: cm

The ash particle diameter is defined within the ASHPLUME model by two parameters: the mean ash particle diameter and the ash particle diameter standard deviation. The mean ash particle diameter for the volcanic eruption is defined in BSC (2003 [166407], Table 38) as a log triangular distribution with a minimum value of 0.001 cm, a mode value of 0.01 cm, and a maximum value 0.1 cm. The rationale for using this range of mean ash particle diameter is discussed in BSC (2003 [166407] Sections 6.3.5.2 and Section 7.1). The lower end of the distribution is intended to capture the respirable fraction between 0.001 cm and 0.01 cm (BSC 2003 [166407] Section 6.3.5.2). BSC (2003 [166407], Section 6.3.5.2) also describes analog data that would justify larger ash particle distributions; however, the model is intentionally biased to overestimate ash dispersal associated with violent Strombolian eruptions. For comparison, Jarzempa (1997 [100460], p. 137) gives a log-triangular distribution with a minimum of 0.01 cm, a median of .1 cm, and a maximum of 10 cm. Although this upper range would account for the larger lapilli sizes and smaller blocks and bombs, these particles would fall on or near the cone and would not contribute much or any mass to the downwind tephra deposit.

6.5.2.5 Ash Particle Diameter Standard Deviation, σ_d

Type: uniform distribution

Value: (-1.9)-(-1.3)

Units: log (cm)

The ash particle diameter standard deviation is discussed in BSC (2003 [166407], Section 6.3.5.2) and is derived from analog data. The referenced report (BSC 2003 [166407], Table 38) suggests a uniform distribution from 1 to 3 phi units (phi units are defined to be the negative logarithm in base 2 of the particle diameter in millimeters). This range is equivalent to -1.9 to -

1.3 log (cm), which are the units required by ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]).

6.5.2.6 Waste Incorporation Ratio, ρ_c

Type: point value

Value: 0.3

Units: N/A

The incorporation ratio describes the ratio of ash/waste particle sizes that can be combined for transport. An incorporation ratio of 0.3 was used by Jarzemba et al. (1997 [100987], Table 5-1) and is used here (see Section 6.5.1 for additional discussion). An incorporation ratio of 0.3 corresponds to a maximum incorporated waste particle size equal to half the diameter of the ash particle (i.e., any waste particles larger than half the ash particle diameter cannot be incorporated into the ash).

The waste mass is distributed among the ash mass based on relative particle sizes. The waste mass is not divided equally among the ash particles. Incorporation of waste particles requires ash particles of a certain size or larger. Thus, larger ash particles will carry more waste mass, and smaller ash particles will carry less or maybe even no waste mass.

The results of an analysis of TSPA sensitivity to variations in the incorporation ratio was documented in the TSPA-SR (CRWMS M&O 2000 [153246]; Section 5.2.9.11), considering variations in ρ_c from 0.1 to 1.0. That analysis showed that the annual eruptive dose rate increased by a negligible factor for an incorporation ratio of 0.1. The incorporation ratio of 0.1 increased the diameter of waste particles that were incorporated in the eruption to those that were 80 percent of the ash particle diameter. An incorporation ratio of 1.0, which decreased the incorporation of particles to ≤ 10 percent of the ash particle diameter, caused a reduction of less than a factor of 2 in the probability-weighted mean annual dose rate. The relative lack of sensitivity to uncertainty in this parameter suggested that most waste particles were being incorporated in the eruption with the value of 0.3 and that, even with the smaller value, only the largest waste particles were not incorporated.

6.5.2.7 Wind Speed, u

Type: empirical distribution

Value: Tables III-14 through III-26

Units: cm/s

NOAA (1995 [154435]) provides wind speed data for the Desert Rock area for a 16-year period from 1978 to 1993. After converting height data to height above Yucca Mountain, data were grouped into 1-km increments from 0 km up to 13 km. The wind speed data for each height interval were then used to calculate CDFs with bins set to ~ 51 cm/s (1 knot) intervals. Attachment III contains a detailed description of the steps required to develop the wind speed CDFs. Although Quiring (1968 [119317]) provides wind speed data for the YMR for a seven-year period from 1957 to 1964, those data do not extend to sufficiently high altitudes to address

fully the range of potential column heights that ASHPLUME considers; thus, the data from Desert Rock are more appropriate.

6.5.2.8 Wind Direction, Determines x and y

Type: empirical distribution
Value: Tables III-28 through III-40
Units: ASHPLUME degrees

NOAA (1995 [154435]) provides wind direction data for the Desert Rock area for a 16-year period from 1978 to 1993. After converting Desert Rock height data to height above Yucca Mountain, data were grouped into 1-km increments from 0 km up to 13 km. The wind direction data for each height interval were then used to calculate probability distribution functions (PDFs) and associated wind-rose diagrams, with bins set to 30-degree intervals. Attachment III contains a detailed description of the steps required to develop the wind direction PDFs. Although Quiring (1968 [119317]) provides wind speed data for the YMR for a seven-year period from 1957 to 1964, those data do not extend to sufficiently high altitudes to address fully the range of potential column heights that ASHPLUME considers; thus, the data from Desert Rock are more appropriate.

6.5.2.9 Mass of Waste Available for Incorporation, U

Value: distribution will be passed to ASHPLUME; determined by the TSPA-LA model
Units: grams

The mass of waste available for incorporation with ash particles is an input for the ASHPLUME V 2.0 code (STN: 10022-2.0-00 [152844]). However, this parameter is not developed within this model report. The waste mass depends upon factors such as waste inventory and the number of waste packages disturbed in a volcanic eruption. These factors are defined elsewhere in the TSPA-LA model, and the resulting waste mass available is passed to ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) at run time.

6.5.2.10 Initial Rise Velocity, W_o

Type: log uniform distribution
Value: $1.0 - 1.2 \times 10^4$
Units: cm/s

Termed “the eruption velocity at the vent” for previous versions of ASHPLUME, the initial rise velocity is assumed to be the minimum velocity required to provide the modeled power to the plume as described in Section 5.2.5. This velocity is a function of vent velocity. Although vent velocities are shown to be a function of magma volatile content in *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002, (BSC (2003 [166407])), those velocities do not reflect the deceleration of the tephra particles that occurs before their entry into the plume, which must be assumed for application of the ASHPLUME model. Hence, this distribution must be calculated by Equations 7a - 7c, using maximum magma bulk density. This calculated distribution is solely a function of eruption power and conduit diameter: the former being a distribution specified in Section 6.5.2.1, and the latter enumerated in BSC (2003

[166407]) as ranging from 500 to 15,000 cm. As stated in Section 5.2.5, the importance of the initial rise velocity is to deliver the thermal mass (power) to the eruption column, and the velocity of the material entering the plume must only be that required to deliver the necessary power. Neglecting the gas-thrust part of the eruption column and given that the heat flux is directly proportional to the mass flux of magma to the vent, the simplest approach to developing the minimum initial rise velocity is to consider the minimum velocity of magma at the vent. This value can be derived from the minimum mass flux and maximum radius; given the ranges in these values (Heiken et al. 2003 [166290], p. 41) and a magma density of 2.6 g/cm^3 (BSC 2003 [166407]), the range in W_0 is 0.001 – 12000 cm/s. Wilson and Head (1981 [101034], p. 2977) report that the minimum practical value for rise speed of basalt in a 0.22-m-radius conduit is 0.12 m/s (12 cm/s); for a conduit in the range of tens of meters in radius (and for the same mass flux), this velocity could drop by an order of magnitude. The minimum value for W_0 has, therefore, been increased to 1.0 cm/s to provide a realistic lower bound while providing appropriate velocity values that successfully deliver the thermal mass to the eruption column. This increase in W_0 implies that, for minimum mass flux, the maximum effective vent radius is about 27 m, which is within the range of analogous conduit radii (DTN: LA0311DK831811.001 [166301]).

6.5.2.11 Ash Particle Density, Ψ_p

Type: point values

Values: Table 15

Units: g/cm^3

The ash particle density used in Equation 4 is defined in Equation 5. The ash particle density is defined to be a function of particle diameter in BSC (2003 [166407], Section 6.3.5.3). The ASHPUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code requires inputs for the densities of large and small ash particles. BSC (2003 [166407]) defines the densities of ash particles as a function of the magma density. This model report uses a magma density of 2.6 g/cm^3 , which is within the range of magma densities reported in BSC (2003 [166407], Table 38). The latter report (BSC 2003 [166407], Table 38) defines the density of a 0.001-cm ash particle to be 80 percent of the magma density (2.08 g/cm^3), whereas a 1.0-cm ash particle has a density of 40 percent of the magma density (1.04 g/cm^3). The particle diameters for input to parameters ρ_a^{high} and ρ_a^{low} must be entered as log values, that is, as log (cm).

6.5.2.12 Ash Particle Shape Factor, F

Type: point value

Value: 0.5

Units: N/A

The ash-particle shape factor is a parameter that is used to describe the shape of the ash particles being transported in the model. The shape factor is used in determining the settling velocity according to Equation 4. The shape factor (F) is defined as $F = (b + c)/2a$, where a , b , and c are the length of the longest, middle, and shortest axes of the particles. BSC (2003 [166407], Table 38) provides a particle shape factor of 0.5. This parameter applies to the ash and does not apply to the waste. The waste is incorporated into ash particles in order to be transported downwind,

and the ASHPLUME model treats all particles (ash and ash/waste combined) as having the same shape factor.

6.5.2.13 Air Density, ρ_a

Type: point value
Value: 0.001117
Units: g/cm³

The air density is used in calculating the particle-settling velocity in Equation 4. Because the density is nearly constant within the altitude range of interest, air density was selected as a point value (constant). The density was selected at an altitude of 1000 m above mean sea level and at ambient temperature of 25°C. The value of 0.001117 g/cm³ was taken from Lide (1994 [147834]).

6.5.2.14 Air Viscosity, η_a

Type: point value
Value: 0.0001758
Units: g/cm-s

The air viscosity is used in calculating the particle-settling velocity in Equation 4. Because the viscosity is nearly constant within the altitude range of interest, air viscosity was selected as a point value (constant). The viscosity was selected at an altitude of 1000 m above mean sea level and at ambient temperature of 25°C. The value of 0.0001758 g/cm-s was taken from Lide (1994 [147834]).

6.5.2.15 Eddy Diffusivity Constant, C

Type: point value
Value: 400
Units: cm²/s^{5/2}

The constant (C) controlling eddy diffusivity relative to particle fall time was modeled by Suzuki (1983 [100489], p. 99). The eddy diffusivity (K) of the particles is expressed by Suzuki as a function of the particle fall time, $K = Ct^{3/2}$, where t is the particle fall time. This relationship is based on turbulent particle diffusion and the simplification that the particle diffusion time equals the particle fall time (i.e., time to settle to the ground in seconds). The above relationship is obtained from Suzuki (1983 [100489], p. 99) because eddy turbulent diffusion occurs over large-scale eddies and can, thus, be related to the particle fall times. The apparent eddy diffusivity in cm²/s (A_L) of particles in the atmosphere is related to the scale of diffusion in cm (L) according to Suzuki (1983 [100489], p. 99) by $A_L = 0.08073C^{2/5}L^{6/5}$. Figure 2 in Suzuki (1983 [100489]) shows a linear relationship between $\log(A_L)$ and $\log(L)$ in the atmosphere and the correlation between L and A_L defined as $A_L = 0.887L^{6/5}$. Combining these equations yields a constant value for C of 400 cm²/s^{5/2}, which is the value selected in this model report.

6.5.2.16 Waste Particle Size (Minimum, Mode, Maximum)

Type: point values

Values: 0.0001 minimum, 0.0016 mode, 0.05 maximum

Units: cm

Waste fuel mass is treated as a log-triangular distribution with particle size in the ASHPLUME model (Equation 10). The minimum, mode, and maximum values defining the distribution are fixed values in the TSPA analyses and are provided to the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code in units of cm. The values are converted to log (cm) within the code. Assumptions providing the minimum (0.0001), mean (0.002), and maximum (0.05) particle diameter in centimeters are discussed in Section 5.2.4. Because ASHPLUME requires a mode value for the log-triangular distribution, the mean value of 0.002 cm (DTN: LL001104412241.019 [155224]) was converted to a mode value of 0.0016 cm according to $\mu = (a + b + c)/3$ where μ is the log of the mean value, a is the log of the minimum value, b is the log of the mode value, and c is the log of the maximum value (Evans et al. 1993 [112115]).

6.5.3 Other Model Inputs

ASHPLUME requires several other input parameter to control code operation that are not directly related to the mathematical model described in this section. These parameters are computational grid locations, maximum particle diameter for transport, minimum height of eruption column considered in transport, threshold limit on ash accumulation, run type, and an option of whether to save particle size information at the grid locations. These additional model inputs are discussed in the following sections.

6.5.3.1 Grid Location and Spacing for the X and Y Axes

Any grid (receptor) location can be specified for calculation of ash and fuel concentrations in the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code. The only limitation is that the volcanic vent location (0, 0) cannot be specified. The grid locations are defined by specifying a minimum and maximum X and Y location and the number of desired grid locations between the minimum and maximum. These parameters are shown in Table 15 in Section 8 for the TSPA-LA model feeds. As an example, to calculate the ash and fuel concentrations at a single point corresponding to the RMEI located approximately 18 km due south of the repository, the minimum and maximum X locations would be specified as 0.0 each, and the minimum and maximum Y locations would be specified as 0.0 and -18 km each, respectively. The number of X and Y locations would be specified as 1 and 2, respectively. In the ASHPLUME coordinate system, the point (0, 0) corresponds to the volcanic vent, 0 degrees is due east, 90 degrees is due north, 180 degrees is due west, and -90 degrees is due south. The appropriate coordinate transformations are made within the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code to be consistent with Equation 2.

6.5.3.2 Maximum Particle Diameter for Transport

The maximum particle diameter that can be transported down wind is specified as 10 cm in this model report. This parameter is a simple check within the code to limit the maximum size of particles that are considered for transport in the model. BSC (2003 [166407], pp. 78 to 79)

describes the range in tephra particle sizes observed at Lathrop Wells, Tolbachik, and Cerro Negro volcanoes, which are three of the analogs for a volcano that could possibly form in the YMR. Lathrop Wells ash, at a distance of 1 to 2 km, ranges in size from 0.125 to 8 mm, and grain sizes with significantly greater fine fractions (<0.125 mm) were noted at Tolbachik and Cerro Negro. BSC (2003 [166407], Table 16) lists coarsest median grain sizes for Lathrop Wells in the greater than 1-km distance as 1.16 mm with a standard deviation of 0.57. Thus, these data support the hypothesis that grain sizes greater than about 1 cm are not transported a significant distance down wind but, rather, fall ballistically near the cone. Therefore, the use of a 10-cm tephra-size cutoff for transport provides reasonable mathematical efficiency without biasing the model results.

6.5.3.3 Minimum Height of Eruption Column

This parameter allows the definition of a lower threshold height below which particle transport is not calculated within the code. It represents the lower limit of the inner integral of Equation 2. A value of 1 m is chosen because this is essentially zero, considering the heights of eruption that are simulated from Equation 7b. A value identically equal to zero is not numerically possible in the ASHPLUME_DLL_LA V 2.0 code (STN: 11117-2.0-00 [166571]).

6.5.3.4 Threshold Limit on Ash Accumulation

The value of 10^{-10} (g/cm²) selected in this model report defines the lower limit for the calculation of ash accumulation; below this value, the ash-concentration value is set to zero in the ASHPLUME_DLL_LA V 2.0 code (STN: 11117-2.0-00 [166571]). This limit is reasonable because any values lower than this will have a negligible effect on model results. This limit is intended to speed code calculations for large grids by eliminating calculations that result in concentrations below this value.

6.5.4 Summary of the Computational Model

The ASHPLUME mathematical model is implemented as a computer code using the standard FORTRAN 77 language. The integrations defined in the mathematical model are solved using standard numerical integration techniques. For use in the TSPA, the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code is implemented directly within the GoldSim software as a DLL. All model inputs are entered in GoldSim templates and passed directly to the ASHPLUME DLL. Table 15 in Section 8 provides a summary of all inputs required by GoldSim and relates ASHPLUME input parameters to the corresponding GoldSim variable names.

Model results are primarily produced within the TSPA model (GoldSim). The model results presented in this report include the calculation of mean fuel concentration at the RMEI location in Section 6.7.2 and the validation activity in Section 7. The ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code is required as a component of the TSPA model of the nuclear waste repository at Yucca Mountain. Within the TSPA, the atmospheric dispersal and deposition of tephra model implemented in the ASHPLUME code is used to predict the ground-level concentration of ash and waste after a violent Strombolian eruption that intersects the repository. The waste concentration is then combined with BDCFs in the TSPA model to calculate an annual dose to a RMEI. ASHPLUME model results are produced at run time within

the TSPA-LA model. The ASHPLUME model inputs discussed in this section, and summarized in Section 8, are provided as inputs to the TSPA-LA model as GoldSim variables. These variables are passed to the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) module at run time, and ASHPLUME calculates ash and fuel deposition in g/cm². The ash and fuel deposition values are passed back to the GoldSim model. Limited base-case model results are provided in the calculation of mean fuel concentration at the RMEI location (Section 6.7.2) via 100 realizations of distributed parameter values (except wind direction, which was held constant). Complete base-case model results will be available when the TSPA GoldSim calculations have been performed.

6.6 ASH REDISTRIBUTION CONCEPTUAL MODEL

The material that is ejected into the atmosphere from a volcanic eruption eventually falls to the ground surface and forms a feature known as a tephra sheet. The depositional process is described in the report, *Characterize Eruptive Processes at Yucca Mountain Nevada*, ANL-MGR-GS-000002, REV 01 (BSC 2003 [166407]). The areal extent and thickness of the tephra sheet is primarily dependent on the volume of ash ejected, the rise velocity, and the wind speed; however, the tephra sheet generally decreases in thickness and grain size away from the vent (see Section 7.3 for a discussion; also, see Figures 8 and 9). If an eruption were to occur through the repository at Yucca Mountain, radioactive waste particulates could be ejected along with the volcanic ash as attached particles (see Section 6.3). The result would be a tephra sheet containing radioactive waste. After deposition of the tephra sheet, the ash and waste would be available for redistribution by normal sedimentary processes (erosion and deposition). This section describes the conceptual model for ash and waste redistribution and abstraction of the model for input to the TSPA model.

6.6.1 Conceptual Model for Tephra Redistribution and Dilution

If a volcano were to intersect the repository, it would most likely result in tephra (contaminated with radioactive waste) being dispersed in the northeasterly direction as determined by the prevailing wind during a future eruption (see Section 5.2.1). Such a primary deposit would blanket the terrain, being thickest (perhaps a few meters) immediately surrounding a cone and gradually thinning and becoming finer-grained towards its distal margins. Only for the relatively less frequent wind directions toward the south (see Section 6.5.2.8 and Attachment 3) would the eruption result in primary tephra (contaminated with high-level waste) deposition at the location of the RMEI to the south of the repository. However, tephra that originally did not fall at the RMEI location could be redistributed to the RMEI location by sedimentary processes.

For the purposes of evaluating the concentrations of redistributed ash at the location of the RMEI, two scenarios are considered. Scenario 1 is that of the primary tephra sheet being deposited at the location of the RMEI. Scenario 2 has the tephra sheet deposited within the Fortymile Wash drainage basin (consistent with prevailing southwestern winds) at some distance upstream from the RMEI location. For the purposes of the TSPA, Scenario 1 should include eruptions for which primary tephra thickness at the RMEI location is greater than or equal to the minimum ash particle size, 0.001 cm. Realizations in which the primary tephra thickness is less than 0.001 cm should be treated as examples of Scenario 2. Scenarios 1 and 2 represent the maximum availability of waste-contaminated ash at the RMEI location. Other tephra-sheet

orientations either eliminate ash from reaching the RMEI location or reduce the available volume of ash to be redistributed to the RMEI location.

6.6.1.1 Scenario 1: Primary Tephra Deposition at the RMEI Location

In the case where tephra is deposited directly at the RMEI location, the following factors will determine the evolution of that deposit with time. Such a deposit is most likely to be thin (1 cm or less, based on the modeling presented in Section 6.7.1) and fine grained, consisting of ash-sized particles (less than or equal to 2 mm). The deposit would initially blanket both distributary channels and interstream divide surfaces, which are several tens of centimeters to a maximum of about 1 m above the channel bottoms. Tephra deposited on interstream divide surfaces may be subject to the following processes: (1) removal by wind, (2) in-situ dilution by eolian sand and silt, and (3) mechanical and chemical infiltration into the underlying soil profile. Extreme flood events could also dilute and transport material that was originally deposited on interstream divide surfaces into runoff channels. Given the strong eolian action in the northern Amargosa Valley (BSC 2003 [166407], Section 6.5), where the RMEI is located, it is highly unlikely that a tephra deposit of the expected thickness and grain size would remain in place and/or undiluted for more than a few decades (see results of the Cs-137 study in Section 6.6.7). For tephra deposited directly onto distributary channel bottoms, the above processes are relevant as well as the additional dilution and redistribution of tephra by occasional flash floods.

6.6.1.2 Scenario 2: Primary Tephra Deposition Upstream in Fortymile Wash

Figure 2 illustrates the conceptual model for redistribution of tephra toward a RMEI. Such redistribution would be dominated by fluvial transport down Fortymile Wash and can best be illustrated by considering the time evolution of tephra concentration on the surface at locations (stations) along the wash. Station A is at the point where Fortymile Wash is closest to the repository, while Stations B and C are progressively downstream, and Station D roughly corresponds to the location of a RMEI at the depositional mouth (alluvial fan) of the wash where it drains into the Amargosa Valley. The plots on the right side of Figure 2 conceptually show the relative concentration of tephra on the surface of the wash, averaged across the wash, as a function of time after the initial eruptive deposition of the tephra. These plots are qualitative and do not represent particular data from the YMR or other sites. Note that Figure 2 can represent both individual flood events and the longer time-averaged behavior of the system.

Immediately after an eruption, the surface concentration of tephra at Station A will be unity, representing the presence of an undisturbed tephra deposit blanketing the wash. With time, this concentration will be reduced as sediment is transported in from upstream sources. Initially, this process will result in upstream-derived sediments being mixed in with, or deposited on the surface of, the primary tephra deposit. Eventually, the primary tephra deposit will be locally incised to its base, exposing underlying sediments, and, ultimately, the primary deposit may be completely incised across the entire width of the wash so that no primary deposit remains. At that time, though, it is likely that tephra will continue to be transported into the wash from the flanks and hill slopes immediately adjacent to the wash (e.g., Yucca Mountain itself). Therefore, the average concentration of tephra at Station A will continue to decline very gradually, rather than immediately going to a value of zero, after an initial phase of cutting through the primary deposit.

For illustration purposes only.

Figure 2. Illustration of Conceptual Model for Redistribution of Tephra Toward a RMEI for Scenario 2

Station B is not blanketed by the primary tephra deposit, so there will be a time lag between the eruption and the first arrival of tephra via sedimentary processes. The tephra concentration at Station B will increase relatively rapidly as the upstream tephra deposit is incised and that material moves downstream. However, *on average*, the tephra concentration will peak at some value less than unity because of dilution of the tephra by other sediments from sources upstream of the tephra deposit, sediment washed directly off of the slopes above the wash near Station B, and by mixing with pre-existing sediments on the floor of the wash. The concentration at Station B will then gradually decline but will continue to be fed by tephra washing in from upstream environs (e.g., around Station A).

Stations C and D will experience successively longer lag times between the eruption and first arrival of tephra via the sediment transport system. In addition, the peak concentration at each will be successively lower due to dilution as described above. The general effect is that of a downstream-propagating tephra “wave” that is progressively diluted, damped, and dispersed. Station D will experience the longest lag time before contaminated tephra arrives and the lowest peak concentration but the longest period during which contaminated tephra is being fed to the location.

The processes of sediment transport in a setting such as Fortymile Wash are complex and sporadic and are very difficult to model. For example, introduction of hill-slope material directly into the wash might occur during relatively localized, intense thunderstorms, but these are not likely to result in transport far downstream in the wash (see more detailed discussion in *Characterize Eruptive Processes at Yucca Mountain Nevada*, ANL-MGR-GS-000002, REV 01, (BSC 2003 [166407], Section 6.5). Major flood events (e.g., 100-year storms) can mobilize hill-slope material into the wash and additionally transport material downwash many kilometers. The effects, both during individual storm events and integrated over long times and many events, should be dominated by: (1) dilution of tephra by arrival of upstream-sourced sediments, (2) dilution of tephra by material washed from the wash flanks directly into the wash, and (3) mixing with pre-existing sediments along the bed of the wash. Also, note that the conceptual plots in Figure 2 represent *average* surface concentration of tephra across the wash – in reality, there may be small sub-channels with very high tephra concentration while other parts of the wash remain free of tephra. In the alluvial fan area of Fortymile Wash (e.g., Station D), tephra variations across the wash might be especially pronounced as the wash branches into distributary channels separated by higher-standing interstream divides that might only receive new sediment during extreme flood events (the distinction between distributary channels and interstream divides becomes important in determining doses to a RMEI). Vertically, in the uppermost deposits in a channel after an eruption, there might also be tephra-rich layers and tephra-poor layers, reflecting a variety of sediment transport and local depositional mechanisms. In practice, it is not possible to predict such details nor is it necessary to model this level of detail because the average behavior is appropriate for the purposes of the analysis.

Rainstorms at Yucca Mountain can be classed into two types: (1) local, infrequent, storms and (2) regional storms that cover very broad areas on scales larger than entire drainage basins (Coe et al. 1992 [104691], p. 15). Typically, regional storms have longer durations with periods of heavy rains during part or most of the storms. These storms occur more commonly in winter, although they can occur at any time of the year.

It is the intense, very localized thunderstorm that would be the likely initiator of movement of the scoria and ash particles from the ridge-top drainage heads into the parallel channels. Undercutting of slopes of scoria and ash could cause sloughing of masses of tephra and result in the addition of disaggregated scoria and ash to the drainage systems. In most localized thunderstorms, water infiltrates into the underlying soil quite rapidly and does not carry its bedload long distances. At Yucca Mountain, these storms seldom feed abundant material into Fortymile Wash (Coe et al. 1997 [104691], pp. 24 to 26). To get abundant material into the wash and to transport it a long distance requires the much broader, longer-period regional rainstorms.

It is, therefore, the broad, regional storms that are responsible for moving most, and maybe all, of the sediment through the lower part of Fortymile Wash below Yucca Mountain. The material being moved and mixed is not only the sediment from the east flanks of Yucca Mountain, but includes the entirety of the sediment that is derived from the drainage basin of Fortymile Wash, including the terraces along the length of the wash.

If overall climate in the YMR were to change to wetter weather patterns, there would be several impacts on the landscape, including a major change in the dominant storm type. During wetter conditions associated with future glacial transition climates (see *Future Climate Analysis*, USGS 2001 [158378]), long-duration regional storms would become more frequent, and summer monsoon storms would become less frequent or, perhaps, disappear. Regardless of the details of such storms, mixing would still be an effective agent in the dilution of contaminated sediment along the journey to the Fortymile Wash alluvial fan and beyond.

6.6.2 General Description of Tephra Dilution Processes

Shortly after deposition of a tephra sheet, normal sedimentary processes (Folk 1980 [164773], Chapter 2) would begin redistributing the ash. Wind and water would begin eroding, transporting, sorting, and depositing the unconsolidated ash and waste in greater or lesser concentrations, depending on the mixing processes. If ash/waste deposition were to occur at the RMEI location, exposure from the radionuclides contained within the redistributed deposits would occur. On this basis, surface redistribution of contaminated tephra deposits is evaluated here for inclusion in the TSPA.

The transport of tephra occurs both by wind and water action; however, while water in a flooding event can transport large amounts and much larger sizes of material in a short period of time, wind is a major source of transport (Bull 1991 [102040], pp. 105 to 106), as evidenced by the presence of dunes in the YMR. Transport of tephra by water begins with hill-slope erosion processes and continues as sediment moves into drainages, then is transported as bedloads in the drainages that coalesce into larger and larger drainage channels. At junctions of all scales within drainage systems, water and sediment from different channels begin a process of mixing that ultimately leads to a homogeneous sediment containing elements derived from all drainages in the basin (Folk 1980 [164773], Chapter 2). This mixing of sediments occurs in all environments where sediment is transported by water or wind, including intermittent as well as perennial stream systems. The mixing in stream channels occurs at higher rates with larger clast sizes in larger drainages and on steeper slopes rather than in smaller drainages and on lower-gradient landscape surfaces, such as the Fortymile Wash alluvial fan with a longitudinal gradient of one-half degree. Mixing also occurs from wind action by transporting sediment across the landscape. Wind is the major erosional force on the Fortymile Wash fan but also is effective in bringing sand onto the fan where it forms coppice dunes around vegetation on the fan surface. However, during high-intensity storms (summer monsoonal thunderstorms), the larger, regional drainage channels that form and flow across newly deposited tephra sheets exhibit the same processes as those observed in streams. After small transport distances, even the channels on newly deposited tephra sheets have well-mixed sediment loads.

In small channels developed on tephra sheets northwest of the Lathrop Wells cone, tephra moves downslope as small debris flows with dimensions typically tens of centimeters wide and tens of meters long. Tephra moves downslope through progressive generations of these small debris flows until it reaches a channel at the base of the slope. The channel may then merge with larger channels. Depending upon initial tephra thickness, each step in the process results in some dilution of the tephra with other material (Harrington 2003 [164775], pp. 14 to 16).

In the region around Yucca Mountain, including the Lathrop Wells cone, sediments in drainage channels are mainly volcanoclastic materials, derived from the dominantly silicic Southern Nevada Volcanic field, and eolian quartz sand and silt. Where basaltic tephra from the Lathrop Wells cone has been transported into a drainage channel containing tuff and quartz clasts, the tephra component is progressively diluted during transport relative to the total sediment volume. In addition, tephra may be diluted prior to fluvial mobilization due to the infiltration of eolian sand and silt.

The sedimentary depositional system at the Lathrop Wells volcanic cone near Yucca Mountain (Harrington 2003 [164775], pp. 14 to 16) was studied to support the presence and significance of the dilution factor in the ash redistribution conceptual model. The dilution rates (see Section 7.3.1) analyzed for the drainages around the Lathrop Wells cone were not included in the abstraction of the ash redistribution conceptual model because the drainage system at Lathrop Wells is very small relative to the Fortymile Wash drainage. In addition, the ash was deposited approximately 77,000 years ago, and the drainage system at the Lathrop Wells cone is most likely nearing equilibrium. Although dilution rates at the Lathrop Wells cone are not necessarily representative of the rates that may be expected from sedimentary processes affecting a young tephra sheet, those dilution rates do demonstrate that the process of dilution is significant.

6.6.3 Rates of Surficial Processes in Fortymile Wash

To understand potential tephra redistribution, it is important to constrain the current rates of surficial processes along the main Fortymile Wash drainage. Fortymile Wash is a major drainage area along the base of the eastern slope of Yucca Mountain. It has a 800-km² drainage basin that includes the entire eastern slope of Yucca Mountain and the Fortymile Wash alluvial fan. In the upper or northern half of the fan, the channels are well defined (Figure 3). The drainage pattern is a distributary system where channels are widely spaced, but there is a sizable interstream area occurring between all pairs of channels. These interstream divide tracts are more prominent on the upper fan. On the lower fan (not shown in Figure 3), they are neither as topographically prominent nor as wide. Estimates of surficial process rates in the Fortymile Wash are based on Cs-137 concentrations in the sediments.

6.6.3.1 Cesium Study on the Fortymile Wash Alluvial Fan

Beginning in the mid-1950s and continuing through the mid-1960s, world-wide above-ground nuclear tests introduced radioactive cesium (Cs-137) into the atmosphere (Ely et al. 1992 [164076], p. 196). Cs-137 is used for two main purposes in this model report. First, when incorporated into alluvial or eolian deposits from radioactive fallout, Cs-137 forms a time-stratigraphic marker, and this marker can be used to assess the extent of local erosion and deposition. Second, the depth to which Cs-137 infiltrates into the soil can be used as a general proxy for the depth to which fine particles—clay, silt, ash—and associated radionuclides from waste may infiltrate into the substrate after deposition with volcanic ash (Section 6.7.2.1).

Soil samples from many locations in the Fortymile Wash drainage were collected for analysis of Cs-137 concentrations. Sampling was focused on the fan portion of the drainage basin (see Figure 4 for sample locations). The use of Cs-137 in geomorphological studies of the Fortymile Wash fan is described in detail in BSC (2003 [166407], Section 6.5.2, pp. 138 to 142). The typical depth profile of Cs-137 used for comparison to the fan samples is a composite derived from reference samples (Figure 5a) taken from stable geomorphic surfaces that have strongly varnished stone pavements that indicate there has been neither erosion nor deposition on the surface for thousands of years. The profile at each sample location is then compared to the typical (reference) profile (Figure 5b).

The analyses of Cs-137 concentrations in the samples (Table 9) from the upper fan support a conclusion that the upper-fan interstream divide areas have been eroding over the last 50+ years and have lost 1 to 2 cm of the upper soil horizon. This stripping was the result of wind erosion primarily (BSC 2003 [166407]). The surface erosion in 50+ years equates to erosion rates of approximately 0.02 to 0.04 cm/yr.

The erosion rate of 0.02 to 0.04 cm/yr is similar to the lower soil loss (erosion) rate of 0.19 kg/m²-yr, equivalent to 0.019 cm/yr, predicted to occur on farmland in Amargosa Valley. This 0.19 kg/m²-yr value is used in the biosphere model (BSC 2003 [161239], Section 6.4.2) (converted to cm/yr using an ash bulk density of 1 g/cm³ (DTN: LA0311DK831811.001 [166301]), 0.19 kg/m²-yr is equivalent to 0.019 cm/yr). This is also similar to the erosion rate of 0.9 to 1.1 tons/acre-yr, equivalent to about 0.02 cm/yr, estimated by the U.S. Department of Agriculture to have occurred on non-cultivated cropland and pastureland in Nevada (USDA 2000 [160548], Table 11) (1 ton/acre-yr x 907 kg/ton x 2.47 x 10⁻⁴ acre/m x 0.001 m³/kg [bulk density] x 100 cm/m = 0.02 cm/yr).

For illustration purposes only.

NOTE: The green-colored areas are distributary channels and equal 18% of the total fan area (Planimeted data from 1:100,000 topographic map). The tan areas are interstream divides and equal 82% of the total fan area (Planimeted data measured from 1:100,000 topographic map). The triangles in the diagram are locations of overbank deposits and coppice dunes that form along the channels on the alluvial fan. Areal weights are calculated in Harrington (2003 [164775], p. 77).

Figure 3. Fortymile Wash Watershed

Source for sample locations: Harrington (2003 [164775]).

NOTE: The Lathrop Wells cone is indicated with a star symbol. Yucca Mountain is the N-S linear mountain in the north-central part of the map. LWASH1 and LWASH 2 represent washes (and sampling points) along the west and east sides of Lathrop Wells cone, respectively.

Figure 4. Sample Locations for Ash Dilution and Surficial Erosion Rates (Cs-137)

DTN: LA0308CH831811.002 [164853].

Figure 5a. Typical Cs-137 Reference Sample Profile with Depth in Soil

DTN: LA0308CH831811.002 [164853].

NOTE: The black line is typical reference sample Cs-137 profile with depth in sediment on the Fortymile Wash fan. The red line represents the Cs-137 profile from which 1 cm of material has been eroded. The blue line represents the Cs-137 profile from which ~ 1 to 1.25 cm has been eroded. The three curves are similar except that the tops of the red and blue curves have been truncated and do not have the upper part that is present on the black curve.

Figure 5b. Example of Cs-137 Profiles Showing Effects of Erosion

A wind-rose diagram of surface winds in Jackass Flats and on the Fortymile Wash fan is shown in Figure 6. Prevailing winds are predominantly from the southwest and move material toward the northeast. Frequently, strong winds blow across the fan, pick up the sand and smaller size fractions (some of which may be contaminated), and remove them from the fan and from the Fortymile Wash drainage, thus, reducing the quantity of contaminated surface material on the Fortymile Wash fan.

Source: CRWMS M&O (2000 [151945], Figure 6.2-6 b).

NOTE: The diagram shows the frequency of occurrence for each direction from which the wind is blowing.

Figure 6. Wind-Rose Plot for 700-mb Levels at Desert Rock Airport

Although the effects of near-surface wind erosion (Figure 6) can be inferred from the Cs-137 data (Table 9), there is also evidence of eolian deposition on some surfaces. The presence of coppice dunes along the edges of the interstream divide areas indicate that some of the eroded materials get trapped by vegetation before the eolian materials can be carried off the divide area. Supporting data for wind transport and deposition of material throughout the Yucca Mountain area include the presence of stratified eolian horizons of fine sand and silt marked by the presence of gas bubble vesicles (Av horizons). Such vesicular soil horizons are found on most geomorphic surfaces that have been stable for several hundred years as are many of the surfaces around Yucca Mountain (YMP 1993 [100520], pp. 24 to 25). The presence of Big Dune in close proximity to the Fortymile Wash fan, from which material is being removed and deposited almost continuously, clearly demonstrates that this is an area where eolian processes play an important role in landscape modification. Such eolian removal processes commonly leave behind a lag of the heavier and coarser-grained materials. Surfaces covered to some degree by these lag materials are similar in origin to the desert pavements that cover most stable geomorphic surfaces in arid environments.

Table 9. Cesium-137 Values and Their Interpretation for the Fortymile Wash Fan

Sample Number	Depth	Cesium-137 in Layer (pCi/g)	Topographic Feature	Interpretation of Cesium and Topography
Cs-071702-A1	0-3 cm	0.259 ± 0.045	Old channel/overbank	1/2 cm removed by wind erosion
Cs-071702-A2	3-6 cm	0.054 ± 0.016		
Cs-071702-B1	0-3 cm	0.146 ± 0.030	Channel	Sediments well mixed before deposition
Cs-071702-B2	3-6 cm	0.125 ± 0.023		
Cs-071702-C1	0-3 cm	0.209 ± 0.036	Interstream divide	1 cm of eolian removal
Cs-071702-C2	3-6 cm	0.049 ± 0.012		
Cs-071702-D1	0-6 cm	0.276 ± 0.049	Flood channel overbank	Old deposit slightly stripped < 0.25 cm
Cs-071702-E1	0-3 cm	0.159 ± 0.030	Interstream divide	1 1/2-2 cm of material removed
Cs-071702-E2	3-6 cm	0.049 ± 0.015		
Cs-071702-F1	0-6 cm	0.306 ± 0.053	Coppice dune	Wind deposition site although temporary
Cs-071702-G1	0-3 cm	0.118 ± 0.025	Interstream divide	Lost more than 2 cm
Cs-071702-G2	3-6 cm	0.000 ± 0.010		
Cs-071802-H1	0-3 cm	0.191 ± 0.035	Interstream divide	Lost ~2 cm
Cs-071802-H2	3-6 cm	0.006 ± 0.013		
Cs-071802-I1	0-3 cm	0.374 ± 0.065	Interstream divide/loose pebbly pavement	Stable site with no removal
Cs-071802-I2	3-6 cm	0.015 ± 0.014		
Cs-071802-J1	0-3 cm	0.099 ± 0.022	Inactive channel bottom	Mixing of sediments during transport in channel
Cs-071802-J2	3-6 cm	0.056 ± 0.025		
Cs-071802-K1	0-3 cm	0.325 ± 0.055	Interstream divide with gravel surface	Stable site, if material removed only 0.2 cm
Cs-071802-K2	3-6 cm	0.015 ± 0.008		
Cs-071802-L1	0-6 cm	0.322 ± 0.057	Coppice dune	Stable sand deposit
Cs-071802-M1	0-3 cm	0.031 ± 0.017	Main channel	Material in channel moved fairly recently
Cs-071802-N1	0-3 cm	0.198 ± 0.037	Flood surface with overbank deposits	Typical overbank deposits
Cs-071802-N2	3-6 cm	0.020 ± 0.012		
Cs-071802-N3	6-9 cm	-0.012 ± 0.013		
Cs-071802-O1	0-6 cm	0.111 ± 0.022	Coppice dune	Sand has been moving across surface

Table 9 (Continued). Cesium-137 Values and Their Interpretation for the Fortymile Wash Fan

Sample Number	Depth	Cesium-137 in Layer (pCi/g)	Topographic Feature	Interpretation of Cesium and Topography
Cs-071802-P1	0-3 cm	0.231 $\pm$ 0.040	Interstream divide	At least 1 cm of removal by wind
Cs-071802-P2	3-6 cm	0.014 $\pm$ 0.013		
Cs-071802-Q1	0-3 cm	0.204 $\pm$ 0.037	Interstream divide with eolian winnowing/lag	At least 2 cm of removal by wind
Cs-071802-Q2	3-6 cm	0.001 $\pm$ 0.012		
Cs-071802-R1	0-3 cm	0.227 $\pm$ 0.042	Interstream divide with pebbly lag/eolian removal	At least 1 cm removal by wind
Cs-071802-R2	3-6 cm	0.010 $\pm$ 0.012		
Cs-071802-S2	0-3 cm	0.251 $\pm$ 0.043	Old fan with poorly developed pavement	Stable fan surface, 1/2 cm removed
Cs-071802-S2	3-6 cm	0.034 $\pm$ 0.010		
Cs-071802-T1	0-6 cm	0.104 $\pm$ 0.022	Coppice	An active dune with sand held only temporary
Cs-071802-U1	0-3 cm	0.073 $\pm$ 0.018	Sand surface near big dune; active sand movement	Active sand movement on this surface
Cs-071802-U2	3-6 cm	0.060 $\pm$ 0.018		
Cs-0071802-V1	0-3 cm	0.322 $\pm$ 0.056	Interstream divide with well-developed pavement	Stable surface, almost no infiltration of cesium
Cs-0071802-V2	3-6 cm	0.002 $\pm$ 0.011		
Cs-071802-W1	0-3 cm	0.097 $\pm$ 0.026	On active fan surface with flood deposits/overbank	Active surface that has had flood/overbank deposition
Cs-071802-W2	3-6 cm	0.038 $\pm$ 0.014		
Cs-071802-X1	0-3 cm	0.200 $\pm$ 0.035	Old fan surface/divide; pebble lag indicates eolian	1 - 1.5 cm of removal by eolian processes
Cs-071802-X2	3-6 cm	0.028 $\pm$ 0.012		
Cs-071802-Y1	0-3 cm	0.088 $\pm$ 0.020	Active fan surface/but seldom flooded	Sediment mixed
Cs-071802-Y2	3-6 cm	0.045 $\pm$ 0.014		
Cs-071802-Z1	0-3 cm	0.240 $\pm$ 0.043	Surface with a silt cap indicating pounding in the past	Surface has been stable except for 1 cm of removal
Cs-071802-Z2	3-6 cm	0.078 $\pm$ 0.016		
Cs-071802-AA1	0-3 cm	0.275 $\pm$ 0.047	Interstream divide area with pebble lag/eolian removal	Surface has 1 cm of removal
Cs-071802-AA2	3-6 cm	0.016 $\pm$ 0.011		
Cs-071802-BB1	0-2 cm	0.255 $\pm$ 0.045	Interstream divide with eolian activity produced a pebble lag	Surface has eolian removal of at least 1 cm
Cs-071802-BB2	2-5 cm	0.066 $\pm$ 0.015		

DTN: LA0308CH831811.002 [164853].

6.7 MODEL RESULTS AND ABSTRACTIONS

This section provides results and abstractions on ash dispersal, deposition, and redistribution for use in the TSPA model. Section 6.7.1 presents ASHPLUME results required to implement selected conditions of the redistribution abstraction. For purposes of this calculation, 100 simulations of a single eruption were conducted with the wind fixed southward. The resulting mean concentrations of radioactive waste in the tephra sheet were calculated at the location of the RMEI, about 18 km south of the repository (Section 6.7.1). Section 6.7.2 presents the overall redistribution abstraction, which uses the ASHPLUME results presented in Section 6.7.1.

6.7.1 Waste-Form Concentrations in Ash from an Ash Plume 18 km from a Vent

This section describes the results of calculations using the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code to estimate the mean concentrations of radioactive waste in the tephra sheet at 18 km from a hypothetical vent. For the purposes of this calculation, 100 simulations of a single eruption were conducted using sampled values for all distributed ASHPLUME inputs except wind direction, which was held fixed so that the mid-line of the plume would be the same in each realization. Distributions for the sampled inputs are as described below. Results are presented in Table 10 in terms of concentration of waste form (“fuel” in ASHPLUME) per unit area (g/cm^2) of ash for each of the 100 realizations. The mean fuel concentration, which incorporates effects of uncertainty in the ASHPLUME inputs, is the value to be used by the TSPA for certain realizations, time periods, and geomorphic surfaces in the model for redistribution described in Section 6.7.2.

Parameter values used in this calculation were chosen using the base-case values and ranges of values presented in Section 6.5.2. For those values with a distribution (beta, dmean, dsigma, initial eruption velocity, power, duration of eruption event, and wind speed), 100 realizations were generated randomly from these distributions by implementing the ASHPLUME code within GoldSim. ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) and GoldSim V 8.01 SP1 (STN: 10344-8.01SP1-00 [166572]) were used to implement this calculation. Wind direction was held fixed (due south towards the RMEI) for each of the 1-km altitude bins in the wind data (Output DTN: MO0312SPADRWSD.001). The validity of each realization (combination of randomly chosen parameter values) was ensured by following the methodology outlined in Section 8.2, which requires that the values of the sampled parameters remain within established ranges. The 100 realizations of distributed input values are provided in Attachment IV.

The value for the total fuel mass available for entrainment was chosen based on the mass of fuel in commercial spent nuclear fuel (CSNF) waste, which is expected to comprise about 90% of the waste in the repository (CRWMS M&O 2001 [153938], p. 49). A total of 63,000 metric tonnes of heavy metals (MTHM) CSNF is expected to be emplaced in 7,860 waste packages (CRWMS M&O 2001 [153938]). The total mass of waste available for entrainment (4.01×10^7 g) was calculated based on a median value of five waste packages calculated to be damaged if a hypothetical eruptive conduit were to intersect the repository (BSC 2003 [161851]; DTN: SN0311T0503303.003 [166297]).

The results of this Monte Carlo analysis are presented in Table 10, including the geometric mean of the concentration of the fuel form calculated for the RMEI at a location 18 km south of the repository (the location of the RMEI for these analyses). The areal ash concentrations reported in Table 10 can be interpreted as ash thicknesses based on a value for ash settled density of 1.0 g/cm³ (BSC 2003 [166407], Table 38; DTN: LA0311DK831811.001 [166301]). The standard deviation for fuel concentration (7.05×10^{-6}) indicates that the variability in fuel form concentration resulting from 100 realizations is relatively small.

Table 10. Calculated Concentration of Ash and Fuel Form in the Midline of a Volcanic Plume at a Location 18 km South of the Repository

Realization Number	Ash Concentration (g/cm ²)	Log Ash Concentration Log (g/cm ²)	Fuel Concentration (g/cm ²)	Log Fuel Concentration Log (g/cm ²)
1	0.19872	-0.701758422	1.81E-06	-5.743354402
2	1.8438	0.265713811	2.31E-06	-5.637065371
3	1.0689	0.028937077	5.68E-06	-5.245949962
4	0.95604	-0.019523937	1.39E-06	-5.857735709
5	0.38013	-0.420067854	5.91E-07	-6.228412519
6	0.43416	-0.362350191	6.76E-07	-6.169899144
7	0.51418	-0.28888482	1.92E-06	-5.717672501
8	0.2212	-0.655214877	3.34E-07	-6.475759707
9	0.023024	-1.637819223	3.66E-07	-6.436696941
10	0.88293	-0.054073727	3.81E-06	-5.41956545
11	3.1838	0.502945778	9.79E-06	-5.009221744
12	0.73462	-0.133937252	1.86E-06	-5.730860803
13	3.6923	0.56729698	9.92E-06	-5.003527731
14	0.10534	-0.977406686	6.45E-07	-6.190251795
15	0.11672	-0.932854721	3.76E-07	-6.424916121
16	0.16412	-0.784838492	4.87E-07	-6.312203589
17	0.50382	-0.297724596	2.29E-07	-6.6397096
18	1.5831	0.199508349	1.08E-06	-5.965732603
19	0.066518	-1.177060817	2.63E-07	-6.580539927
20	2.0183	0.30498572	1.14E-05	-4.943895903
21	0.49076	-0.309130842	4.22E-07	-6.374420057
22	0.17615	-0.754117352	1.39E-06	-5.855612626
23	0.91273	-0.039657675	6.66E-06	-5.176643164
24	1.6595	0.219977257	2.69E-06	-5.569505695
25	0.83142	-0.080179533	1.37E-05	-4.863247734
26	0.4253	-0.371304617	5.15E-06	-5.288260239
27	0.13191	-0.87972228	1.81E-06	-5.743474675
28	0.04206	-1.376130732	6.34E-07	-6.197773762
29	0.24679	-0.607672442	3.91E-07	-6.40751235
30	0.049645	-1.304124485	2.33E-07	-6.632606802

Table 10 (Continued). Calculated Concentration of Ash and Fuel Form in the Midline of a Volcanic Plume at a Location 18 km South of the Repository

Realization Number	Ash Concentration (g/cm ²)	Log Ash Concentration Log (g/cm ²)	Fuel Concentration (g/cm ²)	Log Fuel Concentration Log (g/cm ²)
31	0.68639	-0.163429052	4.74E-07	-6.323791242
32	0.86342	-0.063777896	8.48E-07	-6.071383983
33	0.65569	-0.18330144	1.16E-05	-4.936253938
34	1.316	0.119255889	8.58E-06	-5.06666459
35	1.513	0.179838928	2.11E-06	-5.675470623
36	0.091455	-1.038792546	1.08E-06	-5.966898063
37	1.1957	0.077622229	2.76E-06	-5.558760602
38	0.073531	-1.133529528	3.37E-07	-6.472885888
39	1.0294	0.012584164	1.13E-06	-5.947960493
40	0.086063	-1.065183519	7.43E-07	-6.129256752
41	0.19955	-0.699948268	1.60E-07	-6.794849791
42	0.12195	-0.913818195	3.84E-07	-6.415126247
43	0.6644	-0.177570376	1.48E-06	-5.829386297
44	1.3446	0.128593107	2.80E-06	-5.552345916
45	3.4497	0.537781329	3.59E-06	-5.445462386
46	0.048681	-1.312640509	4.75E-07	-6.323233252
47	0.29776	-0.526133644	4.22E-06	-5.374481771
48	0.5872	-0.231213953	1.96E-06	-5.7080986
49	1.1102	0.045401223	2.67E-05	-4.573732793
50	0.65966	-0.18067985	1.07E-05	-4.968874424
51	0.82971	-0.081073676	1.84E-06	-5.736056366
52	1.8861	0.275564715	1.51E-05	-4.822059693
53	6.38	0.804820679	3.46E-05	-4.460647848
54	0.51978	-0.284180435	5.89E-06	-5.229825722
55	0.99697	-0.00131791	2.13E-06	-5.67157962
56	0.54132	-0.266545927	3.62E-06	-5.441159482
57	2.6406	0.421702619	2.85E-06	-5.545627788
58	1.0372	0.015862508	4.61E-06	-5.336562934
59	0.22714	-0.643706379	2.23E-06	-5.651111277
60	0.079703	-1.098525332	6.02E-07	-6.220259249
61	1.7139	0.233985479	8.05E-06	-5.094317429
62	0.33486	-0.475136727	5.17E-06	-5.286257522
63	0.45043	-0.346372692	6.16E-06	-5.210123279
64	0.35295	-0.452286814	3.20E-06	-5.494999336
65	0.20157	-0.695574104	3.77E-06	-5.423301684
66	3.5274	0.547454711	5.24E-06	-5.280842797
67	0.48647	-0.312943937	3.90E-06	-5.408556942
68	2.0335	0.308244177	2.73E-05	-4.563551099

Table 10 (Continued). Calculated Concentration of Ash and Fuel Form in the Midline of a Volcanic Plume at a Location 18 km South of the Repository

Realization Number	Ash Concentration (g/cm ²)	Log Ash Concentration Log (g/cm ²)	Fuel Concentration (g/cm ²)	Log Fuel Concentration Log (g/cm ²)
69	0.090301	-1.04430744	2.69E-07	-6.569554049
70	0.36756	-0.434671757	5.42E-06	-5.265768404
71	0.45586	-0.341168514	5.28E-06	-5.277316729
72	8.9801	0.953281173	2.80E-05	-4.552935042
73	2.6241	0.418980381	3.64E-05	-4.43947169
74	0.81248	-0.090187321	2.49E-06	-5.604359141
75	0.17919	-0.746686231	3.15E-07	-6.501413791
76	1.9494	0.289900962	1.13E-06	-5.948191706
77	0.16082	-0.793659942	7.01E-07	-6.15404043
78	1.3878	0.142326883	4.75E-06	-5.323224111
79	3.2527	0.51224401	5.83E-06	-5.234316547
80	0.35443	-0.450469525	6.14E-06	-5.211958965
81	0.18507	-0.732663975	1.50E-06	-5.825358807
82	0.16883	-0.77255038	4.48E-06	-5.348741375
83	0.11832	-0.926941839	4.34E-07	-6.362360195
84	13.599	1.133506974	1.27E-05	-4.896504156
85	0.27625	-0.558697713	2.64E-07	-6.578609983
86	0.76424	-0.116770235	7.82E-06	-5.106593362
87	0.44721	-0.349488494	4.08E-06	-5.38919084
88	3.6344	0.560432724	1.88E-05	-4.726443186
89	0.080894	-1.092083689	6.24E-07	-6.20453015
90	0.40743	-0.389946996	6.73E-07	-6.171707541
91	0.14793	-0.829943743	2.42E-07	-6.615933462
92	0.3642	-0.438660059	5.13E-06	-5.289958834
93	1.0179	0.007705114	1.40E-06	-5.854244376
94	1.0793	0.033142177	2.22E-06	-5.653451441
95	0.32679	-0.485731242	3.80E-06	-5.420696679
96	0.16693	-0.777465607	2.87E-07	-6.542799587
97	0.12604	-0.899491605	2.04E-07	-6.690753203
98	0.4204	-0.376337293	4.56E-07	-6.341483016
99	2.0497	0.311690301	4.01E-06	-5.397126469
100	0.43209	-0.364425785	1.40E-06	-5.854151243
Mean of Logs		-0.293643002		-5.692069749
Geometric Mean Concentration	ASH: 0.50857733 g/cm²		FUEL: 2.03203E-06 g/cm²	
Standard Deviation	1.831028		7.05067E-06	

Output DTN: LA0312GK831811.001.

6.7.2 Ash Redistribution Model Abstraction

Field studies of tephra dilution in drainages around the Lathrop Wells cone and of surficial erosion/deposition rates based on Cs-137, along with general considerations of the sediment transport systems around Yucca Mountain, suggest a simple model for TSPA. This model and its output parameters for use in TSPA are summarized in Table 11 in terms of the two tephra fall/redistribution scenarios described in Section 6.6.1, as well as the two main geomorphic features at the RMEI location (interstream divides and distributary channels). For the purposes of TSPA, the distinction between Scenarios 1 and 2 should be made on the basis of the presence of non-negligible thickness of ash at the RMEI location. Non-negligible ash thickness should be defined as greater than or equal to the smallest ash particle diameter of 0.001 cm. This thickness, or greater, of ash constitutes ash fall at the RMEI location (Scenario 1); less than 0.001 cm constitutes Scenario 2.

Table 11. Soil Redistribution Factors for the TSPA Model

	Interstream Divide	Distributary Channels
AREAL WEIGHT (%)	0.82	0.18
Scenario 1 Primary tephra (ash fall) in the vicinity of the RMEI location.	Initial condition Ash-layer (tephra) thickness calculated by ASHPLUME in the TSPA model. Initial waste areal concentration calculated in TSPA for the ash layer at the location of the RMEI. Ash removal At a rate uniformly distributed between 0.02 to 0.04 cm/yr. Residual conditions 9-cm contaminated soil layer beneath initial ash. Volumetric concentration of the waste (see NOTES below) in this layer decreases linearly from the initial value calculated in the ash to 1/100th of that value at 9 cm. This layer is removed at the same rate as the initial ash layer, consistent with Cs-137 observations. The linear volumetric concentration decrease is conservative with respect to the exponential decrease observed for Cs-137. Below the 9-cm layer is an additional 1 to 2 cm (uniform distribution) layer with 1/100th of the initial volumetric concentration. Assumed to remain indefinitely. Represents infiltration from initial ash layer before removal.	Initial condition Initial ash-layer thickness: uniform distribution from 1 to 15 cm, or the initial ash layer thickness calculated for the divide areas in the TSPA model, whichever is greater. Initial waste concentration: geometric mean 18-km ASHPLUME volumetric concentration (see Table 10 and NOTES below) except for realizations in which the ash thickness calculated in the TSPA is greater than the thickness sampled from the 1 to 15 cm uniform distribution; in those cases, use the waste volumetric concentration calculated in TSPA for the ash layer at the location of the RMEI. Ash removal Volumetric concentration of waste in the ash layer decreases linearly from its initial volumetric concentration to 1/100th of its initial volumetric concentration within a time period uniformly distributed between 100 and 1,000 years. <i>This decrease in volumetric concentration represents dilution during removal and replacement of the initial sediment.</i> Residual conditions After removal of the initial volumetric concentration, a layer with the same initial thickness but with 1/100th of the initial volumetric concentration is assumed to remain indefinitely. This residual layer represents lower levels of contamination that may be brought down the wash or exposed from underlying soil.

Table 11 (Continued). Soil Redistribution Factors for the TSPA Model

	Interstream Divide	Distributary Channels
<p>Scenario 2</p> <p>No primary tephra fall on or near the RMEI location. <i>Primary tephra deposition in upper Fortymile Wash drainage basin.</i></p>	<p>Possible contamination by eolian processes or major flood events is approximated by a 1 to 2 cm (uniform distribution) layer with 1/100th of the initial mean volumetric waste concentration from the 18-km ASHPLUME calculations (see Table 10) and is assumed to remain indefinitely.</p>	<p>Initial condition</p> <p>Initial ash-layer thickness: uniform distribution from 1 to 15 cm.</p> <p>Initial waste concentration: geometric mean 18-km ASHPLUME volumetric concentration (see Table 10).</p> <p>Ash removal</p> <p>Volumetric concentration of waste in the ash layer decreases linearly from its initial volumetric concentration to 1/100th of its initial volumetric concentration within a time period uniformly distributed between 100 and 1,000 years. <i>This decrease in volumetric concentration represents dilution during removal and replacement of the initial sediment.</i></p> <p>Residual conditions</p> <p>After removal of the initial volumetric concentration, a layer with the same initial thickness but with 1/100th of the initial volumetric concentration is assumed to remain indefinitely.</p> <p>This residual layer represents lower levels of contamination that may be brought down the wash or exposed from underlying soil.</p>

Output DTN: LA0401CH831811.001.

NOTES:

1. The term "fuel" in Table 10 is used synonymously with the term "waste" in this table.
2. The uniform distribution of erosion rate of 0.02 to 0.04 cm/yr is based on current climate conditions. Although there is considerable uncertainty associated with long term (10,000 yr) erosion rates, the range provided is considered reasonable for the regulatory time frame.
3. Areal weights are developed in Harrington (2003 [164775], p. 77).
4. Volumetric waste concentrations specified in this table should be derived from the mean areal waste concentration calculated at 18 km, at the midpoint of the plume, as reported in Table 10, and from the mean ash layer thickness at the same location, which is also based on the results in Table 10. A value of 1.0 g/cm³ should be used for ash settled density (BSC 2003 [166407], Table 38, DTN: LA0311DK831811.001 [166301]). For example, ash areal concentration (g/cm²) divided by ash settled density (g/cm³) equals ash thickness (cm); waste areal concentration (g/cm²) divided by ash (or deposit) thickness (cm) equals waste volumetric concentration (g/cm³). The resulting volumetric concentration should then be applied to the layer thicknesses (e.g., 1 to 15 cm uniformly distributed or 1 to 2 cm uniformly distributed) in this table.

In Scenario 1, where tephra falls directly upon the RMEI location most likely in the form of a thin (typically a few millimeters) layer (see Section 6.7.1) of fine ash (thickness and radionuclide content determined by ASHPLUME calculations), it is assumed that surficial processes on the interstream divides will not be significantly altered compared to “ambient” conditions (see Table 11). If this assumption is correct, then the rate of removal of the ash and underlying soil by eolian processes will be in the range of 0.02 to 0.04 cm/yr based on interpretation of the Cs-137 data. However, it is assumed that radionuclides from tephra infiltrate (chemically or mechanically) into underlying soil before the tephra are removed by wind. It is assumed that the concentration of radionuclides in the soil decreases linearly to a depth of 9 cm (using the Cs-137 infiltration depth as a proxy), below which the concentration is 1% of the value in the tephra itself. An illustration of this model profile is shown in Figure 7.

The conceptual model for the distribution of radionuclides in soil shown in Figure 7 overestimates the total mass of radionuclides present in the system by allocating radionuclides simultaneously to both the ash layer (which, in theory, should contain the vast majority of radionuclides that ever reach the location of the RMEI in the interstream divide areas) and the underlying soil layer. For situations in which the primary ash layer is relatively thin (e.g., millimeters or less in thickness), the additional mass of radionuclides introduced in the 9-cm soil profile may be greater than the primary mass by factors of tens to hundreds (see Table 11, Note 4). This unrealistic overestimate of total radionuclide mass may cause a significant overestimation of doses from ingestion and external exposure pathways, which include contributions from radionuclides distributed throughout the soil profile. However, the model is appropriate for cases in which the total dose is dominated by inhalation pathways, which include contributions only from radionuclides in a thin surface layer of several millimeters. For estimates of inhalation doses, the additional mass of radionuclides introduced into the soil profile shown in Figure 7 provides a reasonable and conservative approximation of the effects of possible infiltration processes that could keep surface concentrations relatively high, even as erosion exposes deeper and deeper horizons.

As shown in *Disruptive Event Biosphere Dose Conversion Factor Analysis*, ANL-MGR-MD-000003 REV 02 (BSC 2003 [163958]), Section 7.5 and Table 6.2.7), long-term inhalation is the dominant exposure pathway following volcanic eruption. Consistent with that information, the model developed in this report, therefore, emphasizes the inhalation pathway. If future analyses show that the unrealistic dose contributions derived from this model for the ingestion and external exposure pathways become dominant contributors to total dose for the scenario, use of the model in TSPA should be re-evaluated.

For illustration purposes only.

Figure 7. Schematic of Decrease in Radionuclide Concentration in Soil

Processes are likely to be more complex in the distributary channels because tephra can be washed in from upstream areas. Although the data described in Section 6.6.2 indicate that such tephra will be diluted by other sediments, it is conservatively assumed that the initial washed-in tephra will not be diluted and will be deposited in layers ranging from 1- to 15-cm thick. The upper value for this range was chosen on the basis of channel depths; sediment thicknesses greater than 15 cm would likely overtop the channel margins in this area of the alluvial fan. This assumption reflects the uncertainties in application of the tephra dilution data from the Lathrop Wells cone to a potential eruption through Yucca Mountain. After the initial deposition of undiluted tephra in the channels, new tephra-bearing sediment deposited at the RMEI location will be increasingly diluted over a period of 100 to 1,000 years; due to a lack of direct data on this dilution with time, it is assumed that this occurs in a linear fashion until the tephra volume concentration reaches 1%, after which there is no further decline in concentration.

In Scenario 2, tephra falls upstream of the location of the RMEI in the Fortymile Wash drainage and is then available for redistribution by eolian or fluvial processes. It is assumed that radionuclide-bearing tephra can be delivered to interstream divides at the RMEI location by rare wind transport (in a north to south direction) or by rare flood events that fill the channels and spill onto the divides (see Table 11). In both cases, there is likely to be substantial dilution of tephra. Thus, it is assumed that interstream divides will be covered with 1- to 2-cm thick deposits that contain 1% of the radionuclide concentration that is present at a 18-km distance along the primary tephra dispersal axis (calculated by ASHPLUME in Table 10). Tephra can be delivered to distributary channels at the RMEI location by fluvial processes. As with Scenario 1, it is assumed that initial fluvial redistribution produces 1- to 15-cm thick layers of undiluted

tephra to the channels, but that over the following 100 to 1,000 years, this decreases linearly to 1% (volume) of tephra.

The Cs-137 profiles are used as a proxy for all radionuclides because no other radionuclide data are available for the Fortymile Wash fan. Other data sets for the NTS and Yucca Mountain area should be investigated for a more appropriate set of data than the Cs-137 data to use as the proxy for infiltration of radionuclides on the Fortymile Wash fan.

7. MODEL VALIDATION

Validation, or confidence building, is a means to ensure that the system behavior simulated by models is sufficiently consistent with observed behavior to give confidence in model outcomes. Appendix B of the *Scientific Processes Guidelines Manual* (SPGM) (BSC 2002 [160313]) describes three levels of model importance and corresponding validation guidelines commensurate with each level. These levels of model importance are based on the TSPA system sensitivity analyses and conclusions presented in TDR-WIS-PA-000009 (BSC 2002 [160780]), referred to herein as the *Prioritization Report*. Appendix B (p. B-9) of the SPGM refers to a discussion about parameters related to an ash plume during a hypothetical eruption through a repository and TSPA sensitivity studies (see Sections 3.3.13 and 5.1.10 of the *Prioritization Report*). It states that the only parameters of this type that bear significantly on the estimate of the mean annual dose to the RMEI are wind speed and direction. The ASHPLUME model parameters discussed in this model report correspond to this TSPA analysis. Accordingly, the SPGM (Table B.1-1) states that adequate confidence in a model component would be obtained by considering the uncertainties and assumptions in the representation of these factors (e.g., wind speed and direction) and that confidence gained through Level-II model validation should provide an adequate basis for the TSPA-LA. The SPGM approach was adopted for model validation work associated with the ASHPLUME model and is described in this section. Appendix C of the *Technical Work Plan: Igneous Activity Assessment for Disruptive Events*, TWP-WIS-MD-000007, REV 04 (BSC 2003 [166289]) describes the work necessary to validate these models.

The ash redistribution conceptual model was added to this model report after the *Prioritization Report* (BSC 2002 [160780]) was completed. The model procedure (AP-SIII.10Q) does not require post-development model validation for a conceptual model; however, because the ash redistribution conceptual model and its representation in the TSPA may impact dose, the ash redistribution conceptual model is given the same level of importance as the ASHPLUME mathematical model. Appendix C of the TWP (BSC 2003 [166289]) describes the necessary work to validate this model.

7.1 VALIDATION PROCEDURES

The SPGM (BSC 2002 [160313], Appendix B) provides guidance for the approach to validate Level-II models. A single post-development model validation method is required for both Level-I and Level-II importance models, as described in AP-SIII.10Q, *Models* (Section 5.3.3 c). Although the SPGM calls for Level-II validation of the ash dispersal model, sufficient validation activity has been carried out for the ASHPLUME model to meet Level-III standards. Specifically, two post-development model validation methods have been completed for the ASHPLUME model. One method of post-development model validation (independent technical review) was completed for the ash redistribution conceptual model. Table 12 summarizes the validation activities carried out to satisfy the Level-III validation criteria for the ASHPLUME model and specifies the location in this model report in which each activity is discussed.

Table 12. Confidence-Building and Post-Model Development Validation Activities

AP-SIII.10Q Validation Approaches	Location of Discussion in this Model Report
Confidence-Building Activities Related to Model Development	
Evaluate and select input parameters and/or data using a reasonable, credible, technical approach and scientific and engineering principles (confidence building during model development (5.3.3(b))).	Input parameters were selected to represent conditions expected for a volcanic eruption specific to the YMR and to include the range of values representing uncertainty in future eruption parameters, atmospheric conditions, and erosion/dilution rates. Model input discussion is in Sections 6.5 and 6.6.
Formulate defensible assumptions and simplifications (confidence building during model development (5.3.3(b))).	Model assumptions and simplifications are discussed in Section 5.
Ensure consistency with physical principles such as conservation of mass (confidence building during model development (5.3.3(b))).	A special calculation has been completed to demonstrate that the model is mass conservative (DOE 2003 [166506]).
Represent important future state, parameter, and alternative model uncertainties (confidence building during model development (5.3.3(b))).	Parameter uncertainties, including wind speed and direction, are discussed in Sections 4, 6.5, and 6.6.
Ensure simulation conditions have been set up to span the range of intended use, and avoid inconsistent output (confidence building during model development (5.3.3(b))).	A sensitivity analysis in which model simulations were carried out to span the entire range of all parameters represented by distributions and outputs checked for consistency. See Section 7.2.
Ensure that model predictions adequately represent the range of possible outcomes, consistent with important uncertainties (confidence building during model development (5.3.3(b))).	The representation of important model parameters with distributions of values to be used in the TSPA-LA Monte Carlo approach ensures that the range of possible outcomes is fully represented. Discussion of selection of the parameter distributions is in Section 6.5.
Post-Development Model Validation Activities	
Corroboration of model results with data acquired from natural analog studies or other relevant observations (post-development model corroboration (5.3.3(c)(1))).	Calculations were performed to compare ASHPLUME model results to data collected for three volcanoes representative of volcanic ash deposits in the YMR (Cerro Negro, Lathrop Wells, and Cinder Cone). The comparisons are documented in Section 7.3. A corroborative ash dilution study was completed on the Lathrop Wells cone for the ash redistribution conceptual model.
Conduct independent review (post-development model validation (5.3.3(c)(5))).	An independent review was performed by Dr. Frank Spera of the University of California to assess the applicability of the ASHPLUME model. The independent technical review is documented in Section 7.4 (see Attachment V for text of the technical review).
Conduct independent review (post-development model validation (5.3.3(c)(5))).	An independent review was performed by Dr. David Buesch and Dr. Dennis O'Leary, U.S. Geological Survey, to assess the applicability of the ash redistribution conceptual model. The independent technical review is documented in Section 7.4 (see Attachment VI for text of the technical review).

7.2 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to test the ASHPLUME model over the entire range of model input parameter values to be used in the TSPA analysis. This sensitivity analysis both ensured that the model operated as expected over the parameter ranges selected and identified limits to model validity due to any numerical constraints.

The sensitivity analysis was performed by varying the following input parameters: eruptive power, mean particle diameter, particle diameter standard deviation, column diffusion constant (beta), initial rise velocity, wind speed, and wind direction. These parameters were represented in the input set as distributions of parameters (Table II-9). During a TSPA-LA simulation, these parameters might take on any value within the distribution of values defined in Section 6.5. The input parameter values used in the sensitivity runs were selected from the tables shown in Attachment II. The model was run over the full range of values for each parameter shown in the tables.

The results of each ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) run for a given parameter were plotted and evaluated for sensitivity to change in value. The plots shown in Attachment II (Figure II-1 to Figure II-8) exhibit expected trends that are in accordance with increasing parameter values. No discontinuities in results were detected, which indicates numerical convergence in all simulations. The analysis indicates that the ASHPLUME model is most sensitive to eruptive power, wind speed, wind direction, and eruption duration; the variations in these parameters over their respective ranges results in two or three order-of-magnitude changes in ash thickness. The model is much less sensitive to variations in beta, mean particle diameter, particle diameter standard deviation, and initial rise velocity; variations in these parameters over their respective ranges results in variations of ash thickness by less than a factor of two.

The sensitivity of the ASHPLUME model to variation in values for the waste incorporation ratio was analyzed by CRWMS M&O (2000 [153246], Section 5.2.9.11). The results of this analysis are summarized in Section 6.5.2.6.

As described in the *FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses*, (SSPA) (BSC 2001 [155950], Section 14.3.3.4), the DOE completed analyses to evaluate the effects of uncertainties in waste-particle size on dose. This parameter is associated with the volcanic eruption scenario (BSC 2001 [157876], Section 6.1 and Table 4). Waste-particle diameter was varied over a range of values (BSC 2001 [155950], Section 14.3.3.4) sufficient to address uncertainties in the distribution. The sensitivity analysis showed that performance is relatively insensitive to uncertainty in waste-particle size within the range considered in the analysis (BSC 2001 [154659], Section 3.3.1.2.2). The DOE considers that the sensitivity of performance to uncertainties in waste-particle size distribution is well understood and was sufficiently documented in the SSPA Volume 2 (BSC 2001 [154659], Section 3.3.1.2.2). The DOE considers the information in the SSPA volumes as adequate to address this issue for TSPA-LA.

7.3 NATURAL ANALOG STUDIES FOR ASHPLUME AND THE ASH REDISTRIBUTION CONCEPTUAL MODEL

The ASHPLUME mathematical model results were compared with data results from three natural analog studies, which are discussed in Sections 7.3.1, 7.3.2, and 7.3.3 below. The calculated ash thickness from the ASHPLUME model was compared with ash-fall thickness data obtained after the 1995 eruption of the Cerro Negro volcano in Nicaragua (Wunderman and Venzke 1995 [152504]) and with ash thickness data collected at two prehistoric cinder cone eruptions: Lathrop Wells Cone, Nevada (BSC 2003 [166407], Section 6) and Cinder Cone, California (Heiken 1978 [162817]). These comparisons of actual ash thicknesses and distributions with simulations using Version 2.0 (STN: 10022-2.0-00 [152844]) provide confidence that the ASHPLUME model can estimate ash thickness for a future basaltic eruption in the YMR.

The sedimentary processes affecting the tephra sheet at the Lathrop Wells volcanic cone were studied (Harrington 2003 [164775], pp. 14 to 16) to demonstrate that dilution is significant and should be considered in the ash redistribution conceptual model (Section 7.3.2). The significance of the dilution is demonstrated by the estimate of ash dilution rates.

7.3.1 Cerro Negro

The Cerro Negro volcano is one of a number of active basaltic volcanoes within an active volcanic chain in Nicaragua. Cerro Negro is located on the Caribbean tectonic plate, and the volcanic activity expressed within this long volcanic chain, which continues from southern Mexico to Costa Rica, is directly related to subduction of the Pacific tectonic plate under the Caribbean tectonic plate. Volcanism at Cerro Negro has a 150-year history with at least 22 documented eruptions. Its last eruption (1995) produced a tephra volume (0.004 km^3) (Hill et al. 1998 [151040]) similar to, but less than, that of the Lathrop Wells cone ($> 0.04 \text{ km}^3$) (BSC 2003 [166407], Section 6). The volume of the Cerro Negro cinder cone is over four times that of the Lathrop Wells cone (BSC 2003 [166407]), but the 1995 Cerro Negro eruption may be somewhat analogous to the type of eruption that could occur in the YMR. However, Cerro Negro's long history, shape, and magma production rate suggest that it may represent a young composite volcano rather than a simple, long-lived cinder cone (McKnight and Williams 1997 [162827]). Because of the uncertainties associated with the atmospheric and eruption conditions of the Cerro Negro event, comparison of ashfall thicknesses between the observed distribution and the ASHPLUME result is qualitative. However, this comparison provides confidence that the ASHPLUME model can give a reasonable facsimile of ash deposition for the type of a possible future eruption at Yucca Mountain.

As shown in Figure 8 the ASHPLUME calculations compare well with the observed data for distances from the volcanic vent greater than 10 km. For distances less than 10 km, the ASHPLUME results give ash thickness values greater than the observed data. The lobe on the northern side of the measured ash thickness data is interpreted to be a result of a variation in wind direction and/or speed that occurred during the eruption. This variation probably accounts for some of the discrepancy because ASHPLUME assumes a constant wind speed and direction for a given simulation. In addition, ASHPLUME V 1.4LV (STN: 1002201.4LV-02 [161296]) and ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) are compared in Figure 8 to show the overall consistency between the two versions.

Source: CRWMS M&O (2000 [152998], Figure 6).

Figure 8. Comparison of Calculated and Measured Ash Deposition Thickness (cm) for 1995 Cerro Negro Eruption: Isopachs of Model Results from ASHPLUME V 1.4LV and V 2.0 Compared to Observed (Measured) Ash Thickness

7.3.2 Lathrop Wells

At 77,000-years old (Heizler et al. 1999 [107255], p. 803), the Lathrop Wells Cone, Nevada, is the youngest basaltic volcano in the YMR. It is the southern-most surface expression of the Plio-Pleistocene-age Crater Flat Volcanic Zone (CFVZ) (Crowe and Perry 1990 [100973], p. 328) and is located ~18 km south of Yucca Mountain. Characteristics of the volcanism comprising the CFVZ are documented in Perry et al. (1998 [144335], Chapters 2 and 4). Eruptive history of the Lathrop Wells cone and volume estimates of the cone, lava flows, and eruptive tephra are provided in *Characterize Eruptive Processes at Yucca Mountain, Nevada* (BSC 2003 [166407], Section 6). The volume of tephra was estimated from field sample points, which located ashfall deposits that are now shallowly buried beneath younger colluvium and eolian deposits. Due to deeper burial or non-deposition of the tephra, data points to the south of the cone are largely absent, and this results in an apparent tephra fall pattern directed northward from the vent area. Additionally, there are no data for ash deposits less than 1-cm thick, which limits the depiction of the northward extent of the ashfall. The tephra distribution presented in BSC (2003 [166407]) is, therefore, a minimum distribution.

For the Lathrop Wells cone simulation, all parameters were set to base-case values, and several calculations were performed using the full range of wind speeds that will be used for the TSPA-LA. Specifically, wind speeds ranging between 0 cm/s and 2,366 cm/s were simulated, and results were compared to the Lathrop Wells cone data (Figure 9). The figure also shows the results of a simulation using wind speeds of 800 cm/s (Model 4), which most closely matches the Lathrop Wells cone tephra data. The simulations showed that observed Lathrop Wells data fall well within the range of results produced by ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) using the TSPA-LA range of wind speeds.

Source: Heiken et al. (2003 [166290]).

NOTE: Models 3 and 4 demonstrate a close match to observed data: within a factor of 3 proximally and within 5% distally. Observed data are from an isopach map in Krier and Harrington (2003 [164023], p. 153), measured north from the vent. Models are realizations for a wind blowing to the north. Parameters held constant for these comparisons are $\beta = 0.3$, $d = 0.0572$ cm, $\sigma_d = 0.2518$, $\rho_c = 0.3$, and $U = 0$. The following list shows the varied parameters in each model with V calculated from P and T_d by Equations 7a – 7c for a conduit diameter of 10 m (Models 1 and 2) and 4.5 m (Models 3 – 6).

Model 1: $P = 5.0 \times 10^{12}$ W, $V = 0.08$ km³, $T_d = 0.2$ d, $W_0 = 24.5$ m/s, $u = 10$ m/s

Model 2: $P = 5.0 \times 10^{11}$ W, $V = 0.04$ km³, $T_d = 1.0$ d, $W_0 = 12.1$ m/s, $u = 10$ m/s

Model 3: $P = 5.0 \times 10^{10}$ W, $V = 0.004$ km³, $T_d = 1.0$ d, $W_0 = 1.2$ m/s, $u = 10$ m/s

Model 4: $P = 5.0 \times 10^{10}$ W, $V = 0.004$ km³, $T_d = 1.0$ d, $W_0 = 1.2$ m/s, $u = 8$ m/s

Model 5: $P = 6.2 \times 10^8$ W, $V = 0.004$ km³, $T_d = 75.0$ d, $W_0 = 0.01$ m/s, $u = 10$ m/s

Model 6: $P = 6.2 \times 10^8$ W, $V = 0.004$ km³, $T_d = 75.0$ d, $W_0 = 0.01$ m/s, $u = 14$ m/s.

Figure 9. Comparison of ASHPLUME Results to Lathrop Wells Ash Thickness Observations

Redistribution of volcanic ash initiates in small channels developed on tephra sheets northwest of the Lathrop Wells cone. The tephra moves downslope as small debris flows with dimensions typically tens of centimeters wide and tens of meters long. Tephra moves through progressive generations of these small debris flows until it reaches a channel at the base of the slope. The channel may then merge with larger channels. Depending upon initial tephra thickness, each step in the process results in some dilution of the tephra with other material (Harrington 2003 [164775], pp. 14 to 16).

There are two principal drainage systems that transport ash at the Lathrop Wells cone (Figure 10). (1) The western drainage system transports material from the exposed tephra sheet on the northwest side of Lathrop Wells cone west and south into the Amargosa Valley. (2) The eastern drainage system heads near the northern margin of the tephra sheet and transports material around the eastern side of the Lathrop Wells cone. The two drainage systems on the Lathrop Wells tephra sheet were sampled at depths of approximately 0.5 m to evaluate dilution (ratio of tephra to non-tephra) rates. The stream sediment samples were split in the laboratory, analyzed by microscope, and separated by a magnet to obtain the percentages of basaltic ash components relative to their transport distance from the tephra sheet (Table 13).

For illustration purposes only. Photo source: EG&G Mission, August 28, 1994, Photo frame 140, Elevation 32,000 ft.

NOTE: The Lathrop Wells basaltic cone is shown in the center of the photo with a tephra sheet draping the hill to the north. Two sets of samples were collected: one off the tephra and the drainage system that goes east around the cone; the second set follows the drainage channel that lies west of the cone. The Amargosa Valley is south of the photo.

Figure 10. Aerial Photo Showing Lathrop Wells Drainage System

Mixing occurs along the eastward drainage around the Lathrop Wells volcanic cone according to the trend evident in the table of basaltic ash content in the total sediment (Table 13). The data in Table 13 indicate that the concentration of basaltic ash is reduced by more than 50%, within 1-km distance from the head of the tephra-sheet drainage and shows substantial dilution in the first 700 m. The channel on the west side has less than 40% basaltic ash after 1 km of transport. These data are illustrative of the effects of dilution during tephra redistribution in channels but also have uncertainties due to (1) the small number of samples, and (2) the fact that tephra redistribution processes around the Lathrop Wells cone have matured since the eruption approximately 77,000 years ago (Heizler et al. 1999 [107255], p. 803). Dilution rates may have been substantially different shortly after the eruption. Also, differences in catchment area, bedrock types, vegetation, elevation, and precipitation may limit the direct analogy with a potential eruption at Yucca Mountain.

Table 13. Ash Volume Percentages in Samples of Drainage Channels Near Lathrop Wells Cone

Sample Number	Basaltic Ash (wt. %)	Distance from Head of Channel (m)
Lathrop Wells Cone, West Side		
LWASH1-07/11/02-1	98.7	0
LWASH1-07/11/02-3	92.3	~100
LWASH1-07/11/02-5	35.0	~200
LWASH1-07/12/02-3	50.8	~700
LWASH1-07/12/02-5	39.6	~1000
Lathrop Wells Cone, East Side		
LWASH2-08/1/02-1	54.9	0
LWASH2-08/1/02-3	59.4	~400
LWASH2-08/1/02-6	10.1	~1200
LWASH2-08/1/02-8	0.8	~2500

DTN: LA0310CH831811.001 [164852].

NOTE: Sample locations are shown in Figure 4.

7.3.3 Cinder Cone

Basaltic ash thickness data from Cinder Cone, a 277-m-high Holocene cone in Lassen Volcanic National Park, California, is provided in Heiken (1978 [162817]). Cone and tephra-sheet volume (0.038 km^3 and 0.032 km^3 , respectively), composition, monogenetic behavior, and eruptive sequence make Cinder Cone a good analog for a future eruption in the YMR. Several ASHPLUME V 2.0 (STN: 10022-2.0-00 [152844]) simulations were carried out to compare ASHPLUME results (predictions) to observed ash-thickness data. For the Cinder Cone simulation (Figure 11), all parameters were set to base-case values except for particle size and sorting. These parameters were set based on information provided in Heiken (1978 [162817]). Several calculations were performed using the full range of wind speeds used for the TSPA-LA. Similar to the Lathrop Wells analysis, wind speeds ranging between 0 cm/s and 2,366 cm/s were

simulated, and results were compared to the Cinder Cone data. Figure 11 shows the results of the simulation. The 800-cm/s wind speed (Model 4) provides results that most closely match the Cinder Cone data, although the 2,000-cm/s (Model 2) wind speed provides a good fit to the proximal data. The simulations show that observed Cinder Cone data fall well within the range of results produced by ASHPLUME using the TSPA-LA range of wind speeds.

Source: Heiken et al. (2003 [166290]).

NOTE: Model 2 demonstrates a close match to observed data: within a factor of 2 proximally and within 10% distally. Observed data are from Heiken (1978 [162817]). Models are realizations for a wind blowing to the east. Parameters held constant for these comparisons are $\beta = 0.3$, $d = 0.193$ cm, $\sigma_d = -0.78$, $\rho_c = 0.3$, and $U = 0$. The following list shows the varied parameters in each model with V calculated from P and T_d by Equations 7a – 7c for a conduit diameter of 5.0 m (Models 1 and 2) and 8 m (Models 3 and 4).

Model 1: $P = 5.0 \times 10^{10}$ W, $V = 0.004$ km³, $T_d = 1.0$ d, $W_0 = 24.5$ m/s, $u = 10$ m/s

Model 2: $P = 5.0 \times 10^{10}$ W, $V = 0.004$ km³, $T_d = 1.0$ d, $W_0 = 1.2$ m/s, $u = 20$ m/s

Model 3: $P = 7.5 \times 10^{10}$ W, $V = 0.065$ km³, $T_d = 10.0$ d, $W_0 = 0.5$ m/s, $u = 2$ m/s

Model 4: $P = 6.8 \times 10^{10}$ W, $V = 0.018$ km³, $T_d = 3.0$ d, $W_0 = 0.5$ m/s, $u = 8$ m/s.

Figure 11. Comparison of ASHPLUME Results to Cinder Cone Ash Thickness Observations

The Lathrop Wells and Cinder Cone simulations of tephra thicknesses provide additional confidence that the ASHPLUME model and model parameters selected for use in the TSPA-LA can produce ash thickness results that cover the range of values expected for volcanoes in the YMR.

7.4 INDEPENDENT TECHNICAL REVIEW

Independent technical reviews were conducted for both the ASHPLUME model and the ash redistribution conceptual model as part of the validation activities. Summaries of these reviews are presented in Sections 7.4.1 and 7.4.2, respectively.

7.4.1 ASHPLUME Mathematical Model

Consistent with the guidance in AP-SIII.10Q, *Models*, for validation of mathematical models, an independent technical review was conducted to assess the application of ASHPLUME for representing potential future volcanic events at Yucca Mountain. The review was conducted by Dr. Frank Spera, Professor of Geology at the University of California, Santa Barbara, from March 24, 2003 to April 10, 2003. Dr. Spera was also a member of the Peer Review Panel that addressed the approach used by the YMP to evaluate igneous consequences from a potential igneous event intersecting a repository at Yucca Mountain, Nevada (February 2003) (Detournay et al. 2003 [162914]). Dr. Spera was requested to consider if the mathematical model is appropriate for representing the conceptual model, i.e., is ASHPLUME appropriate for its intended use, which is to represent the atmospheric dispersal of waste-contaminated tephra from a potential volcanic eruption at Yucca Mountain. Draft B of this model report (MDL-MGR-GS-000002) was made available to Dr. Spera for his review (see Attachment V) along with other requested material.

Dr. Spera observed that the fundamental factors governing the fallout distribution of volcanic tephra include the height of the steady-state volcanic column, a function of eruptive mass flow rate, total eruptive volume, and the wind speeds and direction affecting the tephra being ejected into the atmosphere at different levels above the volcanic vent. He concluded that, if available, additional analogs should be considered. Since his review, work to characterize the Lathrop Wells tephra sheets has been completed and documented in the revision to the scientific analysis report, *Characterize Eruptive Processes at Yucca Mountain, Nevada*, ANL-MGR-GS-000002, (BSC 2003 [166407]). In addition, analog studies of physical volcanology have been completed and documented in BSC (2003 [166407]) for Cinder Cone. These studies were then used as an additional basis for validation of ASHPLUME in this model report.

Dr. Spera also recommended that the ASHPLUME model be compared to other similar mathematical models. He specifically recommended ASHFALL and HYPAC. Future work to enhance confidence in ASHPLUME may be completed by comparing results of ASHPLUME with results of these other models using information for the same analogs.

Finally, Dr. Spera recommended that greater mass discharge rates and corresponding higher plume heights be considered when ASHPLUME is implemented. In response to this recommendation, new wind information (NOAA 1995 [154435]) has been implemented in this model report to better represent eruption mechanics, including consideration of greater eruptive power and mass discharge rate, and consideration of the behavior of an ash plume at greater altitudes (up to 13 km).

Based on information available and a full understanding of its limitations, Dr. Spera concluded that the outputs of ASHPLUME are a reasonable representation of what may be expected from a volcanic eruption at Yucca Mountain.

7.4.2 Ash Redistribution Conceptual Model

The TWP *Igneous Activity Assessment for Disruptive Events*, REV 04 (BSC 2003 [166289], Appendix C) calls for an independent technical review of the ash redistribution model to be completed as a post-development validation activity to build confidence in the model. The ash redistribution model, as stated, is presently a conceptual model, and only simple mathematical abstractions were completed (see Table 11) for input to the TSPA model; nevertheless, this model has been assigned a “moderate” (Level II) level of importance based on guidance in the *Scientific Processes Guidelines Manual* (BSC 2002 [160313], Appendix B) and the rationale described in the TWP (BSC 2003 [166289], Appendix B). The independent technical review was conducted to assess the ash redistribution conceptual model and its abstraction for representing the deposition of tephra in the vicinity of the RMEI following a potential future volcanic event at Yucca Mountain. Two technical reviewers with expertise in sedimentary processes and Quaternary geology, Dr. David Buesch and Dr. Dennis O’Leary of the U.S. Geological Survey, reviewed the ash redistribution conceptual model between October 31, 2003 and November 19, 2003. Drs. Buesch and O’Leary, both familiar with the Yucca Mountain Project, were requested to evaluate whether the conceptual model and its abstraction are appropriate for their intended use in the TSPA. In other words, do the model and its abstraction represent the sedimentary processes that would affect contaminated ash deposited in Fortymile Wash (the two end members for the deposition of volcanic ash being upstream or at the location of the RMEI) from a hypothetical volcanic eruption at Yucca Mountain? Draft H of this model report (MDL-MGR-GS-000002) was made available to Drs. Buesch and O’Leary for their review (see Attachment VI). While the whole document was made available, the two reviewers were requested to concentrate on Sections 1.0, 4.0, 5.0, 6.6, 6.7, 7.0, and 8.0 of this model report. The following criteria were considered for this review.

- Is the conceptual model reasonable and appropriate for its intended use?
- For given inputs, are the outputs of the model reasonable?
- Are limitations of field and analytical data addressed with respect to the conceptual model described?
- Are there other approaches that may enhance the confidence in use of this model?
- Are there other alternative models that should be considered?.

The reviewers concluded that the conceptual model is reasonably representative of the past sedimentary processes in the Fortymile Wash drainage basin and that the model also represents expected future sedimentary processes. They further conclude that the model abstractions (outputs) were logical and representative of the conceptual model. Both reviewers stated that the database is limited and the conceptual model is preliminary in its development. It can be inferred from the reviews that the conceptual model, as described, and its abstraction are

sufficiently conservative to bound the range of uncertainty in the deposition of the tephra sheet and the post-ash-deposition sedimentary processes. Additional confirmatory studies are recommended that will provide better confidence in the sedimentary processes that are occurring in the Fortymile Wash drainage basin and the application of localized processes to the larger scale of Fortymile Wash. Confirmatory studies are currently under way to address ash dilution in young ash deposits (analog studies) and the sedimentary processes occurring in Fortymile Wash. This information will be available to support the technical basis for the license application. This work will most likely result in a more sophisticated model of ash redistribution with greater confidence than the preliminary conceptual model that is described in Section 6 of this report.

The reviewers also concluded that the limitations of the model were addressed in the model discussions; however, the reviewers differed on the level at which they were addressed. Dr. Buesch believed that the discussions of data and model limitations should be strengthened, while Dr. O'Leary believed that the data and model limitations were adequately addressed. The authors of the text clearly recognize the limitations of both the data and model and have addressed these in the text, where appropriate.

Both reviewers recommended that the description of the conceptual model be edited to better describe the model. The authors have edited the text to better present the conceptual model. The reviewers recommended further development of the conceptual model and the consideration of other conceptual models. It is the belief of Dr. Buesch that a new conceptual model may ultimately surface from consideration of alternative models and further analyses of the Fortymile Wash drainage basin and analog dilution studies of recent ash deposits. The authors agree that, at a minimum, a more sophisticated model is a likely outcome of additional confirmatory activities because additional parameters will most likely be integrated into the model, but the authors contend that the basic conceptual model will remain the same.

The independent technical reviewers identified a number of issues (*italics*) that are addressed in the following paragraphs.

Is it appropriate to extrapolate the local-scale studies of surface erosion (based on cesium-137 profiles) and ash dilution (based on drainages immediately adjacent to the Lathrop Wells volcano) to the larger scale processes that would accompany redistribution of tephra in the Fortymile Wash drainage?

Surface erosion rates for interstream divides are based on data obtained directly in the area of the RMEI and, therefore, should directly apply given current climate and tectonic conditions. A technical basis for how these erosion rates might differ after changes occur in climate and tectonic processes (e.g., subsidence of Amargosa Valley) is lacking. Ash dilution studies around the Lathrop Wells cone are an indicator of ash dilution but are limited in their application due to the size of the Lathrop Wells drainage compared to the Fortymile Wash drainage (scaling) and the age of the tephra sheet (approximately 77,000 years). The dilution factors measured there today might not accurately reflect those in the decades immediately following an eruption, which is key to the TSPA. Therefore, the model that is used for redistribution of tephra down the Fortymile Wash system by the TSPA assumes that the tephra is not diluted by other sedimentary material – rather, it is emplaced as a 1- to 15-cm package of pure tephra (contaminated by

radioactive waste) at the RMEI location. Additional work on ash redistribution from younger cinder cones will be performed and summarized in the next revision of this report.

The model for infiltration of radioactive contamination into soils beneath a primary tephra deposit is based (both in absolute value and in its trend with depth) on measured concentrations of cesium-137. Is cesium-137 an appropriate analog for all significant radionuclides that might be present in tephra erupted through the repository?

This question relates both to the short half-life of Cs-137 compared to spent nuclear fuel (SNF) radionuclides as well as its mobility in the subsurface. At the present time, the Cs-137 data are the only direct data on infiltration of radionuclides into surficial soils. A future revision of this model report may incorporate predicted radionuclide concentration profiles based on numerical flow and transport modeling. Such calculations would provide further information on bounds for SNF-radionuclide concentrations that might result from leaching of a surface tephra deposit.

An eruption through the Yucca Mountain repository is most likely to produce a fallout deposit that extends into Jackass Flats and possibly into the Calico Hills areas that drain into Topopah Wash (rather than Fortymile Wash). Could this be an additional source of material to the RMEI location?

The model proposed in this report is valid regardless of the fluvial pathway of redistributed tephra to the RMEI location. The two end-member redistribution scenarios encompass the conditions in which the maximum concentration of waste would be delivered to the RMEI location; all other scenarios and pathways would deliver lower concentrations.

Data on surface wind speeds, which are available in other Project reports, might be useful in discussing eolian processes, as would more detailed information on the mobilization of tephra off slopes of different steepness and bedrock types.

A future interim change notice (ICN) of this report will consider the surface wind data. Studies at analog sites, if conducted, will allow more detailed and quantitative treatment of local tephra mobilization/redistribution processes and rates. Such studies would test the model parameters described in this report and would be presented in a future revision.

For ASHPLUME calculations, assumptions are made about the nature of incorporation of SNF into ash/tephra particles. Are these same assumptions made in the development of the ash redistribution model?

Yes, these same assumptions are made in the development of the ash redistribution conceptual model.

More information on how ash dilution data from the Lathrop Wells volcano can be extended into the Fortymile Wash transport system, based on data from analog sites such as Sunset Crater, need to be provided.

More work on such analog sites may be completed to enhance confidence in the technical basis.

8. CONCLUSIONS

The objectives of this model report are the following:

- Update documentation of the ASHPLUME conceptual and mathematical models, including parameterization and validation for the ASHPLUME V 2.0 code (STN: 10022-2.0-00 [152844]) and the ASHPLUME_DLL_LA V 2.0 code (STN: 11117-2.0-00 [166571]) as implemented in the TSPA-LA.
- Document a conceptual model for tephra redistribution after a hypothetical volcanic eruption through a repository at Yucca Mountain.
- Present results of a model of ash and waste form concentrations at a point 18 km downwind of a hypothetical volcanic vent.
- Provide representative wind speed and direction data for the YMR at altitudes up to 13 km.

8.1 SUMMARY OF MODELING ACTIVITY

The ASHPLUME conceptual model accounts for incorporation and entrainment of waste fuel particles in an eruption plume and atmospheric transport of the contaminated tephra. The ASHPLUME mathematical model describes the conceptual model in mathematical terms to allow for prediction of radioactive waste/ash deposition on the ground surface in case the hypothetical eruptive event occurs. A key activity in the development of these models is the identification of realistic and representative values for the input parameters. The ASHPLUME mathematical model is implemented by the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) computer code, which is a required component of the TSPA model of the nuclear waste repository at Yucca Mountain. Within the TSPA, the model for atmospheric dispersal and deposition of tephra, implemented in the ASHPLUME code, is used to predict the ground-level concentration (areal density) of ash and waste after a violent Strombolian eruption that intersects the repository. The waste concentration is then combined with BDCFs in the TSPA model to calculate an annual dose to the RMEI. Other uses of ASHPLUME have not been evaluated in this report.

The conceptual model for tephra redistribution from a basaltic cone addresses the sedimentary processes that occur after eruption and deposition of the tephra sheet. In this case, the volcanic eruption occurs through a repository at Yucca Mountain. The erosional processes that occur within Fortymile Wash are representative of what might be expected from the redistribution of ash from a tephra sheet upgradient from the RMEI location. The conceptual model describes the erosional and depositional processes that are expected to occur on two landforms (interstream divides and distributary channels) that may be locally covered by the tephra sheet. The model also describes the characteristics of the different media for transport (water and wind). Supported by the results of site-specific and natural-analog ash dilution and Cs-137 studies, this model report describes the redistribution model that will be implemented in the TSPA-LA. The TSPA redistribution model considers tephra thicknesses and defines the tephra/soil removal rates and long-term residual contamination after erosion of the tephra sheet within the context of these two geomorphic landforms (Section 6.7.2).

8.2 MODEL REPORT OUTPUTS

The output from this model report consists of four components, which are summarized in Table 14. First, a set of input parameter values (points and ranges of values) for ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) are summarized in Table 15 for use in the TSPA modeling. Second, a set of summary data characterizing wind speed and direction in the YMR for heights above the surface of Yucca Mountain up to 13 km are presented in Tables 16 and 17, respectively. (The full set of wind speed and wind direction data are given in Attachment III.) Third, output from the ASHPLUME model providing a mean concentration of waste 18 km downwind of a hypothetical eruption through the repository is presented in Table 10. Fourth, the results of the tephra redistribution model are presented in Table 11. These outputs are described in detail in the following paragraphs.

Table 14. Output Data

Data Description	Data Tracking Number	Location of Output DTNs in this Report
Input parameter values for the ASHPLUME V. 2.0dll model for TSPA	LA0312GK831811.002	Table 15
Desert Rock wind speed and wind direction data analyses for years 1978 – 1995	MO0312SPADRWSD.001	Section 6.7.1; Tables 16 and 17; Figure 12; Table III-1; Tables III 14 through III-40; Figures III-3 through III-15.
Calculation of waste-form concentrations in ash from an ash plume at 18 km from a vent	LA0312GK831811.001	Table 10
Soil redistribution factors for the TSPA model	LA0401CH831811.001	Table 11

Table 15 lists the parameterization and other code inputs required to run the ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) code within the TSPA-LA model, which is implemented within the GoldSim modeling system. GoldSim requires a vector of ASHPLUME inputs for each realization of the model. Some of the ASHPLUME parameters required in GoldSim are represented as point values and do not change from one realization to the next. Some input parameters are represented by distributions that are sampled by GoldSim. The sampled values are then passed to ASHPLUME for each realization. Following are instructions for sampling the distributed parameter values and building an input file for each realization:

1. Sample distributions for the parameters β , d_{mean} , d_{sigma} , W_0 , and P .
2. Calculate limits for the total eruption duration (T_{d_min} , T_{d_max} , in seconds) using Equations 7b and 7c such that the range of allowable total eruption volume (0.004 – 0.08 km³) is respected (using P in watts):

$$T_{d_min} = \frac{V_{min} \phi_s}{\dot{Q}} = \frac{V_{min} \phi_s}{P/(C_p \Delta T)} = \frac{(0.004 \text{ km}^3) \left(10^{18} \frac{\text{W} \cdot \text{s}}{\text{km}^3} \right)}{P \text{ (W)}} \quad (\text{Eq. 12})$$

$$T_{d_max} = \frac{V_{max} \phi_s}{\dot{Q}} = \frac{V_{max} \phi_s}{P/(C_p \Delta T)} = \frac{(0.08 \text{ km}^3) \left(10^{18} \frac{\text{W} \cdot \text{s}}{\text{km}^3} \right)}{P \text{ (W)}}$$

3. Sample T_d from the range (log uniform) bounded by T_{d_min} , T_{d_max} .
4. Calculate eruption column height by Equation 7a: $H = 0.0082(P^{0.25})$, with H in km and P in watts.
5. Use eruption column height to sample appropriate altitude bin in the cumulative distribution functions for wind direction ($udir$) and wind speed (u); if the column height is exactly equal to an altitude bin boundary (e.g., 8.00 km), sample the next higher bin (e.g., 8 to 9 km).

Two outputs are contained in the output vector from ASHP LUME after a single realization within the GoldSim model: (1) $xash$, the ash deposition in g/cm², and (2) $xfuel$, the fuel deposition in g/cm².

All output feeds from this model report to the TSPA-LA model are identified in Tables 11 and 15 and in Attachment III, Tables III-14 through III-40. Table 15 indicates the relative position within the input vector required by ASHP LUME (i.e., the sequence number), the variable name used within GoldSim, a brief description of the parameter, the units of the parameter, the value(s) for the parameter, and the distribution type. Two parameters—wind speed and wind direction—are identified in Table 15 as having distribution type “empirical.” For the empirical-distribution type, the TSPA-LA model requires a tabular listing of the CDF or PDF of the parameter.

In this report, wind speed and wind direction data tables were formulated (Output DTN: MO0312SPADRWSD.001) to be used as input to the TSPA model. These data have also been modified further to fit the specific form and function of the model. The tabular listings for the wind speed CDFs at incremental distances above Yucca Mountain are given in Tables III-14 through III-26. Table 16 (also included as Table III-27) gives a summary of wind speed in relation to height above Yucca Mountain. The tabular listings for wind direction PDF for incremental distances above Yucca Mountain are given in Tables III-28 through III-40, and corresponding wind rose diagrams are given in Figures III-3 through III-15. Tables 16 and 17 and Figure 12 below are representative samples of the more complete listings found in Attachment III.

Section 6.7.2 (Table 11) summarizes the ash redistribution conceptual model to be implemented in the TSPA-LA. The general results of an ash dilution study are assessed in conjunction with results of a Cs-137 study to establish a technical basis for erosion rates. The Cs-137 studies are also directly used in the redistribution model to define parameters related to erosion and removal rates of the tephra sheet and to abstract predicted concentrations of diluted, redeposited sediments. A separate set of ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) calculations are developed to define the mean waste form concentration for those realizations in which there is no ash fall realized at the RMEI location during a particular TSPA realization. As stated, the ASHPLUME Monte Carlo study assumed a wind direction fixed southward toward the location of the RMEI. The mean waste form concentration defined at the mid-line of the ash plume is used in the TSPA model for specific time periods and geomorphic surfaces.

Waste-form concentrations for the above analyses were calculated using ASHPLUME_DLL_LA V 2.0 (STN: 11117-2.0-00 [166571]) (Table 10). The uncertainty in parameter values was incorporated by using a Monte Carlo method involving 100 realizations of distributed input parameters (beta, particle size, standard deviation of particle size, initial eruption velocity, power, duration of eruption event, and wind speed). Individual realizations were screened for validity by following the methodology outlined on the previous page (Section 8.2) to ensure that the values of the sampled parameters were within established ranges. Based on this modeling, the mean concentration of waste form at a point 18 km directly downwind from a volcanic vent is 2.03×10^{-6} g/cm² with a standard deviation of 7.05×10^{-6} .

Table 15. Input Parameter Values for the ASHPLUME_DLL_LA V 2.0 Model for TSPA

Seq. No.*	ASHPLUME Parameter	Description	Units	Value	Distribution Type
1	iscrn	Run type (0 = no screen output)	none	0	point value
2	X_{min}	Minimum X grid location	km	0	point value
3	X_{max}	Maximum X grid location	km	0	point value
4	Y_{min}	Minimum Y grid location	km	0	point value
5	Y_{max}	Maximum Y grid location	km	-18	point value
6	N_x	Number of X grid locations	none	1	point value
7	N_y	Number of Y grid locations	none	2	point value
8	ψ_p^{high}	Ash particle density at minimum particle size	g/cm ³	2.08	point value
9	ψ_p^{low}	Ash particle density at maximum particle size	g/cm ³	1.04	point value
10	ρ_a^{high}	Log ash particle size at minimum ash density	log (cm)	-3	point value
11	ρ_a^{low}	Log ash particle size at maximum ash density	log (cm)	0	point value
12	F	Ash particle shape factor	none	0.5	point value
13	ψ_a	Air density	g/cm ³	0.001117	point value
14	η_a	Air viscosity	g/cm/s	0.0001758	point value
15	C	Eddy diffusivity constant	cm ² /s ^{5/2}	400.0	point value
16	d_{max}	Maximum particle diameter for transport	cm	10	point value
17	ρ_{min}^f	Minimum waste particle size	cm	0.0001	point value
18	ρ_{mode}^f	Mode waste particle size	cm	0.0016	point value
19	ρ_{max}^f	Maximum waste particle size	cm	0.05	point value
20	H_{min}	Minimum height of eruption column	km	0.001	point value
21	Ash Cutoff	Threshold limit on ash accumulation	g/cm ²	1×10^{-10}	point value
22	β	Column diffusion constant (Beta)	none	0.01 – 0.5	uniform
23	d	Mean ash particle diameter	cm	0.001 – 0.01 – 0.1	log triangular
24	σ_d	Ash particle diameter standard deviation	log (cm)	(-1.9) – (-1.3)	uniform
25	ρ_c	Waste incorporation ratio	none	0.3	point value
26	U	Mass of waste to incorporate	g	Calculated within the TSPA model	N/A
27	Wind Direction	Wind Direction	degrees	DTN: MO0312SPADRW SD.001	empirical
28	u	Wind Speed	cm/s	DTN: MO0312SPADRW SD.001	empirical
29	W_0	Initial rise velocity	cm/s	$1.0 \times 10^0 - 1.2 \times 10^4$	log uniform
30	P	Eruptive power	W	$6.17 \times 10^8 - 5 \times 10^{12}$	log uniform
31	T_d	Eruption duration	s	See Eq. 12	log uniform

Output DTN: LA0312GK831811.002.

NOTE: *Seq. No. = GoldSim sequence number.

Table 16. Wind Speed in Relation to Height above Yucca Mountain

Height above YM (km)	Minimum Wind Speed (cm/s)	Maximum Wind Speed (cm/s)	Average Wind Speed (cm/s)
0 to 1	0	2315	332
1 to 2	0	1903	404
2 to 3	0	2572	501
3 to 4	0	3292	604
4 to 5	0	5402	770
5 to 6	0	5505	838
6 to 7	0	5299	1008
7 to 8	0	5659	1076
8 to 9	0	4476	1096
9 to 10	0	4270	1195
10 to 11	0	4579	1224
11 to 12	0	5093	1158
12 to 13	0	3755	1031

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

NOTE: This table is also given as Table III-27 in Attachment III of this report. The data listed in this table are representative of the wind-speed data listed in the attachment.

Table 17. Wind Direction PDF at 3 to 4 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	2770	0.0837
195 to 225	60	4515	0.1364
225 to 255	30	5411	0.1635
255 to 285	0 (East)	4974	0.1503
285 to 315	-30	4476	0.1353
315 to 345	-60	3372	0.1019
345 to 15	-90 (South)	2164	0.0654
15 to 45	-120	1394	0.0421
45 to 75	-150	898	0.0271
75 to 105	180 (West)	764	0.0231
105 to 135	150	896	0.0271
135 to 165	120	1459	0.0441
Total		33,093	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

NOTE: This table is also given as Table III-31 in Attachment III. The data listed in this table are representative of the wind-direction data listed in the attachment to this report.

Source: NOAA 1995 [154435]. Output DTN: MO0308SPADRWSD.001.

NOTE: This figure is also given as Figure III-6 in Attachment III. The wind rose frequency of occurrences shown in this figure are a representation of the wind-direction data listed in Table 16 above (see also Table III-31 in Attachment III).

Figure 12. Wind-Rose Frequency of Occurrences at 3 to 4 km above Yucca Mountain

8.3 OUTPUT UNCERTAINTY

The TSPA model uses Monte Carlo simulation as a method for mapping uncertainty in model parameters and future system states, expressed as probability distributions, into predictions of model output (CRWMS M&O 2000 [153246], Section 2.2.4). Epistemic uncertainties exist in ASHPLUME model input parameters due to the uncertainty in underlying data or imperfect knowledge of other required inputs (model for volcanic eruption). ASHPLUME model parameters that contain uncertainty and that may significantly affect the outcome of TSPA calculations are expressed as probability distributions to be compatible with the Monte Carlo method used in the TSPA model. Table 15 shows all ASHPLUME input parameters and indicates those that are represented by probability distributions and those that use fixed values.

The ash redistribution conceptual model output (Table 11) for the TSPA has considerable uncertainty due to the limited data base and use of Cs-137 as a proxy for representing long-lived radionuclides; however, the output parameter values are considered to be sufficiently conservative to bound any uncertainty. A key factor in the conceptual model for contaminated ash redistribution is dilution. It was observed (Section 7.3) that mixing with non-ash material is significant and that any contaminated ash reaching the location of the RMEI will be significantly diluted by mixing with pre-existing, uncontaminated rock material. Although dilution is a significant factor, it was not considered in the output parameter values provided as input for the TSPA.

These parameter uncertainties, represented by the parameter distributions developed and documented in this model report, are propagated throughout the TSPA-LA model and reflected in the average dose calculated by the TSPA-LA model to the RMEI.

9. INPUTS AND REFERENCES

9.1 DOCUMENTS CITED

The following is a list of the references cited in this document. Column 1 represents the unique six-digit numerical identifier (the Document Input Reference System [DIRS] number), which is placed in the text following the reference callout (e.g., BSC 2002 [160780]). The purpose of these numbers is to assist the reader in locating a specific reference in the DIRS database. Within the reference list, multiple sources by the same author and date (e.g., BSC 2002) are sorted alphabetically by title.

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9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

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- AP-2.22Q, Rev. 1, *Classification Analyses and Maintenance of the Q-List*. U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030807.0002.
- AP-SI.1Q, Rev. 5, ICN 2. *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030902.0003.
- AP-SIII.10Q, Rev. 2, ICN 1. *Models*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC. 20031126. 0002.
- AP-SV.1Q, Rev. 1, ICN 0. *Control of the Electronic Management of Information*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: DOC.20030929.0004.

9.3 SOFTWARE

- 161296 BSC (Bechtel SAIC Company) 2002. *ASHPLUME*. V 1.4LV. PC, Windows 2000/NT. 10022-1.4LV-02.
- 166571 BSC (Bechtel SAIC Company) 2003. *ASHPLUME_DLL_LA*. V 2.0. PC, Windows 2000. 11117-2.0-00.
- 154748 CRWMS M&O 2000. *Software Code: ASHPLUME*. V1.4LV-dll. PC, Windows 95/NT. 10022-1.4LV-dll-00.
- 152844 CRWMS M&O 2001. *Software Code: ASHPLUME*. V2.0. PC. 10022-2.0-00.
- 166572 Golder Associates 2003. *GoldSim*. V 8.01 Service Pack 1. PC, Windows 2000. 10344-8.01SP1-00.

9.4 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

- 164852 LA0310CH831811.001. Basaltic Ash Weight Percentages of Drainage Channel Samples Near Lathrop Wells Cone. Submittal date: 10/08/2003.
- 164853 LA0308CH831811.002. Interpretation of 137-Cesium Profile Values for Samples from the Fortymile Wash Alluvial Fan. Submittal date: 08/20/2003.

- 166301 LA0311DK831811.001. Physical Parameters of Basaltic Magma and Eruption Phenomena. Submittal date: 11/03/2003.
- 155224 LL001104412241.019. An Estimate of the Fuel-Particle Sizes for Physically Degraded Spent Fuel Following a Disruptive Volcanic Event Through the Repository. Submittal date: 11/29/2000.
- 155271 MO0103COV01031.000. Coverage: BORES3Q. Submittal date: 03/22/2001. (Used as reference only).
- 166297 SN0311T0503303.003. Updated Number of Waste Packages Hit by Igneous Intrusion. Submittal date: 11/06/2003.

9.5 OUTPUT DATA, LISTED BY DATA TRACKING NUMBER

LA0312GK831811.001. Calculation of Waste-Form Concentrations in Ash from an Ash Plume at 18 km from a Vent. Submittal date: 12/16/2003.

LA0312GK831811.002. Input Parameter Values for the ASHPLUME V 2.0DLL Model for TSPA. Submittal date: 01/13/04.

LA0401CH831811.001. Soil Redistribution Factors for the TSPA Model. Submittal date: 01/27/2004.

MO0312SPADRWSD.001. Desert Rock Wind Speed and Wind Direction Analyses for Years 1978-1995. Submittal date: 12/04/2003.

10. ATTACHMENTS

ATTACHMENT I: KEY TECHNICAL ISSUES, DOE-NRC AGREEMENTS, AND YUCCA MOUNTAIN REVIEW PLAN ACCEPTANCE CRITERIA

I-1 Background

Early in 1995, the NRC recognized the need to refocus its prelicensing repository program on resolving issues most significant to repository performance. In 1996, the NRC identified 10 key technical issues (KTIs) (Sagar 1997 [145235]) intended to reflect the topics that the NRC considered most important to repository performance. Nine of the issues were technical, and the tenth concerned the development of the dose standard for a repository at Yucca Mountain (see 40 CFR 197 [155216]). The technical issues included igneous activity, and the status of resolution of each issue and associated open items were described by the NRC in a series of Issue Resolution Status Reports (IRSR) (e.g., Reamer 1999 [119693]). In 2002, the NRC consolidated the subissues into a series of integrated subissues and replaced the series of nine issue resolution status reports with an *Integrated Issue Resolution Status Report* (IIRSR) (NRC 2002 [159538]). The IIRSR was based on the realization that the issue resolution process was “mature enough to develop a single IIRSR that would clearly and consistently reflect the interrelationships among the various KTI subissues and the overall resolution status” (NRC 2002 [159538], pp. xviii and xix). The IIRSR and periodic letters from the NRC (e.g., Schlueter 2003 [165740]) provide information about the resolution status of the integrated subissues that are described in the *Yucca Mountain Review Plan*, NUREG-1804 (NRC 2003 [163274]).

I-2 Igneous Activity Key Technical Issue

The KTI for igneous activity (IA) was defined by the NRC staff as “predicting the consequence and probability of igneous activity affecting the repository in relationship to the overall system performance objective” (NRC 1998 [100297], p. 3). Hence, the NRC defined two subissues for the IA KTI: probability and consequences (NRC 1998 [100297], p. 3). The probability subissue addresses the likelihood that future igneous activity would disrupt a repository at Yucca Mountain. The DOE estimated the probability of future disruption of a repository at Yucca Mountain in the *Probabilistic Volcanic Hazard Analysis* (PVHA) (CRWMS M&O 1996 [100116]). For the TSPA-LA, an analysis based on the PVHA results and consideration of the repository LA design were both updated and documented in the scientific analysis report, *Characterize Framework for Igneous Activity at Yucca Mountain, Nevada* (BSC 2003 [163769]).

The consequences subissue examined the effects of igneous activity on various engineered and natural components of the repository system. For the TSPA-SR, the DOE defined two igneous scenarios to evaluate the effects of igneous activity on the repository and its contents (BSC 2001 [157876]): (a) a direct-release scenario featuring penetration of the repository by an ascending basaltic dike followed by eruption of contaminated ash at the surface, and (b) an indirect release or igneous-intrusion, groundwater-release scenario featuring penetration of the repository by an ascending basaltic dike and no surface eruption. In the latter scenario, release of radionuclides would be through the groundwater pathway. Both igneous scenarios are being carried forward for TSPA-LA.

During a series of public meetings between August 2000 and September 2001, the DOE and the NRC negotiated 20 agreements associated with topics for additional study and documentation related to the analyses of the probability and consequences subissues. The agreements are documented in summary highlights of the meetings (Reamer and Williams 2000 [154597]; Krier 2001 [156472]; and Crump 2001 [156332]). The results of the work specified in the agreements will be documented in updates to several igneous activity AMRs and in two new model reports, as described above.

Summaries of the IA KTI agreements addressed in this AMR are provided in Table I-1. The table also provides the resolution status and a generalized summary of how the DOE addressed the agreement as of the time of writing this AMR. The summaries are presented for information purposes only to support traceability and transparency between AMR products and KTI agreements.

Table I-1. Summary of Igneous Activity KTI Agreements, Status, and Summary Statements Associated with *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada*

KTI Agreement or Request for Additional Information (RAI)	Resolution Status	Summary
<p>IA 2.01 Re-examine the ASHPLUME code to confirm that particle density is appropriately changed when waste particles are incorporated into the ash (Eruptive AC-1).</p> <p>The DOE agreed and will correct the description in an ICN to the report, <i>Igneous Consequences Modeling for TSPA-SR</i>, ANL-WIS-MD-000017 (CRWMS M&O 2000 [151560], Section 6.1.1), as needed to address the concern.</p>	<p>Complete (Reamer 2001 [161495], p. 2 of enclosure).</p>	<p>As originally described in the <i>Igneous Consequence Modeling for Total System Performance Assessment for the Site Recommendation</i>, ANL-WIS-MD-000017, Rev 00, ICN 01 (CRWMS M&O 2000 [151560]), the DOE confirmed that particle density is appropriately changed when waste particles are incorporated into the ash. Because the ASHPLUME model appropriately alters particle density to accommodate incorporation of waste particles, no further work is required to address this agreement for the TSPA-LA, and the documentation provided in Section 6 of the ASHPLUME model report addresses this issue for the TSPA-LA.</p>

Table I-1 (Continued). Summary of Igneous Activity KTI Agreements, Status and Summary Statements Associated with *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada*

KTI Agreement or Request for Additional Information (RAI)	Resolution Status	Summary
<p>IA 2.02 Document the results of sensitivity studies for particle size, consistent with (1) above (Eruptive AC-1).</p> <p>The DOE agreed and will document the waste-particle size sensitivity study in a calculation document.</p>	<p>The agreement is considered open pending review and acceptance by the NRC of the information provided in a letter report.</p>	<p>As described in the SSPA, Volume 1, (BSC 2001 [155950], Section 14.3.3.4), the DOE completed analyses to evaluate the effects of uncertainties in waste-particle size on dose. This parameter is associated with the volcanic eruption scenario (BSC 2001 [157876], Section 6.1 and Table 4). Waste-particle diameter was varied over a range of values (BSC 2001 [155950], Section 14.3.3.4) sufficient to address uncertainties in the distribution. The sensitivity analysis showed that performance is relatively insensitive to uncertainty in waste-particle size within the range considered in the analysis (BSC 2001 [154659], Section 3.3.1.2.2). The DOE considers that the sensitivity of performance to uncertainties in waste-particle size distribution is well understood and was sufficiently documented in the SSPA, Volume 2 (BSC 2001 [154659], Section 3.3.1.2.2). The DOE considers the information in the SSPA volumes as adequate to address this issue for TSPA-LA.</p>
<p>IA 2.04 Document that the ASHPLUME model, as used in the DOE performance assessment, has been compared with an analog igneous system. (Eruptive AC-2)</p> <p>The DOE agreed and completed a calculation CAL-WIS-MD-000011 (CRWMS M&O 2000 [152998]) that documented a comparison of the ASHPLUME code results to observed data from the 1995 Cerro Negro eruption.</p> <p>The DOE will consider Cerro Negro as an analog and will document this in an update to the eruptive processes report, ANL-MGR-GS-000002 (BSC 2003 [166407]).</p>	<p>Complete (Reamer 2001 [161495], p. 2 of enclosure).</p>	<p>Reference to Agreement IA 2.04 in this model report is intended to demonstrate that as a follow-up to fulfilling the agreement item, the DOE continues to consider Cerro Negro as an analog.</p> <p>The DOE completed documentation of the comparison of ASHPLUME model results to representative tephra fall deposits from the 1995 eruption of Cerro Negro in a calculation document, CAL-WIS-MD-000011 (CRWMS M&O 2000 [152998]). Based on review of the calculation by the NRC, Agreement Item 2.04 associated with the consequences subissue of the igneous activity, the KTI was closed by the NRC (Reamer 2001 [161495], p. 2 of enclosure).</p> <p>As documented in the eruptive processes report (BSC 2003 [166407]), the DOE has included Cerro Negro in the analogs considered in estimating duration and power output of explosive eruptive phases (Tables 1b and 5) and in estimating bulk grain size for eruptions (Tables 1b and 6). The use of Cerro Negro as an analog for a potential Yucca Mountain igneous eruption was also documented in CRWMS M&O 2000 ([153246], Section C.3.1).</p> <p>The DOE considers that the information provided above and additional information about Cerro Negro as an analog, which is to be provided in a revision to the eruptive processes report (BSC 2003 [166407]) and the discussion in Section 7.4 of this model report, will be sufficient to describe for the TSPA-LA, the consideration of Cerro Negro as an analog.</p>

Table I-1 (Continued). Summary of Igneous Activity KTI Agreements, Status and Summary Statements Associated with *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada*

KTI Agreement or Request for Additional Information (RAI)	Resolution Status	Summary
<p>IA 2.09 Use the appropriate wind speeds for the various heights of eruption columns being modeled.</p> <p>The DOE agreed and will evaluate the wind-speed data appropriate for the height of the eruptive columns being modeled. This will be documented in a calculation document.</p>	<p>The NRC review of the DOE's letter report submittal determined that the information provided by the DOE was not sufficient to resolve and close the agreement. The NRC described a need for additional information consisting of five elements (Schlueter 2003 [165740]).</p>	<p>After the September 5, 2001 DOE/NRC technical exchange, the NRC expressed a concern about use of average values for wind speed rather than a stratified distribution of wind speeds. The NRC's concern was that the DOE's method might result in underestimating dose because of not accounting for the effect of thermal buoyancy, keeping some particles aloft for a longer period of time. While it is true that the DOE analysis assumes that wind speed does not vary with height, the wind speed used in the DOE analysis is not an averaged wind speed. In the DOE analysis, wind speed is treated as a stochastic variable, which is modeled as a distribution of wind speeds. The distribution of wind speeds has been derived from data collected from various heights, times, and wind directions. The data represent the entire range of wind speed expected to occur at all altitudes during a hypothetical future volcanic eruption at Yucca Mountain. For the TSPA analysis, the TSPA model samples from the distribution of wind speeds. For each realization of the model, the analysis uses the discrete value for wind speed obtained during that realization. The model does not use an average value for wind speed. Because the highest wind speeds in the distribution [of wind speeds] are sampled for some TSPA model realizations, longer settling times due to thermal buoyancy for some particles are accounted for in the average dose calculations, and the DOE method should not underestimate dose.</p> <p>As part of the analyses supporting the Site Recommendation, the DOE examined the sensitivity of the dose from the igneous eruptive case. The analysis, which is documented in the SSPA Volume 2 (BSC 2001 [154659], Section 3.3.1.2.1), showed that use of the Desert Rock data increases the probability-weighted mean annual doses by a factor of approximately 2 compared to the TSPA-SR values (CRWMS M&O 2000 [153246], Section 4.2.2).</p> <p>Wind speed is a required input for the ASHPLUME code. As described in the SSPA Volume 1 (BSC 2001 [155950], Section 14.3.3.5), it is possible for violent Strombolian eruptions of the type possible in the YMR to produce ash plumes that reach altitudes less than 4 km. For the TSPA-LA analyses, the DOE will use a distribution for wind-speed data developed in this report (see Attachment III).</p> <p>The DOE considers that the sensitivity analysis documented in the SSPA Volume 2 (BSC 2001 [154659], Section 3.3.1.2.1) and the use of the NOAA (1995 [154435]) wind-speed data for the TSPA-LA addresses this agreement item. The information documented in this report should be sufficient to resolve and close agreement item IA 2.09.</p>

Table I-1 (Continued). Summary of Igneous Activity KTI Agreements, Status and Summary Statements Associated with *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada*

KTI Agreement or Request for Additional Information (RAI)	Resolution Status	Summary
<p>IA 2.17 The DOE will evaluate conclusions that the risk effects (i.e., effective annual dose) of eolian and fluvial remobilization are bounded by conservative modeling assumptions in the TSPA-SR, Rev 00, ICN 01. The DOE will examine rates of eolian and fluvial mobilization off slopes, rates of transport in Fortymile Wash, and rates of deposition or removal at the proposed critical group location. The DOE will evaluate changes in grain size caused by these processes for effects on airborne particle concentrations. The DOE will also evaluate the inherent assumption in the mass loading model that the concentration of radionuclides on soil in the air is equivalent to the concentration of radionuclides on soil on the ground does not underestimate dose (i.e., radionuclides important to dose do not preferentially attach to smaller particles). The DOE will document the results of investigations in the report, <i>Eruptive Processes and Soil Redistribution</i>, ANL-MGR-GS-000002, which is expected to be available in fiscal year 2003, and in the report, <i>Input Parameter Values for External and Inhalation Radiation Exposure Analysis</i>, ANL-MGR-MD-000001, also expected to be available in FY 2003, or another appropriate technical document.</p>	<p>This report addresses only parts of the agreement related to rates of eolian and fluvial mobilization off slopes, rates of transport in Fortymile Wash, and rates of deposition or removal at the RMEI location.</p>	<p>A conceptual model for ash/tephra/soil redistribution is described in this report as the ash redistribution conceptual model (Section 6.6.2). The model is based on data collected at and near Yucca Mountain to model the response of future hypothetical surficial deposits of contaminated ash/tephra/soil to eolian and fluvial mobilization off slopes and into and down Fortymile Wash to the vicinity of the Fortymile Wash alluvial fan.</p> <p>A complete response to this agreement requires inputs from the model for atmospheric dispersal, deposition, and redistribution of tephra from a potential volcanic eruption at Yucca Mountain. Also needed are inputs from the biosphere model to support analysis of effects of surficial processes on grain size and resultant effects on airborne particle concentrations or resuspended particles. The TSPA analyses is needed to evaluate the risk effects of ash/tephra/soil redistribution caused by eolian and fluvial processes coupled with effects of soil resuspension that could result from changes in grain sizes caused by ash/tephra/soil redistribution.</p>

For the TSPA-LA, the direct-release model has been described, and documentation is provided in this model report. For the indirect-release scenario, the potential effects of the repository on the propagation of a basaltic dike, the environmental conditions accompanying intersection of the repository by an ascending dike, and analyses of effects of intrusive igneous activity on repository structures is documented in the model report, *Dike/Drift Interactions*, MDL-MGR-GS-000005 (BSC 2003 [165923]). Similar analyses of effects of intrusive igneous activity on repository contents (waste package and waste form) are to be documented in a new model report, *Igneous Intrusion Impacts on Waste Package and Waste Form*, MDL-EBS-GS-000002 (BSC 2003 [165002]).

In addition, this model report describes the ash redistribution conceptual model and documents the development and validation of this model (Sections 6.6.2 and 7). This conceptual model is potentially important to the TSPA-LA because reworking of contaminated tephra deposits could increase the concentration of radioactive waste material at the RMEI location and, thereby, potentially increase the dose risk to the RMEI.

I-3 Yucca Mountain Review Plan Acceptance Criteria

The *Yucca Mountain Review Plan* (NUREG-1804, NRC 2003 [163274]) associates the integrated subissue of airborne transport of radionuclides with the requirements listed in 10 CFR 63.114 (10 CFR 63 [156605], (a)-(c) and (e)-(g)). NUREG-1804 (NRC 2003 [163274], Sections 2.2.1.3.11 and 2.2.1.3.13) describes the acceptance criteria that the NRC will use to evaluate the adequacy of information addressing the airborne transport of radionuclides in the license application. The following discussion provides a summary of how the information in this model report addresses those criteria that are associated with the development and use of the ASHPLUME model.

In addition, this model report addresses the integrated subissue redistribution of radionuclides in the soil (NUREG-1804, Section 2.2.1.3.13, NRC 2003 [163274]). The information provided below also summarizes how this report addresses the acceptance criteria associated with the integrated subissues.

I-3.1 Integrated Subissue: Airborne Transport of Radionuclides

Acceptance Criterion 1: System Description and Model Integration Are Adequate

1. Total system performance assessment adequately incorporates important design features, physical phenomena, and couplings, and uses consistent and appropriate assumptions throughout the airborne transport of radionuclides abstraction process.

This model report documents the use of the ASHPLUME code to model the airborne transport of radionuclides. This report provides information about the development of the ASHPLUME conceptual model by Suzuki (1983 [100489]) (Section 6.3) and describes the consistency of the conceptual model with physical phenomena associated with violent Strombolian eruptions and the development and propagation of an ash cloud downwind of the eruption site followed by deposition of tephra deposits on the ground surface (Section 6.3). This report also documents the consistency between the conceptual model and the ASHPLUME mathematical model used in the TSPA (Section 6.5). The development of the

individual mathematical formulations for the model has been described in Section 6.5.1 as having the inputs to the model and assumptions needed to use the ASHPLUME model for analysis (Section 6.5.2). The TSPA code, GoldSim, includes the ASHPLUME code (ASHPLUME V 2.0 dll) as a dynamic link library. Inclusion of ASHPLUME as a DLL ensures that physical phenomena and couplings important to the analysis of airborne transport of radionuclides are consistently and appropriately treated in performance assessment.

2. Models used to assess airborne transport of radionuclides are consistent with physical processes generally interpreted from igneous features in the Yucca Mountain region and/or observed at active igneous systems.

This model report provides information about the development of the ASHPLUME conceptual model by Suzuki (1983 [100489]) (Section 6.3) and describes the consistency of the conceptual model with physical phenomena associated with violent Strombolian eruptions and the development and propagation of an ash cloud downwind of the eruption site followed by deposition of tephra deposits on the ground surface (Section 6.3). Base-case model inputs and uncertainties and their consistency with igneous features either observed in the Yucca Mountain region or with features observed at analog igneous systems are described in Section 6.5.2. The bases for the selection of an appropriate distribution for each uncertain parameter are described in this report (Section 6.5.2). Model inputs that are developed and documented in other analyses or models are appropriately identified, described, and cross-referenced.

3. Models account for changes in igneous processes that may occur from interactions with engineered repository systems.

The ASHPLUME model does not account for changes in igneous processes that might result from interactions between processes and components of the engineered barrier system. Such interactions are described in other analyses or model reports, as appropriate (e.g., *Dike/Drift Interactions* (BSC 2003 [165923]) and *Igneous Intrusion Impacts on Waste Package and Waste Form* (BSC 2003 [165002])).

4. Guidance in NUREG-1297 and NUREG-1298 (Altman et al. 1988 [103597]; Altman et al. 1988 [103750]), or in other acceptable approaches for peer review and data qualification is followed.

The independent peer review of the ASHPLUME model is described in Section 7.4.1. The review was done in accordance with the Project procedure, *Peer Review* (AP-2.12Q [155892]) and is found in Attachment V. Quality assurance considerations for modeling activities associated with development of the ASHPLUME V 2.0 software (STN: 10022-2.0-00 [152844]) are described in Section 2. Data, parameters, and other model inputs are described in Section 4.

Acceptance Criterion 2: Data Are Sufficient for Model Justification

1. Parameter values used in the license application to evaluate airborne transport of radionuclides are sufficient and adequately justified. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.

Uses of the parameter values are generally described as part of the mathematical description of the base-case model in Section 6.5.1. The development of all model inputs used for the atmospheric dispersal model is discussed in Section 6.5.2. Subsections describe the individual model input parameters and provide detailed technical bases supporting the use of the numerical value or range for each parameter. Model report outputs for the TSPA-LA are described in Section 8.2.

2. Data used to model processes affecting airborne transport of radionuclides are derived from appropriate techniques. These techniques may include site-specific field measurements, natural analog investigations, and laboratory experiments.

The parameter values used as inputs for ASHPLUME V 2.0 dll are described in the model report in Section 4, and model outputs are described in Section 8.2. Modeling objectives, the characteristics of the base-case model, consideration of alternative conceptual models, and the basis for the selection of ASHPLUME for modeling airborne transport of radionuclides are discussed in Sections 6.1, 6.3, and 6.4, respectively. The formulation of the mathematical model is described in Section 6.5, and the base-case model inputs and their appropriateness are described in Section 6.5.2.

This model report describes the conceptual model, formulation of the mathematical model, identification of parameters, selection of appropriate parameter values or distributions, and discusses the consideration of alternative models. All of these considerations are included in the basis for selection of the ASHPLUME model as appropriate for analyzing the airborne transport of radionuclides for the license application. Section 7 of the report discusses validation of the model and shows how the validation exercises have shown the efficacy of the ASHPLUME model to represent observed variations in tephra deposit thicknesses at analog sites. The validation work also shows that the model is internally consistent and produces numerical convergence in simulations. These lines of evidence demonstrate that the ASHPLUME model is appropriate to analyze the airborne transport of radionuclides.

3. Sufficient data are available to integrate features, events, and processes, relevant to airborne transport of radionuclides into process-level models, including site-specific determination of appropriate interrelationships and parameter correlations.

Features, events, and processes (FEPs) related to the development and use of the ASHPLUME model are discussed in Section 6.2. Table 6 includes descriptions of the specific data elements associated with the FEPs associated with the ASHPLUME model and summarizes how objectives for the integration of FEPs are addressed by the development of the model.

4. Where sufficient data do not exist, the definition of parameter values and associated conceptual models is based on appropriate use of expert elicitation conducted, in accordance

with NUREG-1563 (Kotra et al. 1996 [100909]). If other approaches are used, the U.S. Department of Energy adequately justifies their use.

Sufficient data exist to define the parameter values and associated conceptual models needed to model the atmospheric dispersal and deposition of tephra (Section 6.5.2). Expert elicitation is not used in the definition of parameter values and associated conceptual models.

Acceptance Criterion 3: Data Uncertainty is Characterized and Propagated through the Model Abstraction

1. Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, and do not result in an under-representation of the risk estimate.

The development of the individual mathematical formulations for the model is described in the model report (Section 6.5.1) as are the inputs to the model and assumptions needed to use the ASHPLUME model for analysis (Section 6.5.2). Uncertainties associated with changes in igneous processes are included in ASHPLUME analyses through the use of parameter distributions (Section 6.5.2). The bases for the selection of an appropriate distribution for each uncertain parameter is described in the report (Section 6.5.2). The reasonableness of values and distributions for parameters and their suitability for use are described in Section 6.5.2. Assumptions associated with the appropriateness of the ASHPLUME model are described in Section 5.1, and assumptions associated with specific model parameters are described in Section 5.2. The appropriateness of the base-case model is described in Section 6.3, and the consideration of alternative models is documented in Section 6.4. The screening of an alternative basis for the selection of ASHPLUME is also documented in Section 6.4 (see Table 7). Parameter uncertainty is addressed in Section 4.1.2.

2. Parameter uncertainty accounts quantitatively for the uncertainty in parameter values derived from site data and the available literature (i.e., data precision) and the uncertainty introduced by model abstraction (i.e., data accuracy).

Data precision is addressed in the description of enumeration of the model (Section 6.5.1) and in the development of the input parameters (Section 6.5.2 and subsections). Data accuracy is addressed by evaluating uncertainties introduced by model abstraction. These uncertainties are explicitly addressed by the results of the model validation exercise (Section 7), which shows how well the ASHPLUME model outputs conform to evaluation criteria, including sensitivity of outputs to variations in input parameters (Section 7.2), comparison of model ash thicknesses with observed thicknesses at analog sites (Section 7.3), and conservation of mass (DOE 2003 [166506]) (Section 7.3).

Uncertainties associated with changes in igneous processes are included in ASHPLUME analyses through the use of parameter distributions (Section 6.5.2). The bases for the selection of an appropriate distribution for each uncertain parameter are described in the report (Section 6.5.2). Parameter uncertainty is addressed in Section 4.1.2.

3. Where sufficient data do not exist, the definition of parameter values and associated uncertainty is based on appropriate use of expert elicitation conducted in accordance with

NUREG-1563 (Kotra et al. 1996 [100909]). If other approaches are used, the U.S. Department of Energy adequately justifies their use.

Sufficient data exist to define the parameter values and associated conceptual models needed to model the atmospheric dispersal and deposition of tephra (Section 6.5.2). Expert elicitation has not been used in the definition of parameter values and associated conceptual models.

Acceptance Criterion 4: Model Uncertainty is Characterized and Propagated through the Model Abstraction

1. Alternative modeling approaches to airborne transport of radionuclides are considered and are consistent with the available data and current scientific understandings, and the results and limitations are appropriately considered in the abstraction.

The alternative models that were considered for modeling airborne transport of radionuclides are described in Section 6.4. The screening of an alternative basis for the selection of ASHPLUME is also documented in Section 6.4 (see Table 7). The consistency of the ASHPLUME model with data and current scientific understanding is described in Section 6.5. Section 7 discusses validation of the model and shows how the validation exercises have shown the efficacy of the ASHPLUME model to represent observed variations in tephra deposit thicknesses at analog sites. The validation work shows that the model is internally consistent and produces numerical convergence in simulations. Limitations of the ASHPLUME model are discussed in Section 1.3.

2. Uncertainties in abstracted models are adequately defined and documented, and effects of these uncertainties are assessed in the total system performance assessment.

Uncertainties associated with ASHPLUME model outputs are described in Section 8.3, and input parameters and parameter uncertainties are described in Section 4.1.2. Section 7.2 describes the sensitivity analyses that were done to evaluate the response of the ASHPLUME model over the entire range of model input parameter values. The results show that the model is sensitive to variations in eruptive power, wind speed, wind direction, and eruption duration. TSPA sensitivity to parameter variations is beyond the scope of this report.

3. Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information, and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under representation of the risk estimate.

The description of the enumeration of the base-case conceptual model (Section 6.5.1) identifies association with model parameters and describes how those uncertainties are addressed in the formulation of the mathematical model. Uncertainties in the model outputs are described in Section 8.3, and conservatisms included to assure that model outputs to the TSPA do not result in an under representation of risk are described as part of the conceptual model (Section 6.5.2 and subsections).

The alternative models that were considered for modeling airborne transport of radionuclides are described in Section 6.4. The screening of an alternative basis for the selection of ASHPLUME is also documented in Section 6.4 (see Table 7). The consistency of the ASHPLUME model with data and current scientific understanding is described in Section 6.5. Section 7 discusses validation of the model and shows how the validation exercises have shown the efficacy of the ASHPLUME model to represent observed variations in tephra deposit thicknesses at analog sites. The validation work shows that the model is internally consistent and produces numerical convergence in simulations. Limitations of the ASHPLUME model are discussed in Section 1.3.

Acceptance Criterion 5, Model Abstraction Output is Supported by Objective Comparisons

1. Models implemented in the airborne transport of radionuclides abstraction provide results consistent with output from detailed process-level models and/or empirical observations (laboratory and field testings and/or natural analogs).

Section 6.2 describes the specific FEPs that are included in the ASHPLUME model. Section 6.3 provides a detailed description of the base-case model and the appropriateness of that model for the analysis of airborne transport of radionuclides. Section 6.5.1 provides a detailed description of the mathematical formulation of the base-case model and the consistency of that formulation with natural processes. Section 7 of the model report discusses validation of the model and shows how the validation exercises have shown the efficacy of the ASHPLUME model to represent observed variations in tephra deposit thicknesses at analog sites. The validation work also shows that the model is internally consistent and produces numerical convergence in simulations.

2. Inconsistencies between abstracted models and comparative data are documented, explained, and quantified. The resulting uncertainty is accounted for in the model results.

The model outputs are described in Section 8.2 and model output uncertainties are described in Section 8.3. Section 7 discusses validation of the model and shows how the validation exercises have shown the efficacy of the ASHPLUME model to represent observed variations in tephra deposit thicknesses at analog sites (Section 7.3). The validation work also shows that the model is internally consistent and produces numerical convergence in simulations.

The Yucca Mountain Review Plan (NUREG-1804, NRC 2003 [163274]) associates the integrated subissue of redistribution of radionuclides in soil with the requirements listed in 10 CFR 63.114(1)(a)-(c), (e)-(g), and 63.305 [156605] as they relate to the redistribution of radionuclides in soil abstraction. NUREG-1804 (NRC 2003 [163274], Section 2.2.1.3.13.3) describes the acceptance criteria that the NRC will use to evaluate the adequacy of information addressing the redistribution of radionuclides in soil in the license application. The following discussion provides a summary of how the information in this model report addresses those criteria that are associated with the development and use of the ash redistribution conceptual model.

I-3.2 Integrated Subissue: Redistribution of Radionuclides in Soil

Acceptance Criterion 1: System Description and Model Integration Are Adequate

1. Total system performance assessment adequately incorporates important features, physical phenomena and couplings between different models, and uses consistent and appropriate assumptions throughout the abstraction of redistribution of radionuclides in the soil abstraction process.

Information in this model report is limited to describing the conceptual model for ash redistribution, the validity of the model, and providing model outputs for use in the TSPA-LA. Features, events, and processes included in the model are described in Section 6.2 and discussed in more detail in Table 6. The ash redistribution conceptual model is described in Section 6.6, and the two scenarios used to bound ash redistribution in the Yucca Mountain area are described in Sections 6.6.1.1 and 6.6.1.2. A general description of the tephra dilution process is provided in Section 6.6.2, and rates of surficial processes are described in Section 6.6.3. Assumptions associated with the use of the model are described in Section 5.1.3, and results of the ash redistribution conceptual model are described in Section 6.7.2 and Table 11. Output uncertainties associated with the ash redistribution model are described in Section 8.3.

It is beyond the scope of this report to document the use of model outputs and abstractions in the TSPA-LA.

2. The total system performance assessment model abstraction identified and describes aspects of redistribution of radionuclides in soil that are important to repository performance, including the technical bases for these descriptions. For example, the abstraction should include modeling of the deposition of contaminated material in the soil and the determination of the depth distribution of the deposited radionuclides.

Output from the ASHPLUME model provides estimates of the primary amount of contaminated ash in the tephra blanket in terms of concentration of waste per unit area (g/cm^2) (Table 10). The technical basis for the estimates, including modeling of the depth of contaminated soil and soil removal, is provided in Section 6.7.2, and assumptions used in the model are documented in Section 5.1.3.

3. Relevant site features, events, and processes have been appropriately modeled in the abstraction of redistribution of radionuclides, from surface processes, and sufficient technical bases are provided.

Site FEPs included in the model are described in Section 6.2. The technical bases for the included FEPs are described in detail in Table 6.

4. Guidance in NUREG-1297 and NUREG-1298 (Altman et al. 1988 [103597]; Altman et al. 1988 [103750]), or other acceptable approaches for peer reviews is followed.

The use of independent peer reviews of the ash redistribution conceptual model is described in Section 7.4.2. These reviews were done in accordance with the Project procedure, *Peer Review* (AP-2.12Q), and are found in Attachment VI.

Acceptance Criterion 2: Data Are Sufficient for Model Justification

1. Behavioral, hydrological, and geochemical values used in the license application are adequately justified (e.g., irrigation and precipitation rates, erosion rates, radionuclide solubility values, etc.). Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided.

Data sources that provided inputs for the development of parameters used in the ash redistribution conceptual model are identified in Section 4.1.1. The appropriateness of the data is also discussed. A general description of tephra redistribution processes is provided in Section 6.6.2. Rates of surficial processes that are needed to support model development and use are documented in Section 6.6.3, and the Cs-137 data that form a time stratigraphic marker in the surficial deposits and provide a proxy for determining the soil depths that fine particles and associated radionuclides from waste could penetrate are described in Section 6.6.3.1. Descriptions of data use are provided in Section 6.7.2. Analog studies to support the ash redistribution conceptual model are described in Section 7.3, and the results of an independent review of the ash redistribution model are described in Section 7.4.2 (see Attachment VI for the reviews). Uncertainties associated with the ash redistribution conceptual model are described in Section 8.3. Outputs from the ash redistribution conceptual model are described in Section 6.7.2 and listed in Table 11. Guidelines for using the outputs in the TSPA model are also provided in Section 6.7.2.

2. Sufficient data (e.g., field laboratory, and natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the abstraction of redistribution of radionuclides in soil in the total system performance assessment.

Data sources that provide inputs for the development of parameters used in the ash redistribution conceptual model are identified in Section 4.1.1. The appropriateness of the data is also discussed. Rates of surficial processes that are needed to support model development and use are documented in Section 6.6.3, and the Cs-137 data that form a time stratigraphic marker in the surficial deposits and provide a proxy for determining the soil depths that fine particles and associated radionuclides from waste could penetrate are described in Section 6.6.3.1. Table 11 lists the TSPA factors that are provided by the ash redistribution conceptual model. Guidelines for using the outputs in the TSPA model are provided in Section 6.7.2.

Acceptance Criterion 3: Data Uncertainty Is Characterized and Propagated Through the Model Abstraction.

1. Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are consistent

with the characteristics of the reasonably maximally exposed individual in 10 CFR Part 63 [156605].

Inputs for the ash redistribution conceptual model and the appropriateness of the inputs for use in the model are described in Section 4.1.1. Assumptions are described in Section 5.1.3. Analog studies undertaken in the Yucca Mountain area to ensure the model appropriately considers sedimentary processes that affect tephra sheets are described in Section 7.3. Uncertainties in the model are described in Section 8.3, and conservatisms included to assure that model outputs to the TSPA do not result in an under representation of risk are described as part of the conceptual model in Section 6.6.1. The method to incorporate conservatism is development of two scenarios that bound the mechanisms of ash redistribution in the Yucca Mountain area. These scenarios are described in Sections 6.6.1.1 and 6.6.1.2, respectively.

The development and use of the ash redistribution conceptual model is not dependent on consideration of the characteristics of the reasonably maximally exposed individual. The characteristics of the reasonably maximally exposed individual are documented in the *Biosphere Model Report*, MDL-MGR-MD-000001 (BSC 2003 [164186], Section 6). Agricultural and environmental input parameters for the biosphere model are described in the report, *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003 [160976], Section 6).

2. The technical bases for the parameter values and ranges in the TSPA abstraction are consistent with data from the Yucca Mountain region (e.g., Amargosa Valley survey, Cannon Center for Survey Research, 1997), studies of surface processes in the Fortymile Wash drainage basin, applicable laboratory testings, or other valid sources of data. For example, soil types, crop types, plow depths, and irrigation rates should be consistent with current farming practices, and data on the airborne particulate concentration should be based on the resuspension of appropriate material in a climate and level of disturbance similar to that which is expected to be found at the location of the reasonably maximally exposed individual during the compliance time period.

The ash redistribution conceptual model is based on erosion-rate data, soil-profile data, and surficial-processes information collected in the Yucca Mountain area, including sample locations in Fortymile Wash and surrounding the Lathrop Wells cone. Figure 2 is an illustration of the conceptual model based on information from Fortymile Wash that shows redistribution of tephra toward a RMEI. Sample locations and study areas are shown in Figures 3, 4, and 10. Figure 5 shows a typical Cs-137 profile (concentration vs depth). Figure 6 is an example of a Cs-137 profile in Fortymile Wash that illustrates the effects of erosion. Cesium-137 values and their interpretations for the Fortymile Wash fan are shown in Table 9. Rates of surficial processes in Fortymile Wash are described in Section 6.6.3, and the cesium study on the Fortymile Wash alluvial fan is described in Section 6.6.3.1.

The development and use of the ash redistribution conceptual model is not dependent on consideration of the characteristics of the RMEI, which are documented in the *Biosphere Model Report* (BSC 2003 [164186]). Agricultural and environmental input parameters for the biosphere model are described in the report, *Agricultural and Environmental Input Parameters for the Biosphere Model* (BSC 2003 [160976]).

3. Uncertainty is adequately represented in parameters for conceptual models, process models, and alternative conceptual models considered in developing the total system performance assessment abstraction of redistribution of radionuclides in soil, either through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the total system performance assessment.

Model outputs that provide inputs (factors) for the TSPA are described in Table 11. As can be seen from Table 11, uncertainties in soil redistribution factors are provided as distributions for use in the TSPA. The ash redistribution conceptual model is described in Section 6.6.1. Uncertainties in the model are described in Section 8.3, and conservatisms included to assure that model outputs to the TSPA do not result in an under representation of risk are described as part of the conceptual model in Section 6.6.1. The method to incorporate conservatism is development of two scenarios that bound the mechanisms of ash redistribution in the Yucca Mountain area. These scenarios are described in Sections 6.6.1.1 and 6.6.1.2, respectively. A general description of tephra redistribution processes is provided in Section 6.6.2, and effects of processes such as erosion and eolian inflation on Cs-137 values are described in Section 6.6.3.1. Correlations between sample depth, Cs-137 content, and the geomorphic feature from which the sample was collected are documented in Table 9.

Section 1.3 discusses the limitations of the ash redistribution conceptual model.

4. Parameters or models that most influence repository performance based on the performance measure and time period of compliance, specified in 10 CFR Part 63 [156605], are identified.

Section 8.2 notes that five factors related to the ash redistribution conceptual model are important to repository performance. These factors are described in Section 6.7.2 and are listed in Table 11. Guidance is also provided in Section 6.7.2 for using the factors in the TSPA model to best represent the factors given in this report.

5. Where sufficient data do not exist, the definition of parameter values and conceptual models on appropriate uses of other sources, such as expert elicitation, are conducted in accordance with appropriate guidance, such as NUREG-1563 (Kotra et al. 1996 [100909]).

The ash redistribution conceptual model is based on observations and laboratory data from field work in Fortymile Wash, on the Fortymile Wash alluvial fan, and from drainages near the Lathrop Wells cone. Specifically, the ash redistribution conceptual model is based on erosion-rate data, soil-profile data, and surficial-processes information collected in the Yucca Mountain area, including sample locations in Fortymile Wash and surrounding the Lathrop Wells cone. Figure 2 is an illustration of the conceptual model based on information from Fortymile Wash and shows redistribution of tephra toward a RMEI. Sample locations and study areas are shown in Figures 3, 4 and 10. Figure 5a shows a typical Cs-137 profile (concentration vs depth). Figure 5b is an example Cs-137 profile in Fortymile Wash showing the effects of erosion. Cs-137 values and their interpretations for the Fortymile Wash fan are shown in Table 9. Rates of surficial processes in Fortymile Wash are described in Section 6.6.3, and the cesium study on the Fortymile Wash alluvial fan is described in Section 6.6.3.1. Model limitations are described in Section 1.3.

Development of the conceptual model is based on analog data from sites at and near Yucca Mountain. Model development did not rely on other sources, such as expert elicitation.

Acceptance Criterion 4: Model Uncertainty is Characterized and Propagated Through the Model Abstraction

1. Alternative modeling approaches of features, events, and processes are considered and are consistent with available data, and current scientific understanding, and the results and limitations are appropriately considered in the abstraction.

Consideration of ACMs for ash redistribution is described in Section 6.4.2. Because the ash redistribution conceptual model is a first-of-a-kind, no relevant alternative ACMs have yet been identified. Features, events, and processes included in the ash redistribution conceptual model are described in Section 6.2, and Table 6 provides details about the disposition of FEP 1.2.04.07.0C, Ash Redistribution Via Soil and Sediment Transport. A general description of tephra redistribution processes is provided in Section 6.6.2. Rates of surficial processes that are needed to support model development and use are documented in Section 6.6.3, and the Cs-137 data that form a time stratigraphic marker in the surficial deposits and provide a proxy for determining the soil depths that fine particles and associated radionuclides from waste could penetrate are described in Section 6.6.3.1. Descriptions of how the data are used are provided in Section 6.7.2. Analog studies to support the ash redistribution conceptual model are described in Section 7.3, and the results of an independent review of this model are described in Section 7.4.2. Uncertainties associated with the ash redistribution conceptual model are described in Section 8.3. Model limitations are described in Section 1.3.

2. Sufficient evidence is provided that alternative conceptual models of features, events, and processes have been considered; that the preferred models (if any) are consistent with available data (e.g., field, laboratory, and natural analog) and current scientific understanding; and that the effect on total system performance assessment of uncertainties from these alternative conceptual models has been evaluated.

The ash redistribution conceptual model is new, but consideration of ACMs for ash redistribution is discussed in Section 6.4.2. Because the ash redistribution conceptual model is a first-of-a-kind, no relevant alternative ACMs have yet been identified. There are no ACMs to describe. Development of the ash redistribution conceptual model is based on analog data from sites at and near Yucca Mountain. Features, events, and processes included in the ash redistribution conceptual model are described in Section 6.2, and Table 6 provides details about the disposition of FEP 1.2.04.07.0C, Ash Redistribution Via Soil and Sediment Transport. A general description of tephra redistribution processes is provided in Section 6.6.2.

Rates of surficial processes that are needed to support model development and use are documented in Section 6.6.3, and the Cs-137 data that form a time stratigraphic marker in the surficial deposits and provide a proxy for determining the soil depths that fine particles and associated radionuclides from waste could penetrate are described in Section 6.6.3.1. Descriptions of how the data are used are provided in Section 6.7.2. Analog studies to support the ash redistribution conceptual model are described in Section 7.3. Uncertainties associated with the ash redistribution conceptual model are described in Section 8.3. Model limitations are described in Section 1.3.

Section 8.2 notes that the abstraction from the ash redistribution conceptual model is important to repository performance (see Section 6.7.2 and Table 11).

3. Consideration of conceptual model uncertainty is consistent with available site characterization data, laboratory experiments, field measurements, natural analog information and process-level modeling studies; and the treatment of conceptual model uncertainty does not result in an under-representation of the risk estimate.

Inputs for the ash redistribution conceptual model and the appropriateness of the inputs for use in the model are described in Section 4.1.1. Assumptions are described in Section 5.1.3. Analog studies undertaken in the Yucca Mountain area to ensure the model appropriately considers sedimentary processes that affect tephra sheets are described in Section 7.3. Uncertainties in the model are described in Section 8.3, and conservatisms included to assure that model outputs to the TSPA do not result in an under representation of risk are described as part of the conceptual model in Section 6.6.1.

Section 8.2 notes that the abstraction from the ash redistribution conceptual model is important to repository performance (see Section 6.7.2 and Table 11).

Acceptance Criterion 5: Model Abstraction Output Is Supported by Objective Comparisons

1. Models implemented in the abstraction provide results consistent with output from detailed process-level models and/or empirical observations (e.g., laboratory testing, field measurements, and/or natural analogs).

Inputs for the ash redistribution conceptual model and the appropriateness of the inputs for use in the model are described in Section 4.1.1. Assumptions are described in Section 5.1.3. Analog studies undertaken in the Yucca Mountain area to ensure the model appropriately considers sedimentary processes that affect tephra sheets are described in Section 7.3. Section 8.2 notes that the abstraction from the ash redistribution conceptual model is important to repository performance (see Section 6.7.2 and Table 11).

ATTACHMENT II: SENSITIVITY STUDIES

Sensitivity analyses were performed both to ensure that the ASHPLUME model operated over the parameter ranges selected and to demonstrate that there were not limitations in model validity due to numerical constraints (Heiken et al. 2003 [166290], pp. 96 to 107). The sensitivity analyses were performed by varying the value of the following input parameters: eruptive power, mean ash particle diameter, ash particle diameter standard deviation, column diffusion constant (beta), initial rise velocity, wind speed, wind direction, and eruption duration. The range for each of these parameters is provided in Table 15. Values were chosen for the sensitivity analyses in order to evaluate the entire range of each parameter, and values for non-varying parameters were set at base-case values (Table II-9). Sensitivity analyses results are presented in this attachment in the form of tables and graphs that display the varying parameter values and calculated values for ash and fuel deposition (g/cm^2). These analyses are discussed in greater detail in Heiken et al. (2003 [166290], pp. 96 to 107.)

Table II-1. Sensitivity of Calculated Ash and Fuel Concentration to Eruptive Power

Power (W)	Calculated Ash Deposition (g/cm^2)	Calculated Fuel Deposition (g/cm^2)
6.17E+08	3.33E-02	4.57E-06
1.52E+09	8.59E-02	6.74E-06
3.73E+09	2.22E-01	7.26E-06
9.18E+09	5.75E-01	7.81E-06
2.26E+10	1.49E+00	8.41E-06
5.55E+10	3.89E+00	9.11E-06
1.37E+11	1.02E+01	9.89E-06
3.36E+11	2.68E+01	1.08E-05
8.26E+11	7.14E+01	1.19E-05
2.03E+12	1.89E+02	1.31E-05
5.00E+12	5.07E+02	1.44E-05

Figure II-1. Sensitivity of Calculated Ash and Fuel Concentration to Eruptive Power

Table II-2. Sensitivity of Calculated Ash and Fuel Concentration to Mean Ash Particle Diameter

Mean Ash Particle Diameter (cm)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
0.00100	3.32E+00	2.58E-06
0.00158	3.54E+00	3.03E-06
0.00251	3.72E+00	3.53E-06
0.00398	3.88E+00	4.11E-06
0.00631	3.95E+00	4.74E-06
0.01000	3.97E+00	5.47E-06
0.01585	3.93E+00	6.27E-06
0.02512	3.83E+00	7.16E-06
0.03981	3.68E+00	8.18E-06
0.06310	3.47E+00	9.27E-06
0.10000	3.24E+00	1.05E-05

Figure II-2. Sensitivity of Calculated Ash and Fuel Concentration to Mean Ash Particle Diameter

Table II-3. Sensitivity of Calculated Ash and Fuel Concentration to Ash Particle Diameter Standard Deviation

Ash Particle Diameter Standard Deviation (log (cm))	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
-1.9	3.08E+00	6.31E-06
-1.84	3.15E+00	6.70E-06
-1.78	3.24E+00	7.18E-06
-1.72	3.01E+00	7.71E-06
-1.66	3.43E+00	8.33E-06
-1.6	3.52E+00	9.03E-06
-1.54	3.62E+00	9.85E-06
-1.48	3.73E+00	1.09E-05
-1.42	3.83E+00	1.20E-05
-1.36	3.96E+00	1.35E-05
-1.3	4.06E+00	1.52E-05

Figure II-3. Sensitivity of Calculated Ash and Fuel Concentration to Ash Particle Diameter Standard Deviation

Table II-4. Sensitivity of Calculated Ash and Fuel Concentration to Column Diffusion Constant (Beta)

Column Diffusion Constant (Beta)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
0.0100	3.90E+00	9.69E-06
0.0148	3.89E+00	9.67E-06
0.0219	3.87E+00	9.64E-06
0.0323	3.84E+00	9.60E-06
0.0478	3.81E+00	9.56E-06
0.0707	3.77E+00	9.49E-06
0.1046	3.72E+00	9.40E-06
0.1546	3.66E+00	9.29E-06
0.2287	3.58E+00	9.15E-06
0.3381	3.49E+00	8.98E-06
0.5000	3.39E+00	8.79E-06

Figure II-4. Sensitivity of Calculated Ash and Fuel Concentration to Column Diffusion Constant (Beta)

Table II-5. Sensitivity of Calculated Ash and Fuel Concentration to Initial Rise Velocity

Initial Rise Velocity (cm/s)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
1	3.90E+00	9.69E-06
3	3.85E+00	9.62E-06
7	3.78E+00	9.51E-06
17	3.66E+00	9.29E-06
43	3.46E+00	8.91E-06
110	3.22E+00	8.44E-06
280	3.07E+00	8.22E-06
717	3.28E+00	8.95E-06
1834	3.98E+00	1.10E-05
4691	4.68E+00	1.31E-05
12000	5.07E+00	1.43E-05

Figure II-5. Sensitivity of Calculated Ash and Fuel Concentration to Initial Rise Velocity

Table II-6. Sensitivity of Calculated Ash and Fuel Concentration to Wind Speed

Wind Speed (cm/s)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
0	2.67E-01	6.20E-07
566	4.26E+00	1.10E-05
1132	1.28E+01	3.51E-05
1698	2.43E+01	6.92E-05
2264	3.20E+01	9.47E-05
2830	5.32E+01	1.56E-04
3396	7.83E+01	2.27E-04
3962	8.56E+01	2.54E-04
4528	1.00E+02	2.99E-04
5094	1.16E+02	3.45E-04
5660	1.34E+02	4.08E-04

Figure II-6. Sensitivity of Calculated Ash and Fuel Concentration to Wind Speed

Table II-7. Sensitivity of Calculated Ash and Fuel Concentration to Wind Direction

Wind Direction (degrees)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
-150	4.41E-02	1.06E-07
-117	9.75E-01	2.48E-06
-84	3.29E+00	8.42E-06
-51	3.16E-01	7.93E-07
-18	1.85E-02	4.26E-08
15	4.49E-03	9.43E-09
48	2.40E-03	4.78E-09
81	1.90E-03	3.72E-09
114	2.03E-03	4.00E-09
147	3.00E-03	6.08E-09
180	7.41E-03	1.61E-08

Figure II-7. Sensitivity of Calculated Ash and Fuel Concentration to Wind Direction

Table II-8. Sensitivity of Calculated Ash and Fuel Concentration to Eruption Duration

Eruption Duration (s)	Calculated Ash Deposition (g/cm ²)	Calculated Fuel Deposition (g/cm ²)
8.64E+04	1.18E-01	9.03E-06
1.33E+05	1.81E-01	9.03E-06
2.05E+05	2.79E-01	9.03E-06
3.16E+05	4.30E-01	9.03E-06
4.86E+05	6.61E-01	9.03E-06
7.48E+05	1.02E+00	9.03E-06
1.15E+06	1.56E+00	9.03E-06
1.77E+06	2.41E+00	9.03E-06
2.73E+06	3.71E+00	9.03E-06
4.21E+06	5.73E+00	9.03E-06
6.48E+06	8.81E+00	9.03E-06

Figure II-8. Sensitivity of Calculated Ash and Fuel Concentration to Eruption Duration

Table II-9. Input Parameter Values for ASHPLUME Sensitivity Studies

Input Parameters	Base Case (total range)	Base Case (50th %ile or representative)	Sensitivity Analysis							
			P	dmean	dsigma	beta	velocity	wind speed	wind direction	eruption duration
Ashdenmin	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08
ashdenmax	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Ashrholow	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
Ashrhohi	0	0	0	0	0	0	0	0	0	0
Fshape	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Beta	0.01-0.5	0.3	0.3	0.3	0.3	0.01-0.5	0.3	0.3	0.3	0.3
particle (dmean)	0.001-0.01-0.1	0.0572	0.0572	0.001 - 0.1	0.0572	0.0572	0.0572	0.0572	0.0572	0.0572
Dsigma (log (cm))	(-1.9)-(-1.3)	-1.6	-1.6	-1.6	(-1.9)-(-1.3)	-1.6	-1.6	-1.6	-1.6	-1.6
wind dir (degrees)	-180 - +180	-90	-90	-90	-90	-90	-90	-90	-180 - +180	-90
wind speed (cm/s)	0 - 5660	500	500	500	500	500	500	0 - 5660	500	500
inital rise velocity (cm/s)	1.0E+00 - 1.2E+04	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01	1.0E+00 - 1.2E+04	3.30E+01	3.30E+01	3.30E+01
power (W)	6.17E+08 - 5E+12	5.06E+10	6.17E+08 - 5E+12	5.06E+10	5.06E+10	5.06E+10	5.06E+10	5.06E+10	5.06E+10	5.06E+10
duration (s)	8.64E+04 - 6.48E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06	2.59E+06	8.64E+04 - 6.48E+06
mass of waste (g)	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08	1.13E+08

NOTE: The analyzed range in wind speed spans the total range of observed values and is held fixed at the average wind speed for the 2 to 3 km altitude bin for evaluating ranges of the other parameters. The analyzed range in wind direction spans the total range of observed values and is held constant blowing due south (-90°) for evaluations of other parameters.

ATTACHMENT III: DESERT ROCK WIND DATA ANALYSES

A need exists to develop parameter distributions for atmospheric data inputs to the TSPA model according to AP-SV.1Q, *Control of the Electronic Management of Information*. Statistical analyses are performed on a qualified data set to develop these parameter distributions. The parameter distributions developed from these data account for uncertainty in the observed data. The parameters under consideration are wind speed and wind direction. Both the data and the methods used to develop these parameter distributions are contained in Output DTN: MO0312SPADRWSD.001. Tables III-1 through III-12 illustrate this method as documented in the DTN.

The first step in analyzing Desert Rock wind data involved importing data file DRA UA 1978-1995.txt from the data CD provided by W. Statham of Framatome ANP on July 7, 2003 (NOAA 1995 [154435]) into Microsoft Access. Next, titles were added to each column based on the associated word file (Metadata for Desert Rock Upper Air Data) (NOAA 1995 [154435]). This resulted in 742,638 lines of data.

Next, a search for “999” (i.e., the designator for blank data fields) was completed for the height column (#6), as stated in the associated word file. This column did not contain “999”, but rather “-99999”, which indicated a blank data field. This was determined by observation of the last four columns of the table, which had “999” designators for temperature, humidity, wind direction, and wind speed data. In all, there were 9,712 lines of data with “-99999” in the height column (see Table III-1).

Table III-1. Combined Desert Rock Wind Data

Year	Month	Day	Hour of observation	Pressure	Height (m)	Temperature	Humidity	Wind Direction	Wind speed (knots)
1978	8	26	0	4105	-99999	-999	999	999	999

As wind direction and wind speed data were unavailable, these lines (9,712) were removed from the dataset by completing an advanced filter/sort and setting the criteria to “99999” in the height column, selecting all resulting records, and then deleting them.

Next, 50,882 data lines without wind direction and wind speed readings (noted by “999”) were deleted in the same manner.

A search for completely blank lines resulted in the following:

- 1 blank wind speed cell
- 42 blank temperature cells
- 34 blank temperature and height cells
- 70,580 blank height cells (for 1994 and 1995 only)
- 97 blank pressure and height cells.

Because there is a relationship between pressure and height, height can be estimated for lines with missing values by using its pressure reading. Data lines without pressure or height readings were eliminated from the database, totaling 97 data lines. Additionally, the data line without a wind speed value (blank cell) was removed.

To determine the relationship between pressure and height for 1994 and 1995 datasets, all blank height data lines were removed from the dataset, and a line graph was constructed in Microsoft Excel using the average corresponding heights for the corresponding pressure. As a result of this analysis, the graphs were determined to be quite different from earlier years. Tables III-2 and III-3 show a comparison of data for pressure and height data for 1994 and 1995. The differences in range cannot be explained by missing data because the ranges for available pressure data for 1994 and 1995, which lacked height data, match those presented here in these tables. In addition, for 1993 data, a pressure reading of around 700 kPa correlates with a height of approximately 17,000 ft, while for 1994 and 1995 data, a pressure reading of around 700 kPa correlates with a height of approximately 3,000 ft. Because approximately 75 percent of the 1994 and 1995 data lack height values and the relationship between pressure and height does not closely match that for earlier years, 1994 and 1995 data are excluded from the data analyses (95,845 data lines total).

Table III-2. Desert Rock Pressure Data (in kilopascals)

Year	Minimum	Maximum	Average	Count
1978	50	9167	3541	20813
1979	70	9177	3602	33506
1980	70	9150	3599	32841
1981	40	9157	3508	35200
1982	50	9170	3691	34533
1983	30	9116	3712	34514
1984	40	9160	3680	34566
1985	50	9160	3576	33898
1986	40	9153	3592	33181
1987	50	9136	3329	34947
1988	70	9174	3322	34467
1989	50	9170	3259	34555
1990	50	9143	3228	45604
1991	60	9160	3235	49675
1992	40	9157	3473	46447
1993	20	9174	3302	47354
1994	73	2891	828	49583
1995	73	2881	834	46262

Table III-3. Desert Rock Height Data (in meters)

Year	Minimum	Maximum	Average	Count
1978	1007	35817	11370	20813
1979	1007	34186	11022	33506
1980	1007	33815	11054	32841
1981	1007	37665	11509	35200
1982	1007	35287	10994	34533
1983	1007	39660	10833	34514
1984	1007	37490	10924	34566
1985	1007	36229	11331	33898
1986	1007	37689	11153	33181
1987	1007	36064	12280	34947
1988	1007	34126	12338	34467
1989	1007	36187	12487	34555
1990	1007	36148	12181	45604
1991	1007	35058	11973	49675
1992	1007	36786	11222	46447
1993	1007	40661	11888	47354
1994	1007	6783	3054	12977
1995	1007	6970	3062	12385

Analysis of the wind speed and direction columns resulted in the discovery of fields filled with “0.” One data line was removed due to the fact that there was a direction reading without speed.

A total of 1,232 lines contained “0” for both the wind speed and direction fields. These data appear to be representations of times when it was calm and wind speed could not be determined. As such, these were left in the database for a total of 586,100 data lines.

Height Conversion

At the repository site, the crest of Yucca Mountain is approximately 4,905 ft (1,495 m) above sea level (CRWMS M&O 2000 [153246], Figure 3.2-10; DTN: MO0103COV01031.000 [155271], boring SD-6). To obtain the height in kilometers above Yucca Mountain, 1,495 m (4,905 ft) are subtracted from the height data that are presented in meters in the data files.

Specifically, meters were converted to kilometers above Yucca Mountain by using the update query function, with the following formula inserted in the “update to” field:

$$([\text{height (m)}] - 1,495 [\text{Yucca Mountain elevation}]) \\ * 0.001 (\text{conversion from m to km}) = \text{wind height in km}$$

Table III-4 shows the first 28 lines of the table used in the height conversion update query. A Height [km] column has been added to show how Microsoft Access applied the update query function.

WIND SPEED CONVERSION

Wind speed was converted from knots to cm/s by the following formula inserted in the “update to” field:

$$[\text{wind speed (knots)}] * 51.44444 = \text{wind speed in cm/s (Lide 2002 [160832], pp. 1 to 41)}$$

Table III-5 is the result of the height conversion update query and is used for the wind speed query update function. A column has been added (wind speed [cm/s]) to show how Microsoft Access applied the update query function.

Table III-6 is the result of the wind speed conversion and is used for the height segregation query function described below.

Table III-4. Desert Rock Data Used for Height Conversion

ID	Year	Month	Day	Hour	Pressure (kPa)	Height (m)	Height (km)	Temperature (x 0.1 °C)	Humidity (relative, %)	Wind Direction (degrees from N)	Wind Speed (knots)
2	1978	5	16	0	8860	1046	= (height (m) – 1495) *.001	248	19	197	13
3	1978	5	16	0	8690	1215	= (height (m) – 1495) *.001	229	20	193	14
4	1978	5	16	0	8500	1407	= (height (m) – 1495) *.001	214	20	191	14
5	1978	5	16	0	8000	1927	= (height (m) – 1495) *.001	165	21	192	16
6	1978	5	16	0	7500	2471	= (height (m) – 1495) *.001	113	24	198	15
7	1978	5	16	0	7000	3040	= (height (m) – 1495) *.001	57	28	203	14
8	1978	5	16	0	6740	3348	= (height (m) – 1495) *.001	28	32	217	13
9	1978	5	16	0	6630	3481	= (height (m) – 1495) *.001	28	29	231	13
10	1978	5	16	0	6580	3543	= (height (m) – 1495) *.001	37	24	237	13
11	1978	5	16	0	6500	3642	= (height (m) – 1495) *.001	35	22	249	14
12	1978	5	16	0	6460	3692	= (height (m) – 1495) *.001	33	20	254	15
13	1978	5	16	0	6220	4000	= (height (m) – 1495) *.001	50	19	259	23
14	1978	5	16	0	6100	4159	= (height (m) – 1495) *.001	45	19	256	23
15	1978	5	16	0	6000	4293	= (height (m) – 1495) *.001	36	19	255	23
16	1978	5	16	0	5750	4637	= (height (m) – 1495) *.001	12	19	251	22
17	1978	5	16	0	5500	4992	= (height (m) – 1495) *.001	-19	19	249	22
18	1978	5	16	0	5430	5094	= (height (m) – 1495) *.001	-28	19	248	22
19	1978	5	16	0	5000	5740	= (height (m) – 1495) *.001	-88	19	248	23
20	1978	5	16	0	4500	6544	= (height (m) – 1495) *.001	-165	19	246	25
21	1978	5	16	0	4440	6645	= (height (m) – 1495) *.001	-175	20	246	25
22	1978	5	16	0	4000	7416	= (height (m) – 1495) *.001	-241	20	249	23
23	1978	5	16	0	3600	8177	= (height (m) – 1495) *.001	-294	20	249	24
24	1978	5	16	0	3500	8380	= (height (m) – 1495) *.001	-309	20	249	25
25	1978	5	16	0	3000	9452	= (height (m) – 1495) *.001	-396	20	249	24
26	1978	5	16	0	2650	10289	= (height (m) – 1495) *.001	-462	999	245	27
27	1978	5	16	0	2500	10674	= (height (m) – 1495) *.001	-494	999	247	26
28	1978	5	16	0	2360	11050	= (height (m) – 1495) *.001	-519	999	248	26

Table III-5. Result of Height Conversion in Table III-4 Used for Wind Speed Conversion

ID	Year	Month	Day	Hour	Pressure (kPa)	Height (km)	Temperature (x 0.1 °C)	Humidity (relative, %)	Wind Direction (degrees from N)	Wind Speed (knots)	Wind Speed (cm/s)
2	1978	5	16	0	8860	-0.449	248	19	197	13	=Wind speed (knots) *51.44444
3	1978	5	16	0	8690	-0.28	229	20	193	14	=Wind speed (knots) *51.44444
4	1978	5	16	0	8500	-0.088	214	20	191	14	=Wind speed (knots) *51.44444
5	1978	5	16	0	8000	0.432	165	21	192	16	=Wind speed (knots) *51.44444
6	1978	5	16	0	7500	0.976	113	24	198	15	=Wind speed (knots) *51.44444
7	1978	5	16	0	7000	1.545	57	28	203	14	=Wind speed (knots) *51.44444
8	1978	5	16	0	6740	1.853	28	32	217	13	=Wind speed (knots) *51.44444
9	1978	5	16	0	6630	1.986	28	29	231	13	=Wind speed (knots) *51.44444
10	1978	5	16	0	6580	2.048	37	24	237	13	=Wind speed (knots) *51.44444
11	1978	5	16	0	6500	2.147	35	22	249	14	=Wind speed (knots) *51.44444
12	1978	5	16	0	6460	2.197	33	20	254	15	=Wind speed (knots) *51.44444
13	1978	5	16	0	6220	2.505	50	19	259	23	=Wind speed (knots) *51.44444
14	1978	5	16	0	6100	2.664	45	19	256	23	=Wind speed (knots) *51.44444
15	1978	5	16	0	6000	2.798	36	19	255	23	=Wind speed (knots) *51.44444
16	1978	5	16	0	5750	3.142	12	19	251	22	=Wind speed (knots) *51.44444
17	1978	5	16	0	5500	3.497	-19	19	249	22	=Wind speed (knots) *51.44444
18	1978	5	16	0	5430	3.599	-28	19	248	22	=Wind speed (knots) *51.44444
19	1978	5	16	0	5000	4.245	-88	19	248	23	=Wind speed (knots) *51.44444
20	1978	5	16	0	4500	5.049	-165	19	246	25	=Wind speed (knots) *51.44444
21	1978	5	16	0	4440	5.15	-175	20	246	25	=Wind speed (knots) *51.44444
22	1978	5	16	0	4000	5.921	-241	20	249	23	=Wind speed (knots) *51.44444
23	1978	5	16	0	3600	6.682	-294	20	249	24	=Wind speed (knots) *51.44444
24	1978	5	16	0	3500	6.885	-309	20	249	25	=Wind speed (knots) *51.44444
25	1978	5	16	0	3000	7.957	-396	20	249	24	=Wind speed (knots) *51.44444
26	1978	5	16	0	2650	8.794	-462	999	245	27	=Wind speed (knots) *51.44444
27	1978	5	16	0	2500	9.179	-494	999	247	26	=Wind speed (knots) *51.44444
28	1978	5	16	0	2360	9.555	-519	999	248	26	=Wind speed (knots) *51.44444

Table III-6. Result of Table III-5 Used for Height Segregation

ID	Year	Month	Day	Hour of Observation	Pressure (kPa)	Height (km)	Temperature (x 0.1 °C)	Humidity (relative, %)	Wind Direction (degrees from N)	Wind Speed (cm/s)
2	1978	5	16	0	8860	-0.449	248	19	197	668.77772
3	1978	5	16	0	8690	-0.28	229	20	193	720.22216
4	1978	5	16	0	8500	-0.088	214	20	191	720.22216
5	1978	5	16	0	8000	0.432	165	21	192	823.11104
6	1978	5	16	0	7500	0.976	113	24	198	771.6666
7	1978	5	16	0	7000	1.545	57	28	203	720.22216
8	1978	5	16	0	6740	1.853	28	32	217	668.77772
9	1978	5	16	0	6630	1.986	28	29	231	668.77772
10	1978	5	16	0	6580	2.048	37	24	237	668.77772
11	1978	5	16	0	6500	2.147	35	22	249	720.22216
12	1978	5	16	0	6460	2.197	33	20	254	771.6666
13	1978	5	16	0	6220	2.505	50	19	259	1183.22212
14	1978	5	16	0	6100	2.664	45	19	256	1183.22212
15	1978	5	16	0	6000	2.798	36	19	255	1183.22212
16	1978	5	16	0	5750	3.142	12	19	251	1131.77768
17	1978	5	16	0	5500	3.497	-19	19	249	1131.77768
18	1978	5	16	0	5430	3.599	-28	19	248	1131.77768
19	1978	5	16	0	5000	4.245	-88	19	248	1183.22212
20	1978	5	16	0	4500	5.049	-165	19	246	1286.111
21	1978	5	16	0	4440	5.15	-175	20	246	1286.111
22	1978	5	16	0	4000	5.921	-241	20	249	1183.22212
23	1978	5	16	0	3600	6.682	-294	20	249	1234.66656
24	1978	5	16	0	3500	6.885	-309	20	249	1286.111
25	1978	5	16	0	3000	7.957	-396	20	249	1234.66656
26	1978	5	16	0	2650	8.794	-462	999	245	1388.99988
27	1978	5	16	0	2500	9.179	-494	999	247	1337.55544
28	1978	5	16	0	2360	9.555	-519	999	248	1337.55544

After these conversions, the table was then separated by designated height intervals using Microsoft Access. Twelve tables were constructed using the query criteria provided in Table III-7:

Table III-7. Height Segregation Query Criteria

Height Interval	Query Criteria
0 to 1 km (28,647 data lines)	≥ 0 and < 1
1 up to 2 km (35,547 data lines)	≥ 1 and < 2
2 up to 3 km (44,878 data lines)	≥ 2 and < 3
3 up to 4 km (33,093 data lines)	≥ 3 and < 4
4 up to 5 km (28,471 data lines)	≥ 4 and < 5
5 up to 6 km (27,711 data lines)	≥ 5 and < 6
6 up to 7 km (23,939 data lines)	≥ 6 and < 7
7 up to 8 km (20,306 data lines)	≥ 7 and < 8
8 up to 9 km (15,210 data lines)	≥ 8 and < 9
9 up to 10 km (17,382 data lines)	≥ 9 and < 10
10 up to 11 km (20,052 data lines)	≥ 10 and < 11
11 up to 12 km (24,192 data lines)	≥ 11 and < 12
12 up to 13 km (18,642 data lines)	≥ 12 and < 13

These tables were then exported from Microsoft Access to Microsoft Excel for further analyses of wind direction and speed.

Wind Direction

The wind directions given in the raw data were in compass degrees *from* the indicated direction and needed to be converted to ASHPLUME degrees *toward* the indicated direction. For each of the heights indicated above, data were initially grouped into bins using the histogram function under the data analysis selection under the tools menu in Excel. Degree bins were entered manually into column L of the spreadsheet. After choosing tools, data analyses, and then histograms, a popup menu appeared and requested choices regarding input and output options. For the input, the wind direction data were entered (column J in the spreadsheet) in the input range cell like the following for the 0- to 1-km data table, “\$J\$2:\$J\$29012.” Column L (bin degrees) was then chosen as the input for the bin range and typed in as: “\$L\$2:\$L\$15” under the Histogram function. This process was repeated for each of the remaining height groupings.

Table III-8. 0- to 1-km Desert Rock Data (only the first 28 rows are shown)

	A	B	C	D	E	F	G	H	I	J	K	L	M
	ID	Year	Month	Day	Hour of Observation	Pressure (kPa)	Height (km)	Temperature (x 0.1 °C)	Humidity (relative, %)	Wind Direction (degrees from N)	Wind Speed (cm/s)	Degree bins	Windspeed bins
1													
2	5	1978	5	16	0	8000	0.432	165	21	192	823	0	0
3	6	1978	5	16	0	7500	0.976	113	24	198	772	14	51
4	62	1978	5	16	12	8000	0.45	62	24	347	463	44	103
5	63	1978	5	16	12	7500	0.975	22	30	320	360	74	154
6	111	1978	5	17	0	8000	0.487	89	22	25	412	104	206
7	168	1978	5	17	12	8500	0.01	90	30	29	360	134	257
8	169	1978	5	17	12	8000	0.508	51	32	19	412	164	309
9	219	1978	5	18	0	8500	0.507	162	20	22	360	194	360
10	220	1978	5	18	0	8000	0.003	113	22	2	309	224	412
11	252	1978	5	18	12	8500	0.509	129	23	77	309	254	463
12	253	1978	5	18	12	8000	0.004	93	25	71	51	284	514
13	292	1978	5	19	0	8500	0.519	193	21	325	154	314	566
14	293	1978	5	19	0	8000	0.014	136	21	141	103	344	617
15	331	1978	5	19	12	8500	0.084	167	22	98	154	360	669
16	332	1978	5	19	12	8430	0.526	167	22	98	103		720
17	333	1978	5	19	12	8000	0.014	129	23	100	51		772
18	376	1978	5	20	0	8500	0.535	220	19	328	103		823
19	377	1978	5	20	0	8000	0.001	175	19	228	206		875
20	416	1978	5	20	12	8500	0.519	205	19	119	206		926
21	417	1978	5	20	12	8000	0.002	159	19	142	154		977
22	459	1978	5	21	0	8500	0.527	244	19	246	154		1029
23	460	1978	5	21	0	8000	0.504	188	19	235	463		1080
24	555	1978	5	22	0	8000	0.475	195	20	214	669		1132
25	584	1978	5	22	12	8000	0.483	163	19	217	514		1183
26	634	1978	5	23	0	8000	0.973	178	19	225	514		1235
27	635	1978	5	23	0	7550	0.417	130	20	207	617		1286
28	723	1978	5	24	0	8000	0.95	108	19	203	566		1338

Table III-9 provides the histogram function analysis output.

Table III-9. 0 to 1 Histogram Function Output

Bin (in compass degrees)	Frequency
0	124
14	907
44	2671
74	2548
104	1835
134	1148
164	1039
194	3536
224	7699
254	2765
284	1253
314	1120
344	1205
360	797

Bins 0, 14, and 360 were combined to represent the 345- to 15-degree interval on the compass. The remaining bins represent the degree intervals as indicated in Table III-10 below.

Table III-10. Bins Converted to Compass Degree Intervals

Compass Degree Intervals	Representative Bins
345 to 15	0, 14, and 360
15 to 45	44
45 to 75	74
75 to 105	104
105 to 135	134
135 to 165	164
165 to 195	194
195 to 225	224
225 to 255	254
255 to 285	284
285 to 315	314
315 to 345	344

ASHPLUME degrees (Figure III-1, ASHPLUME degrees are around the perimeter, compass degrees are inside) *toward* the indicated direction were determined by selecting the ASHPLUME direction exactly opposite of the indicated compass-degree interval and recording the midpoint of the degree interval (Table III-11).

Figure III-1. Compass (inside numbers) and ASHPLUME (outside numbers) Degree Comparison

Table III-11. Compass Degrees from Direction Converted to ASHPLUME Degrees toward Direction

Compass Degrees	ASHPLUME Degrees
165 to 195	90 (North)
195 to 225	60
225 to 255	30
255 to 285	0 (East)
285 to 315	-30
315 to 345	-60
345 to 15	-90 (South)
15 to 45	-120
45 to 75	-150
75 to 105	180 (West)
105 to 135	150
135 to 165	120

Next, a probability distribution function (PDF) was completed using Microsoft Excel for each data grouping. This was performed by taking the sample count for each interval and dividing by the total number of samples for that particular height interval. The ASHPLUME degrees and count were then plotted against one another using the radar-type graph under the chart function to produce a “wind rose” diagram like Figure III-2 below.

Specifically, Table III-12 was constructed for the 0 to 1 km interval in Excel. For final insertion into the TSPA model, significant figures were reduced for the PDF values. ASHPLUME Degrees were arranged sequentially, and the “Frequency” and “Compass Degrees” columns were deleted as shown in Output DTN: MO0312SPADRWSD.001.

Table III-12. PDF Results.

	A	B	C	D*	D
1	Compass Degrees	ASHPLUME degrees	Count/ Frequency	PDF	PDF
2	165 to 195	90 (North)	3536	=C2/(sumC2:C13)	0.1234
3	195 to 225	60	7699	=C3/(sumC2:C13)	0.2688
4	225 to 255	30	2765	=C4/(sumC2:C13)	0.0965
5	255 to 285	0 (East)	1253	=C5/(sumC2:C13)	0.0437
6	285 to 315	-30	1120	=C6/(sumC2:C13)	0.0391
7	315 to 345	-60	1205	=C7/(sumC2:C13)	0.0421
8	345 to 15	-90 (South)	1828	=C8/(sumC2:C13)	0.0638
9	15 to 45	-120	2671	=C9/(sumC2:C13)	0.0932
10	45 to 75	-150	2548	=C10/(sumC2:C13)	0.0889
11	75 to 105	180 (West)	1835	=C11/(sumC2:C13)	0.0641
12	105 to 135	150	1148	=C12/(sumC2:C13)	0.0401
13	135 to 165	120	1039	=C13/(sumC2:C13)	0.0363

NOTE: *= visible cell calculation

Under the insert pull-down menu, chart was selected, radar was selected, and then the last example of radar graphs was chosen. Following, Columns B and C were plotted against each other to form the Figure III-2 below for the 0- to 1-km interval.

NOTE: This figure illustrates the method used in presenting information graphically using a radar-type graph. This figure is the same as Figure III-3, which lists the source of information (NOAA 1995 [154435]) and the data output (Output DTN: MO0312SPADRWSD 001).

Figure III-2. Wind Rose Diagram for 0 to 1 km above Yucca Mountain (YM)

WIND SPEED

A cumulative distribution function (CDF) was calculated for each grouping also using the Histogram function under the data analysis menu in Microsoft Excel. Wind-speed bin intervals consisting of 51.44444 cm/s (1 knot) each were then pasted to each Excel table in Column M (Table III-8, formatting of cell only displays whole numbers although decimals are still in the cells when selected). In order for accurate binning to occur, values in Columns K and M in Table III-8 were then rounded to the nearest whole number to ensure accurate binning using the “= round (number, where to round to)” function in Excel and then placed in Columns N and O, respectively. After choosing tools, data analysis, and then histogram, a popup menu appeared and asked for input and output options. For the input, the wind-speed data were entered in the input range cell, “\$N\$2:\$N\$28648,” for the 0- to 1-km example. This column was then chosen as the input for the bin range cell and typed in as: “\$O\$2:\$O\$112” under the Histogram function.

Additionally, the cumulative percentage (converted to decimal in the tables below) and chart output boxes in the output menu were selected which resulted in a table similar to the following:

Table III-13. 0 to 1 km CDF Table

Bin	Frequency	Cumulative Probability
0	124	0.00433
51	1840	0.06856
103	2804	0.16644
154	3101	0.27469
206	3131	0.38398
257	2908	0.48550
309	2666	0.57856
360	2337	0.66014
412	2108	0.73372
463	1756	0.79502
514	1412	0.84431
566	1083	0.88212
617	831	0.91113
669	678	0.93479
720	484	0.95169
772	388	0.96523
823	209	0.97253
875	175	0.97864
926	159	0.98419
977	112	0.98810
1029	107	0.99183
1080	64	0.99407
1132	75	0.99668
1183	25	0.99756
1235	26	0.99846
1286	25	0.99934
1338	4	0.99948
1389	3	0.99958
1440	5	0.99976
1492	3	0.99986
1543	1	0.99990
1595	1	0.99993
1646	0	0.99993
1698	0	0.99993
1749	0	0.99993
1801	0	0.99993
1852	0	0.99993
1903	0	0.99993
1955	1	0.99997
2006	0	0.99997
2058	0	0.99997
2109	0	0.99997
2161	0	0.99997
2212	0	0.99997
2264	0	0.99997
2315	1	1.00000

This same procedure was followed for the remaining 12 tables (1 to 2 km, 2 to 3 km, 3 to 4 km, 4 to 5 km, 5 to 6 km, 6 to 7 km, 7 to 8 km, 8 to 9 km, 9 to 10 km, 10 to 11 km, 11 to 12 km, and 12 to 13 km).

For insertion into the TSPA model, these tables were modified further. Specifically, all bins without samples were deleted from the tables, the “Frequency” column was deleted, and significant figures were reduced for the CDF values. Additionally, the TSPA model requires the first bin CDF value to equal zero. As such, the zero wind speed bin was replaced with 1E-30 to account for data having a wind speed of zero, and the first bin was added to equal zero.

Table III-14. Wind Speed CDF for 0 to 1 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	124	0.00433
51	1840	0.06856
103	2804	0.16644
154	3101	0.27469
206	3131	0.38398
257	2908	0.48550
309	2666	0.57856
360	2337	0.66014
412	2108	0.73372
463	1756	0.79502
514	1412	0.84431
566	1083	0.88212
617	831	0.91113
669	678	0.93479
720	484	0.95169
772	388	0.96523
823	209	0.97253
875	175	0.97864
926	159	0.98419
977	112	0.98810
1029	107	0.99183
1080	64	0.99407
1132	75	0.99668
1183	25	0.99756
1235	26	0.99846
1286	25	0.99934
1338	4	0.99948
1389	3	0.99958
1440	5	0.99976
1492	3	0.99986
1543	1	0.99990
1595	1	0.99993
1646	0	0.99993
1698	0	0.99993
1749	0	0.99993
1801	0	0.99993
1852	0	0.99993
1903	0	0.99993
1955	1	0.99997
2006	0	0.99997

Table III-14 (Continued). Wind Speed CDF for 0 to 1 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	0	0.99997
2109	0	0.99997
2161	0	0.99997
2212	0	0.99997
2264	0	0.99997
2315	1	1.00000
2366	0	1.00000
2418	0	1.00000
2469	0	1.00000
2521	0	1.00000
2572	0	1.00000
2624	0	1.00000
2675	0	1.00000
2727	0	1.00000
2778	0	1.00000
2829	0	1.00000
2881	0	1.00000
2932	0	1.00000
2984	0	1.00000
3035	0	1.00000
3087	0	1.00000
3138	0	1.00000
3190	0	1.00000
3241	0	1.00000
3292	0	1.00000
3344	0	1.00000
3395	0	1.00000
3447	0	1.00000
3498	0	1.00000
3550	0	1.00000
3601	0	1.00000
3653	0	1.00000
3704	0	1.00000
3755	0	1.00000
3807	0	1.00000
3858	0	1.00000
3910	0	1.00000
3961	0	1.00000
4013	0	1.00000
4064	0	1.00000

Table III-14 (Continued). Wind Speed CDF for 0 to 1 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4116	0	1.00000
4167	0	1.00000
4218	0	1.00000
4270	0	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-15. Wind Speed CDF for 1 to 2 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	74	0.00208
51	1506	0.04445
103	2351	0.11059
154	2925	0.19287
206	3136	0.28109
257	3223	0.37176
309	3168	0.46088
360	2884	0.54201
412	2674	0.61724
463	2402	0.68481
514	2106	0.74406
566	1816	0.79514
617	1481	0.83681
669	1205	0.87071
720	1068	0.90075
772	794	0.92309
823	598	0.93991
875	458	0.95279
926	448	0.96540
977	337	0.97488
1029	255	0.98205
1080	194	0.98751
1132	133	0.99125
1183	100	0.99406
1235	67	0.99595
1286	46	0.99724
1338	33	0.99817
1389	18	0.99868
1440	19	0.99921
1492	13	0.99958
1543	6	0.99975
1595	3	0.99983
1646	2	0.99989
1698	1	0.99992
1749	1	0.99994
1801	1	0.99997
1852	0	0.99997
1903	1	1.00000
1955	0	1.00000
2006	0	1.00000

Table III-15 (Continued). Wind Speed CDF for 1 to 2 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	0	1.00000
2109	0	1.00000
2161	0	1.00000
2212	0	1.00000
2264	0	1.00000
2315	0	1.00000
2366	0	1.00000
2418	0	1.00000
2469	0	1.00000
2521	0	1.00000
2572	0	1.00000
2624	0	1.00000
2675	0	1.00000
2727	0	1.00000
2778	0	1.00000
2829	0	1.00000
2881	0	1.00000
2932	0	1.00000
2984	0	1.00000
3035	0	1.00000
3087	0	1.00000
3138	0	1.00000
3190	0	1.00000
3241	0	1.00000
3292	0	1.00000
3344	0	1.00000
3395	0	1.00000
3447	0	1.00000
3498	0	1.00000
3550	0	1.00000
3601	0	1.00000
3653	0	1.00000
3704	0	1.00000
3755	0	1.00000
3807	0	1.00000
3858	0	1.00000
3910	0	1.00000
3961	0	1.00000
4013	0	1.00000
4064	0	1.00000
4116	0	1.00000

Table III-15 (Continued). Wind Speed CDF for 1 to 2 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	1.00000
4218	0	1.00000
4270	0	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-16. Wind Speed CDF for 2 to 3 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	78	0.00174
51	1194	0.02834
103	1948	0.07175
154	2540	0.12835
206	3020	0.19564
257	3305	0.26929
309	3551	0.34841
360	3524	0.42694
412	3273	0.49987
463	3049	0.56781
514	2733	0.62870
566	2356	0.68120
617	2126	0.72858
669	1896	0.77082
720	1647	0.80752
772	1360	0.83783
823	986	0.85980
875	892	0.87967
926	914	0.90004
977	862	0.91925
1029	712	0.93511
1080	572	0.94786
1132	496	0.95891
1183	389	0.96758
1235	329	0.97491
1286	260	0.98070
1338	199	0.98514
1389	122	0.98786
1440	128	0.99071
1492	88	0.99267
1543	81	0.99447
1595	71	0.99606
1646	56	0.99730
1698	37	0.99813
1749	22	0.99862
1801	25	0.99918
1852	9	0.99938
1903	11	0.99962
1955	4	0.99971
2006	3	0.99978

Table III-16 (Continued). Wind Speed CDF for 2 to 3 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	3	0.99984
2109	4	0.99993
2161	0	0.99993
2212	1	0.99996
2264	1	0.99998
2315	0	0.99998
2366	0	0.99998
2418	0	0.99998
2469	0	0.99998
2521	0	0.99998
2572	1	1.00000
2624	0	1.00000
2675	0	1.00000
2727	0	1.00000
2778	0	1.00000
2829	0	1.00000
2881	0	1.00000
2932	0	1.00000
2984	0	1.00000
3035	0	1.00000
3087	0	1.00000
3138	0	1.00000
3190	0	1.00000
3241	0	1.00000
3292	0	1.00000
3344	0	1.00000
3395	0	1.00000
3447	0	1.00000
3498	0	1.00000
3550	0	1.00000
3601	0	1.00000
3653	0	1.00000
3704	0	1.00000
3755	0	1.00000
3807	0	1.00000
3858	0	1.00000
3910	0	1.00000
3961	0	1.00000
4013	0	1.00000
4064	0	1.00000
4116	0	1.00000

Table III-16 (Continued). Wind Speed CDF for 2 to 3 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	1.00000
4218	0	1.00000
4270	0	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD. 001.

Table III-17. Wind Speed CDF for 3 to 4 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	19	0.00057
51	619	0.01928
103	1044	0.05083
154	1466	0.09513
206	1901	0.15257
257	1889	0.20965
309	2081	0.27253
360	2150	0.33750
412	2147	0.40238
463	2033	0.46381
514	1975	0.52349
566	1780	0.57728
617	1699	0.62862
669	1474	0.67316
720	1263	0.71133
772	1143	0.74587
823	948	0.77451
875	694	0.79549
926	851	0.82120
977	757	0.84408
1029	745	0.86659
1080	648	0.88617
1132	556	0.90297
1183	496	0.91796
1235	414	0.93047
1286	362	0.94141
1338	307	0.95068
1389	252	0.95830
1440	213	0.96474
1492	204	0.97090
1543	175	0.97619
1595	111	0.97954
1646	124	0.98329
1698	92	0.98607
1749	76	0.98837
1801	74	0.99060
1852	53	0.99220
1903	58	0.99396
1955	38	0.99510
2006	29	0.99598

Table III-17 (Continued). Wind Speed CDF for 3 to 4 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	26	0.99677
2109	20	0.99737
2161	15	0.99782
2212	18	0.99837
2264	8	0.99861
2315	10	0.99891
2366	4	0.99903
2418	7	0.99924
2469	3	0.99934
2521	3	0.99943
2572	3	0.99952
2624	3	0.99961
2675	2	0.99967
2727	3	0.99976
2778	1	0.99979
2829	1	0.99982
2881	0	0.99982
2932	1	0.99985
2984	0	0.99985
3035	0	0.99985
3087	0	0.99985
3138	0	0.99985
3190	0	0.99985
3241	3	0.99994
3292	2	1.00000
3344	0	1.00000
3395	0	1.00000
3447	0	1.00000
3498	0	1.00000
3550	0	1.00000
3601	0	1.00000
3653	0	1.00000
3704	0	1.00000
3755	0	1.00000
3807	0	1.00000
3858	0	1.00000
3910	0	1.00000
3961	0	1.00000
4013	0	1.00000
4064	0	1.00000
4116	0	1.00000

Table III-17 (Continued). Wind Speed CDF for 3 to 4 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	1.00000
4218	0	1.00000
4270	0	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-18. Wind Speed CDF for 4 to 5 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	11	0.00039
51	344	0.01247
103	599	0.03351
154	897	0.06501
206	1085	0.10312
257	1255	0.14720
309	1358	0.19490
360	1291	0.24024
412	1337	0.28720
463	1448	0.33806
514	1354	0.38562
566	1309	0.43160
617	1282	0.47663
669	1247	0.52042
720	1187	0.56212
772	1065	0.59952
823	866	0.62994
875	758	0.65656
926	877	0.68737
977	865	0.71775
1029	835	0.74708
1080	767	0.77402
1132	712	0.79902
1183	643	0.82161
1235	553	0.84103
1286	547	0.86024
1338	513	0.87826
1389	466	0.89463
1440	368	0.90756
1492	344	0.91964
1543	348	0.93186
1595	249	0.94061
1646	215	0.94816
1698	166	0.95399
1749	142	0.95898
1801	179	0.96526
1852	146	0.97039
1903	114	0.97439
1955	101	0.97794
2006	100	0.98145

Table III-18 (Continued). Wind Speed CDF for 4 to 5 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	73	0.98402
2109	75	0.98665
2161	60	0.98876
2212	58	0.99080
2264	43	0.99231
2315	45	0.99389
2366	38	0.99522
2418	21	0.99596
2469	12	0.99638
2521	22	0.99715
2572	18	0.99779
2624	11	0.99817
2675	8	0.99845
2727	7	0.99870
2778	6	0.99891
2829	3	0.99902
2881	7	0.99926
2932	2	0.99933
2984	2	0.99940
3035	2	0.99947
3087	2	0.99954
3138	2	0.99961
3190	1	0.99965
3241	1	0.99968
3292	0	0.99968
3344	2	0.99975
3395	0	0.99975
3447	0	0.99975
3498	0	0.99975
3550	0	0.99975
3601	0	0.99975
3653	1	0.99979
3704	2	0.99986
3755	0	0.99986
3807	1	0.99989
3858	1	0.99993
3910	0	0.99993
3961	1	0.99996
4013	0	0.99996
4064	0	0.99996
4116	0	0.99996

Table III-18 (Continued). Wind Speed CDF for 4 to 5 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	0.99996
4218	0	0.99996
4270	0	0.99996
4321	0	0.99996
4373	0	0.99996
4424	0	0.99996
4476	0	0.99996
4527	0	0.99996
4579	0	0.99996
4630	0	0.99996
4681	0	0.99996
4733	0	0.99996
4784	0	0.99996
4836	0	0.99996
4887	0	0.99996
4939	0	0.99996
4990	0	0.99996
5042	0	0.99996
5093	0	0.99996
5144	0	0.99996
5196	0	0.99996
5247	0	0.99996
5299	0	0.99996
5350	0	0.99996
5402	1	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-19. Wind Speed CDF for 5 to 6 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	8	0.00029
51	254	0.00945
103	479	0.02674
154	688	0.05157
206	914	0.08455
257	1064	0.12295
309	1110	0.16300
360	1172	0.20530
412	1149	0.24676
463	1274	0.29274
514	1225	0.33694
566	1267	0.38266
617	1125	0.42326
669	1140	0.46440
720	1144	0.50568
772	1078	0.54459
823	862	0.57569
875	743	0.60250
926	943	0.63653
977	903	0.66912
1029	900	0.70160
1080	807	0.73072
1132	747	0.75768
1183	722	0.78373
1235	593	0.80513
1286	576	0.82592
1338	556	0.84598
1389	454	0.86237
1440	505	0.88059
1492	394	0.89481
1543	342	0.90715
1595	310	0.91834
1646	282	0.92851
1698	240	0.93717
1749	144	0.94237
1801	201	0.94962
1852	186	0.95634
1903	151	0.96178
1955	134	0.96662
2006	138	0.97160

Table III-19 (Continued). Wind Speed CDF for 5 to 6 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	116	0.97579
2109	98	0.97932
2161	86	0.98243
2212	84	0.98546
2264	63	0.98773
2315	52	0.98961
2366	44	0.99119
2418	41	0.99267
2469	33	0.99387
2521	26	0.99480
2572	20	0.99553
2624	18	0.99617
2675	17	0.99679
2727	11	0.99719
2778	13	0.99765
2829	18	0.99830
2881	6	0.99852
2932	7	0.99877
2984	8	0.99906
3035	3	0.99917
3087	3	0.99928
3138	5	0.99946
3190	2	0.99953
3241	1	0.99957
3292	2	0.99964
3344	0	0.99964
3395	0	0.99964
3447	0	0.99964
3498	1	0.99968
3550	3	0.99978
3601	1	0.99982
3653	2	0.99989
3704	0	0.99989
3755	0	0.99989
3807	1	0.99993
3858	1	0.99996
3910	0	0.99996
3961	0	0.99996
4013	0	0.99996
4064	0	0.99996
4116	0	0.99996

Table III-19 (Continued). Wind Speed CDF for 5 to 6 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	0.99996
4218	0	0.99996
4270	0	0.99996
4321	0	0.99996
4373	0	0.99996
4424	0	0.99996
4476	0	0.99996
4527	0	0.99996
4579	0	0.99996
4630	0	0.99996
4681	0	0.99996
4733	0	0.99996
4784	0	0.99996
4836	0	0.99996
4887	0	0.99996
4939	0	0.99996
4990	0	0.99996
5042	0	0.99996
5093	0	0.99996
5144	0	0.99996
5196	0	0.99996
5247	0	0.99996
5299	0	0.99996
5350	0	0.99996
5402	0	0.99996
5453	0	0.99996
5505	1	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-20. Wind Speed CDF for 6 to 7 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	13	0.00054
51	166	0.00748
103	263	0.01846
154	401	0.03521
206	534	0.05752
257	564	0.08108
309	719	0.11112
360	752	0.14253
412	772	0.17478
463	828	0.20937
514	865	0.24550
566	871	0.28188
617	906	0.31973
669	859	0.35561
720	923	0.39417
772	835	0.42905
823	764	0.46096
875	617	0.48674
926	780	0.51932
977	761	0.55111
1029	745	0.58223
1080	685	0.61084
1132	716	0.64075
1183	684	0.66933
1235	614	0.69497
1286	571	0.71883
1338	602	0.74397
1389	505	0.76507
1440	579	0.78926
1492	484	0.80947
1543	440	0.82785
1595	375	0.84352
1646	411	0.86069
1698	343	0.87502
1749	231	0.88467
1801	305	0.89741
1852	262	0.90835
1903	262	0.91929
1955	255	0.92995
2006	195	0.93809

Table III-20 (Continued). Wind Speed CDF for 6 to 7 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	184	0.94578
2109	151	0.95209
2161	163	0.95890
2212	148	0.96508
2264	126	0.97034
2315	109	0.97489
2366	87	0.97853
2418	81	0.98191
2469	70	0.98484
2521	51	0.98697
2572	34	0.98839
2624	39	0.99002
2675	37	0.99156
2727	21	0.99244
2778	20	0.99327
2829	23	0.99424
2881	27	0.99536
2932	18	0.99612
2984	21	0.99699
3035	11	0.99745
3087	6	0.99770
3138	8	0.99804
3190	6	0.99829
3241	6	0.99854
3292	10	0.99896
3344	4	0.99912
3395	2	0.99921
3447	3	0.99933
3498	3	0.99946
3550	2	0.99954
3601	2	0.99962
3653	0	0.99962
3704	0	0.99962
3755	1	0.99967
3807	0	0.99967
3858	2	0.99975
3910	0	0.99975
3961	1	0.99979
4013	0	0.99979
4064	0	0.99979
4116	0	0.99979

Table III-20 (Continued). Wind Speed CDF for 6 to 7 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	0.99979
4218	1	0.99983
4270	0	0.99983
4321	1	0.99987
4373	0	0.99987
4424	1	0.99992
4476	0	0.99992
4527	0	0.99992
4579	0	0.99992
4630	1	0.99996
4681	0	0.99996
4733	0	0.99996
4784	0	0.99996
4836	0	0.99996
4887	0	0.99996
4939	0	0.99996
4990	0	0.99996
5042	0	0.99996
5093	0	0.99996
5144	0	0.99996
5196	0	0.99996
5247	0	0.99996
5299	1	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-21. Wind Speed CDF for 7 to 8 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	9	0.00044
51	120	0.00635
103	191	0.01576
154	282	0.02965
206	388	0.04875
257	457	0.07126
309	490	0.09539
360	534	0.12169
412	598	0.15114
463	629	0.18211
514	687	0.21595
566	685	0.24968
617	738	0.28602
669	731	0.32202
720	745	0.35871
772	677	0.39205
823	597	0.42145
875	543	0.44819
926	658	0.48060
977	662	0.51320
1029	650	0.54521
1080	611	0.57530
1132	542	0.60199
1183	553	0.62922
1235	494	0.65355
1286	495	0.67793
1338	477	0.70142
1389	482	0.72516
1440	457	0.74766
1492	435	0.76908
1543	439	0.79070
1595	398	0.81030
1646	362	0.82813
1698	334	0.84458
1749	219	0.85536
1801	259	0.86812
1852	267	0.88127
1903	270	0.89456
1955	235	0.90614
2006	215	0.91672

Table III-21 (Continued). Wind Speed CDF for 7 to 8 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	233	0.92820
2109	179	0.93701
2161	137	0.94376
2212	149	0.95110
2264	110	0.95652
2315	101	0.96149
2366	99	0.96636
2418	85	0.97055
2469	93	0.97513
2521	83	0.97922
2572	65	0.98242
2624	60	0.98537
2675	43	0.98749
2727	44	0.98966
2778	35	0.99138
2829	18	0.99227
2881	17	0.99311
2932	26	0.99439
2984	16	0.99517
3035	17	0.99601
3087	16	0.99680
3138	14	0.99749
3190	9	0.99793
3241	8	0.99833
3292	6	0.99862
3344	4	0.99882
3395	2	0.99892
3447	1	0.99897
3498	2	0.99906
3550	0	0.99906
3601	4	0.99926
3653	1	0.99931
3704	1	0.99936
3755	0	0.99936
3807	0	0.99936
3858	3	0.99951
3910	1	0.99956
3961	1	0.99961
4013	0	0.99961
4064	0	0.99961
4116	0	0.99961

Table III-21 (Continued). Wind Speed CDF for 7 to 8 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	0.99961
4218	1	0.99966
4270	0	0.99966
4321	0	0.99966
4373	1	0.99970
4424	0	0.99970
4476	1	0.99975
4527	0	0.99975
4579	0	0.99975
4630	0	0.99975
4681	1	0.99980
4733	0	0.99980
4784	0	0.99980
4836	0	0.99980
4887	0	0.99980
4939	1	0.99985
4990	0	0.99985
5042	0	0.99985
5093	0	0.99985
5144	1	0.99990
5196	0	0.99990
5247	0	0.99990
5299	0	0.99990
5350	0	0.99990
5402	0	0.99990
5453	0	0.99990
5505	1	0.99995
5556	0	0.99995
5607	0	0.99995
5659	1	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-22. Wind Speed CDF for 8 to 9 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	2	0.00013
51	86	0.00579
103	110	0.01302
154	183	0.02505
206	246	0.04122
257	289	0.06022
309	348	0.08310
360	385	0.10842
412	400	0.13471
463	463	0.16515
514	448	0.19461
566	473	0.22571
617	497	0.25838
669	507	0.29172
720	533	0.32676
772	551	0.36298
823	450	0.39257
875	446	0.42189
926	542	0.45753
977	562	0.49448
1029	521	0.52873
1080	490	0.56095
1132	489	0.59310
1183	452	0.62281
1235	374	0.64740
1286	423	0.67521
1338	405	0.70184
1389	372	0.72630
1440	332	0.74813
1492	320	0.76917
1543	306	0.78928
1595	299	0.80894
1646	289	0.82794
1698	248	0.84425
1749	172	0.85556
1801	216	0.86976
1852	205	0.88323
1903	192	0.89586
1955	188	0.90822
2006	144	0.91769

Table III-22 (Continued). Wind Speed CDF for 8 to 9 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	167	0.92867
2109	131	0.93728
2161	118	0.94504
2212	106	0.95201
2264	102	0.95871
2315	84	0.96423
2366	69	0.96877
2418	62	0.97285
2469	61	0.97686
2521	33	0.97903
2572	44	0.98192
2624	37	0.98435
2675	27	0.98613
2727	33	0.98830
2778	28	0.99014
2829	30	0.99211
2881	17	0.99323
2932	10	0.99389
2984	19	0.99513
3035	10	0.99579
3087	8	0.99632
3138	9	0.99691
3190	3	0.99711
3241	9	0.99770
3292	3	0.99790
3344	6	0.99829
3395	7	0.99875
3447	0	0.99875
3498	4	0.99901
3550	3	0.99921
3601	2	0.99934
3653	0	0.99934
3704	2	0.99947
3755	2	0.99961
3807	1	0.99967
3858	0	0.99967
3910	0	0.99967
3961	2	0.99980
4013	0	0.99980
4064	0	0.99980
4116	0	0.99980

Table III-22 (Continued). Wind Speed CDF for 8 to 9 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	1	0.99987
4218	0	0.99987
4270	0	0.99987
4321	1	0.99993
4373	0	0.99993
4424	0	0.99993
4476	1	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-23. Wind Speed CDF for 9 to 10 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	3	0.00017
51	53	0.00322
103	100	0.00897
154	142	0.01714
206	198	0.02854
257	232	0.04188
309	291	0.05862
360	326	0.07738
412	329	0.09631
463	371	0.11765
514	445	0.14325
566	451	0.16920
617	491	0.19745
669	513	0.22696
720	508	0.25618
772	506	0.28530
823	512	0.31475
875	394	0.33742
926	594	0.37159
977	566	0.40415
1029	592	0.43821
1080	605	0.47302
1132	579	0.50633
1183	593	0.54044
1235	564	0.57289
1286	567	0.60551
1338	524	0.63566
1389	522	0.66569
1440	447	0.69140
1492	520	0.72132
1543	442	0.74675
1595	426	0.77126
1646	381	0.79318
1698	338	0.81262
1749	268	0.82804
1801	286	0.84449
1852	311	0.86239
1903	266	0.87769
1955	242	0.89161
2006	229	0.90479

Table III-23 (Continued). Wind Speed CDF for 9 to 10 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	215	0.91716
2109	184	0.92774
2161	173	0.93769
2212	160	0.94690
2264	148	0.95541
2315	117	0.96214
2366	92	0.96744
2418	90	0.97262
2469	79	0.97716
2521	59	0.98055
2572	60	0.98401
2624	34	0.98596
2675	30	0.98769
2727	38	0.98987
2778	25	0.99131
2829	21	0.99252
2881	16	0.99344
2932	12	0.99413
2984	16	0.99505
3035	14	0.99586
3087	13	0.99661
3138	5	0.99689
3190	4	0.99712
3241	10	0.99770
3292	8	0.99816
3344	3	0.99833
3395	3	0.99850
3447	2	0.99862
3498	2	0.99873
3550	2	0.99885
3601	2	0.99896
3653	3	0.99914
3704	4	0.99937
3755	4	0.99960
3807	1	0.99965
3858	1	0.99971
3910	1	0.99977
3961	1	0.99983
4013	1	0.99988
4064	0	0.99988
4116	0	0.99988

Table III-23 (Continued). Wind Speed CDF for 9 to 10 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	1	0.99994
4218	0	0.99994
4270	1	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-24. Wind Speed CDF for 10 to 11 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	1	0.00005
51	52	0.00264
103	70	0.00613
154	112	0.01172
206	171	0.02025
257	207	0.03057
309	257	0.04339
360	311	0.05890
412	306	0.07416
463	407	0.09445
514	380	0.11341
566	476	0.13714
617	581	0.16612
669	530	0.19255
720	602	0.22257
772	610	0.25299
823	535	0.27967
875	491	0.30416
926	618	0.33498
977	702	0.36999
1029	681	0.40395
1080	718	0.43976
1132	740	0.47666
1183	677	0.51042
1235	686	0.54463
1286	703	0.57969
1338	673	0.61326
1389	703	0.64831
1440	669	0.68168
1492	620	0.71260
1543	571	0.74107
1595	526	0.76731
1646	493	0.79189
1698	469	0.81528
1749	327	0.83159
1801	381	0.85059
1852	387	0.86989
1903	356	0.88764
1955	292	0.90220
2006	265	0.91542

Table III-24 (Continued). Wind Speed CDF for 10 to 11 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	231	0.92694
2109	186	0.93622
2161	207	0.94654
2212	145	0.95377
2264	122	0.95985
2315	124	0.96604
2366	93	0.97068
2418	93	0.97531
2469	98	0.98020
2521	69	0.98364
2572	41	0.98569
2624	41	0.98773
2675	30	0.98923
2727	27	0.99057
2778	26	0.99187
2829	20	0.99287
2881	18	0.99377
2932	24	0.99496
2984	17	0.99581
3035	19	0.99676
3087	8	0.99716
3138	11	0.99771
3190	7	0.99806
3241	8	0.99845
3292	5	0.99870
3344	1	0.99875
3395	4	0.99895
3447	4	0.99915
3498	3	0.99930
3550	2	0.99940
3601	1	0.99945
3653	3	0.99960
3704	2	0.99970
3755	0	0.99970
3807	1	0.99975
3858	0	0.99975
3910	1	0.99980
3961	0	0.99980
4013	0	0.99980
4064	0	0.99980
4116	1	0.99985

Table III-24 (Continued). Wind Speed CDF for 10 to 11 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	1	0.99990
4218	0	0.99990
4270	0	0.99990
4321	0	0.99990
4373	0	0.99990
4424	1	0.99995
4476	0	0.99995
4527	0	0.99995
4579	1	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-25. Wind Speed CDF for 11 to 12 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	3	0.00012
51	54	0.00236
103	83	0.00579
154	147	0.01186
206	204	0.02030
257	227	0.02968
309	331	0.04336
360	352	0.05791
412	462	0.07701
463	508	0.09801
514	590	0.12240
566	650	0.14926
617	715	0.17882
669	710	0.20817
720	773	0.24012
772	727	0.27017
823	696	0.29894
875	659	0.32618
926	861	0.36177
977	907	0.39926
1029	964	0.43911
1080	928	0.47747
1132	896	0.51451
1183	986	0.55527
1235	932	0.59379
1286	888	0.63050
1338	871	0.66650
1389	887	0.70317
1440	747	0.73404
1492	783	0.76641
1543	651	0.79332
1595	653	0.82031
1646	579	0.84425
1698	472	0.86376
1749	373	0.87917
1801	385	0.89509
1852	363	0.91009
1903	308	0.92283
1955	259	0.93353
2006	222	0.94271

Table III-25 (Continued). Wind Speed CDF for 11 to 12 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	208	0.95131
2109	213	0.96011
2161	157	0.96660
2212	147	0.97268
2264	109	0.97718
2315	84	0.98065
2366	79	0.98392
2418	62	0.98648
2469	44	0.98830
2521	40	0.98996
2572	39	0.99157
2624	25	0.99260
2675	23	0.99355
2727	19	0.99434
2778	18	0.99508
2829	9	0.99545
2881	18	0.99620
2932	12	0.99669
2984	11	0.99715
3035	8	0.99748
3087	9	0.99785
3138	12	0.99835
3190	9	0.99872
3241	4	0.99888
3292	2	0.99897
3344	4	0.99913
3395	2	0.99921
3447	3	0.99934
3498	3	0.99946
3550	4	0.99963
3601	4	0.99979
3653	0	0.99979
3704	1	0.99983
3755	0	0.99983
3807	1	0.99988
3858	0	0.99988
3910	0	0.99988
3961	0	0.99988
4013	0	0.99988
4064	1	0.99992
4116	0	0.99992

Table III-25 (Continued). Wind Speed CDF for 11 to 12 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	0.99992
4218	0	0.99992
4270	0	0.99992
4321	0	0.99992
4373	0	0.99992
4424	0	0.99992
4476	0	0.99992
4527	1	0.99996
4579	0	0.99996
4630	0	0.99996
4681	0	0.99996
4733	0	0.99996
4784	0	0.99996
4836	0	0.99996
4887	0	0.99996
4939	0	0.99996
4990	0	0.99996
5042	0	0.99996
5093	1	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-26. Wind Speed CDF for 12 to 13 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
0	1	0.00005
51	61	0.00333
103	85	0.00789
154	132	0.01497
206	177	0.02446
257	231	0.03685
309	286	0.05219
360	375	0.07231
412	414	0.09452
463	503	0.12150
514	558	0.15143
566	594	0.18330
617	638	0.21752
669	690	0.25453
720	723	0.29332
772	738	0.33290
823	689	0.36986
875	587	0.40135
926	797	0.44410
977	812	0.48766
1029	867	0.53417
1080	857	0.58014
1132	750	0.62037
1183	810	0.66382
1235	713	0.70207
1286	735	0.74150
1338	604	0.77390
1389	607	0.80646
1440	521	0.83441
1492	471	0.85967
1543	396	0.88091
1595	344	0.89937
1646	338	0.91750
1698	236	0.93016
1749	174	0.93949
1801	174	0.94883
1852	150	0.95687
1903	148	0.96481
1955	101	0.97023
2006	99	0.97554

Table III-26 (Continued). Wind Speed CDF for 12 to 13 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
2058	84	0.98005
2109	55	0.98300
2161	55	0.98595
2212	51	0.98868
2264	51	0.99142
2315	36	0.99335
2366	16	0.99421
2418	22	0.99539
2469	14	0.99614
2521	11	0.99673
2572	11	0.99732
2624	4	0.99753
2675	6	0.99785
2727	5	0.99812
2778	6	0.99844
2829	8	0.99887
2881	2	0.99898
2932	2	0.99909
2984	3	0.99925
3035	3	0.99941
3087	0	0.99941
3138	4	0.99962
3190	2	0.99973
3241	1	0.99979
3292	1	0.99984
3344	1	0.99989
3395	0	0.99989
3447	0	0.99989
3498	1	0.99995
3550	0	0.99995
3601	0	0.99995
3653	0	0.99995
3704	0	0.99995
3755	1	1.00000
3807	0	1.00000
3858	0	1.00000
3910	0	1.00000
3961	0	1.00000
4013	0	1.00000
4064	0	1.00000
4116	0	1.00000

Table III-26 (Continued). Wind Speed CDF for 12 to 13 km above Yucca Mountain

Bin (cm/s)	Frequency	Cumulative Probability
4167	0	1.00000
4218	0	1.00000
4270	0	1.00000
4321	0	1.00000
4373	0	1.00000
4424	0	1.00000
4476	0	1.00000
4527	0	1.00000
4579	0	1.00000
4630	0	1.00000
4681	0	1.00000
4733	0	1.00000
4784	0	1.00000
4836	0	1.00000
4887	0	1.00000
4939	0	1.00000
4990	0	1.00000
5042	0	1.00000
5093	0	1.00000
5144	0	1.00000
5196	0	1.00000
5247	0	1.00000
5299	0	1.00000
5350	0	1.00000
5402	0	1.00000
5453	0	1.00000
5505	0	1.00000
5556	0	1.00000
5607	0	1.00000
5659	0	1.00000

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD.001.

Table III-27. Wind Speed in Relation to Height above Yucca Mountain

Height above YM (km)	Min Wind Speed (cm/s)	Max Wind Speed (cm/s)	Avg Wind Speed (cm/s)
0 to 1	0	2315	332
1 to 2	0	1903	404
2 to 3	0	2572	501
3 to 4	0	3292	604
4 to 5	0	5402	770
5 to 6	0	5505	838
6 to 7	0	5299	1008
7 to 8	0	5659	1076
8 to 9	0	4476	1096
9 to 10	0	4270	1195
10 to 11	0	4579	1224
11 to 12	0	5093	1158
12 to 13	0	3755	1031

Input Source: NOAA (1995 [154435]). Output DTN: MO0312SPADRWSD. 001.

Table III-28. Wind Direction PDF at 0 to 1 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	3536	0.1234
195 to 225	60	7699	0.2688
225 to 255	30	2765	0.0965
255 to 285	0 (East)	1253	0.0437
285 to 315	-30	1120	0.0391
315 to 345	-60	1205	0.0421
345 to 15	-90 (South)	1828	0.0638
15 to 45	-120	2671	0.0932
45 to 75	-150	2548	0.0889
75 to 105	180 (West)	1835	0.0641
105 to 135	150	1148	0.0401
135 to 165	120	1039	0.0363
Total		28,647	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-3. Wind Rose Frequency of Occurrences at 0 to 1 km above Yucca Mountain

Table III-29. Wind Direction PDF at 1 to 2 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	4619	0.1299
195 to 225	60	8182	0.2302
225 to 255	30	4149	0.1167
255 to 285	0 (East)	2215	0.0623
285 to 315	-30	2296	0.0646
315 to 345	-60	2984	0.0839
345 to 15	-90 (South)	3161	0.0889
15 to 45	-120	2755	0.0775
45 to 75	-150	1677	0.0472
75 to 105	180 (West)	985	0.0277
105 to 135	150	1019	0.0287
135 to 165	120	1505	0.0423
Total		35,547	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-4. Wind Rose Frequency of Occurrences at 1 to 2 km above Yucca Mountain

Table III-30. Wind Direction PDF at 2 to 3 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	4441	0.0990
195 to 225	60	6834	0.1523
225 to 255	30	6735	0.1501
255 to 285	0 (East)	4971	0.1108
285 to 315	-30	4913	0.1095
315 to 345	-60	4990	0.1112
345 to 15	-90 (South)	3568	0.0795
15 to 45	-120	2108	0.0470
45 to 75	-150	1362	0.0303
75 to 105	180 (West)	1136	0.0253
105 to 135	150	1399	0.0312
135 to 165	120	2421	0.0539
Total		44,878	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-5. Wind Rose Frequency of Occurrences at 2 to 3 km above Yucca Mountain

Table III-31. Wind Direction PDF at 3 to 4 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	2770	0.0837
195 to 225	60	4515	0.1364
225 to 255	30	5411	0.1635
255 to 285	0 (East)	4974	0.1503
285 to 315	-30	4476	0.1353
315 to 345	-60	3372	0.1019
345 to 15	-90 (South)	2164	0.0654
15 to 45	-120	1394	0.0421
45 to 75	-150	898	0.0271
75 to 105	180 (West)	764	0.0231
105 to 135	150	896	0.0271
135 to 165	120	1459	0.0441
Total		33,093	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-6. Wind Rose Frequency of Occurrences at 3 to 4 km above Yucca Mountain

Table III-32. Wind Direction PDF at 4 to 5 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	1731	0.0608
195 to 225	60	3744	0.1315
225 to 255	30	5344	0.1877
255 to 285	0 (East)	5244	0.1842
285 to 315	-30	4161	0.1461
315 to 345	-60	2869	0.1008
345 to 15	-90 (South)	1734	0.0609
15 to 45	-120	1075	0.0378
45 to 75	-150	662	0.0233
75 to 105	180 (West)	530	0.0186
105 to 135	150	543	0.0191
135 to 165	120	834	0.0293
Total		28471	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-7. Wind Rose Frequency of Occurrences at 4 to 5 km above Yucca Mountain

Table III-33. Wind Direction PDF at 5 to 6 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	1468	0.0530
195 to 225	60	3826	0.1381
225 to 255	30	5730	0.2068
255 to 285	0 (East)	5343	0.1928
285 to 315	-30	4027	0.1453
315 to 345	-60	2602	0.0939
345 to 15	-90 (South)	1571	0.0567
15 to 45	-120	918	0.0331
45 to 75	-150	608	0.0219
75 to 105	180 (West)	397	0.0143
105 to 135	150	517	0.0187
135 to 165	120	704	0.0254
Total		27,711	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-8. Wind Rose Frequency of Occurrences at 5 to 6 km above Yucca Mountain

Table III-34. Wind Direction PDF at 6 to 7 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	1133	0.0473
195 to 225	60	3044	0.1272
225 to 255	30	5263	0.2199
255 to 285	0 (East)	4961	0.2072
285 to 315	-30	3472	0.1450
315 to 345	-60	2296	0.0959
345 to 15	-90 (South)	1356	0.0566
15 to 45	-120	831	0.0347
45 to 75	-150	437	0.0183
75 to 105	180 (West)	301	0.0126
105 to 135	150	308	0.0129
135 to 165	120	537	0.0224
Total		23,939	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-9. Wind Rose Frequency of Occurrences at 6 to 7 km above Yucca Mountain

Table III-35. Wind Direction PDF at 7 to 8 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	1066	0.0525
195 to 225	60	2473	0.1218
225 to 255	30	4515	0.2223
255 to 285	0 (East)	4209	0.2073
285 to 315	-30	3005	0.1480
315 to 345	-60	1972	0.0971
345 to 15	-90 (South)	1131	0.0557
15 to 45	-120	712	0.0351
45 to 75	-150	353	0.0174
75 to 105	180 (West)	211	0.0104
105 to 135	150	243	0.0120
135 to 165	120	416	0.0205
Total		20,306	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-10. Wind Rose Frequency of Occurrences at 7 to 8 km above Yucca Mountain

Table III-36. Wind Direction PDF at 8 to 9 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	772	0.0508
195 to 225	60	1959	0.1288
225 to 255	30	3796	0.2496
255 to 285	0 (East)	3319	0.2182
285 to 315	-30	2020	0.1328
315 to 345	-60	1276	0.0839
345 to 15	-90 (South)	820	0.0539
15 to 45	-120	449	0.0295
45 to 75	-150	261	0.0172
75 to 105	180 (West)	139	0.0091
105 to 135	150	138	0.0091
135 to 165	120	261	0.0172
Total		15,210	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-11. Wind Rose Frequency of Occurrences at 8 to 9 km above Yucca Mountain

Table III-37. Wind Direction PDF at 9 to 10 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	653	0.0376
195 to 225	60	1929	0.1110
225 to 255	30	4151	0.2388
255 to 285	0 (East)	4087	0.2351
285 to 315	-30	2732	0.1572
315 to 345	-60	1611	0.0927
345 to 15	-90 (South)	975	0.0561
15 to 45	-120	568	0.0327
45 to 75	-150	238	0.0137
75 to 105	180 (West)	119	0.0068
105 to 135	150	102	0.0059
135 to 165	120	217	0.0125
Total		17,382	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-12. Wind Rose Frequency of Occurrences at 9 to 10 km above Yucca Mountain

Table III-38. Wind Direction PDF at 10 to 11 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	532	0.0265
195 to 225	60	1867	0.0931
225 to 255	30	4622	0.2305
255 to 285	0 (East)	5496	0.2741
285 to 315	-30	3741	0.1866
315 to 345	-60	1858	0.0927
345 to 15	-90 (South)	950	0.0474
15 to 45	-120	479	0.0239
45 to 75	-150	205	0.0102
75 to 105	180 (West)	108	0.0054
105 to 135	150	75	0.0037
135 to 165	120	119	0.0059
Total		20,052	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-13. Wind Rose Frequency of Occurrences at 10 to 11 km above Yucca Mountain

Table III-39. Wind Direction PDF at 11 to 12 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	510	0.0211
195 to 225	60	2111	0.0873
225 to 255	30	5625	0.2325
255 to 285	0 (East)	7239	0.2992
285 to 315	-30	4748	0.1963
315 to 345	-60	2098	0.0867
345 to 15	-90 (South)	933	0.0386
15 to 45	-120	419	0.0173
45 to 75	-150	179	0.0074
75 to 105	180 (West)	93	0.0038
105 to 135	150	101	0.0042
135 to 165	120	136	0.0056
Total		24,192	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-14. Wind Rose Frequency of Occurrences at 11 to 12 km above Yucca Mountain

Table III-40. Wind Direction PDF at 12 to 13 km above Yucca Mountain

Compass Degrees	ASHPLUME Degrees	Count	PDF
165 to 195	90 (North)	411	0.0220
195 to 225	60	1566	0.0840
225 to 255	30	4633	0.2485
255 to 285	0 (East)	5821	0.3123
285 to 315	-30	3675	0.1971
315 to 345	-60	1415	0.0759
345 to 15	-90 (South)	585	0.0314
15 to 45	-120	213	0.0114
45 to 75	-150	121	0.0065
75 to 105	180 (West)	56	0.0030
105 to 135	150	50	0.0027
135 to 165	120	96	0.0051
Total		18,642	1.0000

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Source: NOAA 1995 [154435]. Output DTN: MO0312SPADRWSD.001.

Figure III-15. Wind Rose Frequency of Occurrences at 12 to 13 km above Yucca Mountain

ATTACHMENT IV: **INPUT VALUES FOR WASTE FORM CONCENTRATION AT THE RMEI LOCATION**

The following tables contain the values of ASHPLUME parameters that were used to calculate the mean concentration at the RMEI used in the ash redistribution model discussed in Section 6.7. Table IV-1 contains the fixed (deterministic) values and Table IV-2 contains the sampled (stochastic) values for each realization of the GoldSim/ASHPLUME simulation. The GoldSim model file (Table_10.gsm) used to generate the values in Table IV-2 and the results in Table 10 of Section 6.7 are in Output DTN: LA0312GK831811.001.

Table IV-1. Fixed Input Values for ASHPLUME

Input Parameters	Value ^a
xmin, xmax (km)	0,0
ymin, ymax (km)	-18,-18
numptsx	1
numptsy	1
ashdenmin	2.08
ashdenmax	1.04
ashrholow	-3
ashrhohi	0
fshape	0.5
airden	.001117
airvis	0.0001758
c	400.0
dmax	10.0
acutoff	1e-10
hmin	.001
fdmin, fdmean, fdmax	.0001, .002, .05
Rhocut	.3
mass of waste (g)	4.01e7 ^b

- NOTE: a. Parameter values are from "Base Case" values in Table 15 (see text).
b. Mass of fuel available for entrainment derived from CRWMS M&O (2001 [153938], p. 49): 63,000 MTHM emplaced in 7,860 packages = 8.02E+06 g/package; assume 5 waste packages hit (median value from BSC 2003 [161851]).

Table IV-2. Realizations for Distributed Parameter Values

Sampled									Calculated	
Realization Number	Beta	Mean Ash Diameter (cm)	Ash Sigma	Wind Direction (Degrees)	Wind Speed (cm/s)	Eruptive Velocity (cm/s)	Event Power (W)	Event Duration (s)	Height (km)	Volume (km ³)
1	0.035	0.0112	-1.38	-90	398.66	4772.40	4.26E+10	2.07E+05	3.72E+00	0.012
2	0.394	0.0301	-1.61	-90	553.79	188.92	9.78E+08	7.68E+07	1.45E+00	0.102
3	0.129	0.0093	-1.86	-90	1012.30	453.92	7.29E+11	18081	7.58E+00	0.018
4	0.205	0.0021	-1.43	-90	446.92	9362.60	5.48E+09	5.86E+06	2.23E+00	0.044
5	0.318	0.0218	-1.75	-90	135.58	5899.80	2.11E+10	2.45E+06	3.13E+00	0.070
6	0.238	0.0050	-1.66	-90	196.96	6236.60	1.67E+11	2.24E+05	5.24E+00	0.051
7	0.198	0.0077	-1.53	-90	490.40	47.97	3.99E+10	4.21E+05	3.67E+00	0.023
8	0.218	0.0137	-1.62	-90	121.11	131.70	2.04E+10	2.21E+06	3.10E+00	0.061
9	0.413	0.0092	-1.67	-90	84.37	3073.60	2.95E+10	1.36E+05	3.40E+00	0.005
10	0.449	0.0075	-1.64	-90	721.06	83.15	1.01E+12	15537	8.23E+00	0.021
11	0.161	0.0084	-1.41	-90	1068.60	12.91	1.94E+12	12894	9.68E+00	0.034
12	0.267	0.0259	-1.36	-90	339.83	31.17	9.33E+09	4.45E+06	2.55E+00	0.057
13	0.079	0.0342	-1.72	-90	1154.40	155.70	6.92E+10	5.49E+05	4.21E+00	0.052
14	0.014	0.0061	-1.59	-90	293.77	802.78	2.26E+09	3.68E+06	1.79E+00	0.011
15	0.163	0.0105	-1.81	-90	145.40	2043.20	6.29E+08	2.81E+07	1.30E+00	0.024
16	0.058	0.0034	-1.90	-90	228.98	10049.00	1.07E+10	1.53E+06	2.63E+00	0.022
17	0.155	0.0014	-1.71	-90	177.93	10.00	1.39E+09	4.83E+07	1.58E+00	0.091

Table IV-2 (Continued). Realizations for Distributed Parameter Values

Sampled									Calculated	
Realization Number	Beta	Mean Ash Diameter (cm)	Ash Sigma	Wind Direction (Degrees)	Wind Speed (cm/s)	Eruptive Velocity (cm/s)	Event Power (W)	Event Duration (s)	Height (km)	Volume (km ³)
18	0.141	0.0063	-1.85	-90	422.56	10.00	8.72E+09	8.27E+06	2.51E+00	0.098
19	0.485	0.0027	-1.72	-90	172.66	22.71	6.90E+09	1.49E+06	2.36E+00	0.014
20	0.043	0.0058	-1.74	-90	1576.10	59.16	4.11E+12	2935.3	1.17E+01	0.016
21	0.298	0.0053	-1.31	-90	103.61	2743.10	1.08E+09	5.94E+07	1.49E+00	0.087
22	0.305	0.0580	-1.86	-90	249.11	4239.90	1.20E+11	1.15E+05	4.83E+00	0.019
23	0.365	0.0023	-1.55	-90	1357.80	10.00	1.48E+11	46775	5.09E+00	0.009
24	0.484	0.0122	-1.54	-90	524.38	103.74	4.36E+11	1.11E+05	6.66E+00	0.066
25	0.452	0.0130	-1.46	-90	1452.30	1712.20	3.49E+12	1599.4	1.12E+01	0.008
26	0.191	0.0181	-1.32	-90	541.34	1889.10	2.11E+12	4313.1	9.88E+00	0.012
27	0.274	0.0565	-1.35	-90	209.00	1510.40	1.71E+10	7.15E+05	2.97E+00	0.017
28	0.072	0.0358	-1.68	-90	180.78	538.48	7.62E+10	83633	4.31E+00	0.009
29	0.124	0.0071	-1.58	-90	186.66	332.24	1.91E+09	1.80E+07	1.72E+00	0.047
30	0.282	0.0109	-1.82	-90	111.50	28.69	4.95E+09	2.32E+06	2.17E+00	0.016
31	0.496	0.0032	-1.76	-90	258.90	75.52	9.08E+10	7.64E+05	4.50E+00	0.094
32	0.404	0.0049	-1.56	-90	237.03	10.00	4.63E+12	12560	1.20E+01	0.079
33	0.428	0.0115	-1.30	-90	1039.80	10.00	8.89E+11	5764.7	7.96E+00	0.007
34	0.045	0.0887	-1.42	-90	540.43	10.00	1.34E+12	23136	8.82E+00	0.042
35	0.207	0.0235	-1.38	-90	409.33	10.00	1.22E+09	5.36E+07	1.53E+00	0.089
36	0.102	0.0284	-1.86	-90	348.44	192.87	2.37E+10	2.85E+05	3.22E+00	0.009
37	0.021	0.0025	-1.66	-90	1006.80	1578.60	3.41E+09	5.96E+06	1.98E+00	0.028
38	0.118	0.0079	-1.79	-90	181.69	10.00	8.02E+08	1.21E+07	1.38E+00	0.013

Table IV-2 (Continued). Realizations for Distributed Parameter Values

Sampled									Calculated	
Realization Number	Beta	Mean Ash Diameter (cm)	Ash Sigma	Wind Direction (Degrees)	Wind Speed (cm/s)	Eruptive Velocity (cm/s)	Event Power (W)	Event Duration (s)	Height (km)	Volume (km ³)
39	0.095	0.0040	-1.88	-90	484.94	10.00	4.70E+09	8.50E+06	2.15E+00	0.054
40	0.252	0.0017	-1.77	-90	422.70	10.00	2.95E+09	1.41E+06	1.91E+00	0.006
41	0.089	0.0046	-1.80	-90	46.81	10.89	5.42E+10	1.01E+06	3.96E+00	0.074
42	0.350	0.0039	-1.60	-90	202.99	10.00	2.63E+09	5.09E+06	1.86E+00	0.018
43	0.104	0.0099	-1.80	-90	402.65	10.00	3.24E+11	86176	6.18E+00	0.038
44	0.322	0.0037	-1.49	-90	776.13	10.00	3.68E+09	6.42E+06	2.02E+00	0.032
45	0.227	0.0163	-1.78	-90	730.96	925.46	1.94E+11	4.02E+05	5.44E+00	0.106
46	0.469	0.0042	-1.52	-90	204.74	297.97	3.39E+10	1.60E+05	3.52E+00	0.007
47	0.233	0.0142	-1.63	-90	523.77	8026.00	2.75E+12	2201.8	1.06E+01	0.008
48	0.354	0.0087	-1.34	-90	454.74	136.42	3.62E+10	6.01E+05	3.58E+00	0.030
49	0.426	0.0426	-1.63	-90	1525.10	8803.30	3.65E+11	14524	6.37E+00	0.007
50	0.373	0.0090	-1.48	-90	1164.20	10.00	1.28E+12	3673.6	8.73E+00	0.006
51	0.359	0.0170	-1.39	-90	309.94	18.89	4.95E+11	83016	6.88E+00	0.056
52	0.492	0.0277	-1.46	-90	964.21	4303.50	3.94E+11	38466	6.50E+00	0.021
53	0.258	0.0192	-1.47	-90	2401.00	258.52	4.26E+12	4533.9	1.18E+01	0.026
54	0.051	0.0178	-1.31	-90	663.91	10.00	5.85E+10	1.48E+05	4.03E+00	0.012
55	0.381	0.0699	-1.60	-90	438.27	175.02	1.31E+09	4.66E+07	1.56E+00	0.083
56	0.341	0.0100	-1.85	-90	773.14	213.30	5.30E+11	19717	7.00E+00	0.014
57	0.113	0.0026	-1.45	-90	701.07	10.00	2.72E+11	1.68E+05	5.92E+00	0.062
58	0.215	0.0197	-1.49	-90	681.59	2380.30	4.43E+09	4.78E+06	2.12E+00	0.029
59	0.246	0.0158	-1.77	-90	466.30	3885.80	2.58E+10	3.05E+05	3.29E+00	0.011
60	0.222	0.0045	-1.65	-90	255.36	21.36	5.02E+10	1.29E+05	3.88E+00	0.009

Table IV-2 (Continued). Realizations for Distributed Parameter Values

Sampled									Calculated	
Realization Number	Beta	Mean Ash Diameter (cm)	Ash Sigma	Wind Direction (Degrees)	Wind Speed (cm/s)	Eruptive Velocity (cm/s)	Event Power (W)	Event Duration (s)	Height (km)	Volume (km ³)
61	0.195	0.0082	-1.61	-90	1265.60	16.18	3.14E+10	4.53E+05	3.45E+00	0.019
62	0.325	0.0098	-1.64	-90	1015.70	63.96	1.74E+10	2.56E+05	2.98E+00	0.006
63	0.310	0.0085	-1.68	-90	1023.70	39.79	2.01E+11	24964	5.49E+00	0.007
64	0.181	0.0072	-1.51	-90	660.45	116.60	1.54E+11	47269	5.14E+00	0.010
65	0.460	0.0145	-1.53	-90	695.92	10.00	1.37E+10	3.31E+05	2.80E+00	0.006
66	0.443	0.0131	-1.69	-90	748.85	13.94	2.35E+12	22546	1.01E+01	0.072
67	0.387	0.0068	-1.35	-90	625.20	1241.90	1.84E+12	5066.8	9.55E+00	0.013
68	0.167	0.0393	-1.37	-90	1418.20	1026.20	5.93E+11	19092	7.20E+00	0.015
69	0.261	0.0329	-1.44	-90	0.25	423.38	1.19E+10	3.05E+06	2.71E+00	0.049
70	0.371	0.0207	-1.70	-90	896.64	96.76	6.43E+10	91025	4.13E+00	0.008
71	0.410	0.0065	-1.59	-90	761.40	5450.70	4.69E+11	40219	6.79E+00	0.026
72	0.388	0.0104	-1.46	-90	2367.90	37.07	9.89E+11	27064	8.18E+00	0.036
73	0.033	0.0187	-1.41	-90	2176.20	10.00	6.89E+11	11011	7.47E+00	0.010
74	0.086	0.0247	-1.44	-90	473.68	10.00	9.51E+08	3.03E+07	1.44E+00	0.039
75	0.333	0.0216	-1.87	-90	140.90	10.00	2.57E+09	1.36E+07	1.85E+00	0.048
76	0.028	0.0020	-1.81	-90	474.55	251.30	2.26E+11	3.39E+05	5.65E+00	0.104
77	0.464	0.0036	-1.50	-90	247.17	7419.70	8.25E+08	1.34E+07	1.39E+00	0.015
78	0.398	0.0149	-1.88	-90	808.14	623.62	2.59E+12	9046.4	1.04E+01	0.032
79	0.473	0.0018	-1.35	-90	1620.00	1328.70	7.81E+11	38250	7.71E+00	0.041
80	0.291	0.0414	-1.42	-90	539.00	674.69	3.05E+12	2668	1.08E+01	0.011
81	0.064	0.0232	-1.33	-90	236.90	10.00	1.05E+11	1.22E+05	4.66E+00	0.017

Table IV-2 (Continued). Realizations for Distributed Parameter Values

Sampled									Calculated	
Realization Number	Beta	Mean Ash Diameter (cm)	Ash Sigma	Wind Direction (Degrees)	Wind Speed (cm/s)	Eruptive Velocity (cm/s)	Event Power (W)	Event Duration (s)	Height (km)	Volume (km ³)
82	0.061	0.0477	-1.56	-90	689.20	74.33	1.79E+09	2.39E+06	1.69E+00	0.006
83	0.441	0.0120	-1.83	-90	218.68	10.00	1.53E+09	9.54E+06	1.62E+00	0.020
84	0.147	0.0030	-1.84	-90	2217.30	32.98	1.67E+12	36520	9.32E+00	0.083
85	0.336	0.0029	-1.38	-90	107.87	352.29	7.99E+09	6.01E+06	2.45E+00	0.065
86	0.478	0.0314	-1.73	-90	1001.50	389.70	2.44E+11	41233	5.76E+00	0.014
87	0.419	0.0057	-1.50	-90	681.13	10.00	3.43E+12	2064.8	1.12E+01	0.010
88	0.018	0.0153	-1.33	-90	1355.80	3234.70	1.12E+12	17736	8.43E+00	0.027
89	0.176	0.0484	-1.40	-90	96.94	775.00	7.35E+08	2.33E+07	1.35E+00	0.023
90	0.289	0.0263	-1.89	-90	250.51	16.94	1.27E+10	3.37E+06	2.75E+00	0.059
91	0.304	0.0015	-1.70	-90	143.33	10.00	9.72E+10	2.33E+05	4.58E+00	0.031
92	0.347	0.0066	-1.56	-90	730.35	11214.00	1.29E+11	38168	4.91E+00	0.007
93	0.135	0.0118	-1.55	-90	321.85	2579.80	2.86E+11	1.97E+05	6.00E+00	0.077
94	0.112	0.0124	-1.49	-90	490.03	11.58	6.14E+09	5.44E+06	2.30E+00	0.046
95	0.184	0.0163	-1.75	-90	854.83	55.06	3.84E+09	1.62E+06	2.04E+00	0.008
96	0.077	0.0053	-1.78	-90	141.01	26.54	1.50E+10	1.76E+06	2.87E+00	0.036
97	0.146	0.0043	-1.69	-90	104.34	10.00	2.11E+09	1.16E+07	1.76E+00	0.033
98	0.275	0.0069	-1.82	-90	215.95	543.22	7.03E+09	7.20E+06	2.37E+00	0.069
99	0.436	0.0033	-1.74	-90	1040.90	1114.00	8.12E+10	3.58E+05	4.38E+00	0.040
100	0.243	0.0055	-1.57	-90	368.69	46.93	1.45E+12	12723	8.99E+00	0.025

**ATTACHMENT V:
INDEPENDENT TECHNICAL REVIEW OF MDL-MGR-GS 000002 REV 00B**

CONDUCTED BY

**DR. FRANK SPERA,
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REVIEW of MDL-MGR-GS 000002 REV 00B

This document presents a review of Project document MDL-MGR-GS 000002 REV 00B. The structure of this review is based on six review criteria set out in "Exhibit D Amended Scope of Work: Independent Review for Model Validation". The review criteria are listed below as a series of questions. The analysis provided below addresses each of these issues.

1. Is the mathematical model (ASHPLUME) appropriate for representing the conceptual model, i.e., is this model appropriate for its intended use?
2. Are the inputs sufficient
3. Were all reasonable alternative models identified and adequately treated? If not, what are they, what are their capabilities, and what are their limitations?
4. Are the assumptions appropriate for use in the model
5. Do the outputs of the model represent the inputs, or are the limitations to the model such that the outputs are not representative of possible future states?
6. Are the outputs of the model a reasonable representation of what may be expected from a volcanic eruption at Yucca Mountain?

No computer codes were run during the course of this review. The review focuses on the conceptual and technical bases of Project work regarding the dispersal of volcanic ash using the computer code ASHPLUME. Results from ASHPLUME are used as input for the TSPA. This review was conducted by F.J. Spera in the period 24 March - April 10, 2003.

Is the mathematical model (ASHPLUME) appropriate for representing the conceptual model, i.e., is this model appropriate for its intended use?

Introduction

There are a number of ash dispersal mathematical models of differing sophistication. It is beyond the scope of this report to review the history of ash dispersal modeling. ASHPLUME traces its origin back to the model of Suzuki (1983). The Suzuki model applies to a steady eruption (constant eruptive mass flow rate, $\dot{M}$) from a circular cross-sectional vent. The fundamental factors governing the fallout distribution of volcanic tephra include the height of the steady state volcanic column (H), which is a function of the eruptive mass flow rate, $\dot{M}$, the total eruptive volume (V) and the spatial and temporal structure of the winds aloft during the eruptive event of duration t_d . The relationship between the total eruptive volume (V) and the volumetric eruptive rate ($\dot{V}$) for a steady eruption is simply $V = \dot{V} t_d$. Because the density of ash (ρ_e) is essentially constant, there is a simple relationship between the eruptive mass flow rate, $\dot{M}$ and the volumetric

eruption rate $\dot{V}$. The relationship is $\dot{V} = \dot{M} / \rho_e$ where ρ_e is the density of tephra particles at the vent. The size distribution of tephra also plays a role in ash dispersal. The distribution of ash particle size is relatively well-known based on granulometric studies of tephra from Strombolian eruptions and varies between reasonably well-defined bounds.

Plume Height (H), Mass Flow ($\dot{M}$) and Eruptive Volume(V)

Volcanic plume height (H) scales with the eruptive mass flow rate, $\dot{M}$ according to:

$$H \propto \dot{M}^{1/4} \quad (1)$$

An example of a quantitative parameterization is the expression:

$$H = 0.24 \dot{M}^{1/4} \quad (2)$$

with H measured in kilometers and the eruptive mass flow measured in kg/s. The scaling relation (1) comes from momentum-buoyancy plume theory and rests on a solid fluid dynamical footing. The determination of the constant in eq (2) comes from an empirical calibration using data from a small number (~ 10- 20) of volcanic eruptions for which column height is independently known. Its value may be uncertain by $\pm 20\%$ due to unsteadiness of column height and the intrinsic difficulty of measuring column height during an eruption. Note that (2) is strictly valid for steady eruptions where $\dot{M}$ (or $\dot{V}$) is constant. In fact, no volcanic eruption is truly steady. Variations in mass flow during eruptions give rise to time-varying column heights. For example, during the 1980 eruption at Mount Saint Helens, the mass flow (and hence column height) varied significantly in non-monotonic fashion during the ~ 10 hour Plinian phase of the eruption. Although the expected eruptive style at Yucca Mountain is Strombolian and not Plinian, eruptive unsteadiness is typical of all styles of eruption, even eruptive events dominated by lava flows. One way of incorporating unsteadiness into ash dispersal is to model a single eruption as a sequence of smaller eruptive phases each with its own characteristic parameters. In effect one could use the ASHPLUME steady state model serially to evaluate the effects of eruption unsteadiness at least to a first approximation. Whether or not this is important depends on the timescale associated with wind and magma discharge unsteadiness. For example, if the timescale for changes in wind direction are comparable to or shorter than eruptive duration (t_d) then unsteady winds could have a marked effect on the distribution of ash at the surface.

In the model used by the Project, critical input comes from two relations expressed as eqs (7a) and (7b) on p.39 of MDL-MGR-GS 000002 REV 00B. The

first is an assumed relationship between the eruptive volume of ash (V) and the duration of the eruption (t_d). This essentially defines the eruptive volume flow rate (and the eruptive mass flow rate) as a function of total eruptive volume (V). That is, eq (7a) may be recast as:

$$V/t_d = e^{-a} V^{1-b} \quad (3)$$

with $a = 15.29$ and $b = 0.527$ and the units of V in km^3 and t_d in seconds. Because

$$\dot{V} = \dot{M} / \rho_e \quad (4)$$

it follows from the Project model that the eruptive mass flow rate is a function of eruptive volume:

$$\dot{M} = k \rho_e V^{1-b} \quad (5)$$

with $k = 229$, V in km^3 , ρ_e in kg/m^3 and $\dot{M}$ in kg/s . On p. 44 of MDL-MGR-GS 000002 REV 00B the bounds on V are set between 0.004 km^3 and 0.08 km^3 . This gives limits for $\dot{M}$ between $2.5 \times 10^4 \text{ kg/s}$ and $1.1 \times 10^5 \text{ kg/s}$ assuming an ash density of 1500 kg/m^3 . These values define bounds that vary by $\sim$ one order of magnitude which seems somewhat on the small side of its potential range. Eruptive mass flow rates in the range 10^4 kg/s to 10^6 kg/s have been cited for Strombolian eruptions by some volcanologists (e.g., see Mastin, 2002; Mastin and Ghiorso, 2000; Mastin and Ghiorso, 2001). *On what grounds can eruptions with mass flows $\sim 10^6 \text{ kg/s}$ be excluded?*

According to eq (7b) on p.39 of MDL-MGR-GS 000002 REV, column heights corresponding to volumes of 0.004 km^3 and 0.08 km^3 are 2.2 km and 3.8 km, respectively. Again this is a rather small range and at the low to intermediate end for Strombolian eruptions. According to eq (2), the aforementioned limits ($2.5 \times 10^4 \text{ kg/s}$ and $1.1 \times 10^5 \text{ kg/s}$) for $\dot{M}$ correspond to column heights between 3 km and 4.3 km in good agreement with Project calculations.

The main point is that eruptive mass flow rates up to 10^6 kg/s should not be excluded. At $\dot{M} = 10^6 \text{ kg/s}$, a column height $H = 7.6 \text{ km}$ is predicted from eq (2). Because the *a priori* assumption in Project ash dispersal calculations is the relationship between eruptive duration and eruptive volume, the range of corresponding eruptive mass flow rates is uniquely defined. It is the opinion of this reviewer that starting off by bounding eruptive mass flow rates ($\dot{M}$) rather than volume (V) might be advantageous partly because it is the correlation between $\dot{M}$ and H that has some fluid dynamical basis (i.e., unlike the V - t_d correlation which is

entirely empirical) and partly because the limits on $\dot{M}$ between $\sim 10^4$ kg/ to 10^6 kg/s encompass the range for normal Strombolian eruptions. Violent Strombolian eruption can attain even greater eruptive mass flow rates, up to 10^7 kg/s. According to eq (2), a violent Strombolian eruption with $\dot{M} = 10^7$ kg/s would generate a column height $H = 13$ km. It is not argued here that such a value is 'typical'. However, the range 2 to 4 km considered by the Project seems unduly restrictive. Should the Project wish to consider additional higher mass flow eruptions, it would not be difficult to perform the simulations using Project models (but see section 5.2.3 in this report).

Structure and Variability of Winds Aloft

In addition to plume column height, the structure of prevailing winds during an eruption is critical to determination of ash dispersal. In the most detailed model, one can imagine wind velocity (direction and magnitude) prescribed on a three-dimensional grid of specified spatial resolution. Because upper atmosphere winds are often different from low level winds, it is important to get a complete profile of wind versus height from the vent up to the top of the eruption column. The wind velocity (speed and direction) can also vary temporally. Indeed, the eruption used by the Project (see section 7.4 NATURAL ANALOG STUDY on p. 56 in MDL-MGR-GS 000002 REV) to "ground test" ASHPLUME shows how variations in winds aloft *during* an eruption influence ash distribution. In the simplest ash dispersal model, the wind speed and direction is spatially constant (speed and direction) with no temporal variability during the eruptive interval (t_d). ASHPLUME implements a simple model of constant wind speed and direction and uses the wind vector from a height equal to "upper elevations to which the ash plume reaches". Presumably this corresponds to the height of the eruption column (H) derived from the relationship between eruptive volume (V) and column height (H).

Summary

ASHPLUME is applicable to steady volcanic eruptions (constant mass flow, $\dot{M}$) characterized by eruption columns of fixed height (H). Although no volcanic eruption is truly steady, the state-of-the-art in volcanic plume modeling is not sufficiently advanced to consider eruptions with unsteady discharge. ASHPLUME can be used serially to approximately model discharge unsteadiness and/or variable winds.

Two critical factors affecting ash dispersal are the column height and structure of winds aloft. ASHPLUME uses an empirically calibrated correlation between eruptive volume (V) and column height, H . In fluid dynamical terms, the height of an eruption column (H) scales with the mass flow, $\dot{M}$ according to $H \sim \dot{M}^{1/4}$. The eruptive volume (V) as given in eq (3) correlates to H provided the

plume-generating eruption is steady (i.e., $\dot{M}$ is constant) and the density of ash is constant. Regarding the issue of the winds aloft, any single ASHPLUME realization of ash dispersal assumes a constant wind speed and direction. Clearly this is a gross approximation; the vertical structure of the winds will generally depend on height above the vent. On the other hand, predicting the structure of the winds aloft at some time in the future 10000 years is not easily accomplished. The Monte Carlo method of drawing a constant wind velocity from a meteorologically-based distribution and performing many realizations and then sampled for TSPA purposes is sound.

The range of eruptive volumes leads to a range of eruptive mass flows that are in the low to intermediate range for Strombolian eruptions. Eruptive mass flow rates of 10^6 kg/s cannot be precluded and should be computed.

Are the inputs sufficient?

discussion is keyed to numbered sections in MDL-MGR-GS 000002 REV 00B

4.1.1 DATA

The variation of volcanic ash size distributions for Strombolian eruptions based on granulometric studies of G.P.L. Walker and co-workers beginning in the early 1970's and continuing to the present today is well-known. Although the precise distribution of particle size is unique to a given eruption, the variations are not large. Similarly, waste particle size distributions are adequately known for the purposes of the TSPA given other limitations of the ASHPLUME model.

4.1.2 PARAMETERS AND PARAMETER UNCERTAINTY

The method of developing probability distributions for compatibility with MC methods used in the TSPA is a sound practice.

4.1.3 OTHER MODEL INPUTS

Items in Table 4, p. 20 of MDL-MGR-GS 000002 REV 00B are needed to perform ASHPLUME simulations and are commented on here.

The mathematical model of Suzuki is the starting point. The Suzuki model was used by Jarzemba (1997) with an important correction (see eq (2) in Jarzemba) in order to achieve mass conservation, a constraint that must be incorporated in any ash dispersal model. However, the paper by Jarzemba has at least two errors. The first is that eq (1) in Jarzemba (1997) is missing a negative sign in front of the numerator in the exponential term. The second is that there is a missing factor of g in the third term in the denominator of eq (3) in Jarzemba. I note that these errors **have** been corrected in the Project work; that is, eq (2) and

eq (4) on p. 37 and p.38 in MDL-MGR-GS 000002 REV 00B are correct unlike the analogous equations in Jarzempa (1997).

The physical properties used for air (viscosity and density) from Lide (1994) are adequate for the purposes of the TSPA.

Are the Assumptions Justified?

discussion is keyed to numbered sections in MDL-MGR-GS 000002 REV 00B

5.1.1

The two-dimensional model may be sufficient for the purposes of the TSPA. It is hard to determine the level of confidence one should assign to ASHPLUME results without making a direct comparison between ASHPLUME and a 3-dimensional code such as the one by G. Macedonio and co-workers (Armienti et al, 1988; Macedonia et al, 1988, 1990). Approximations are made in contracting a 3-D model to a 2-D model. The neglect of vertical diffusion is probably justified because vertical advection is many orders-of-magnitude larger than vertical diffusion. In the 2-D models one can increase the 2-D eddy diffusivity to roughly account for 3-D effects. The only way to evaluate the quality of the 2-D approximations is to carry out the full 3-D calculation and compare results. This reviewer has not made this comparison. Presumably, if the Project felt this was important, they could contact the Italian volcanologists mentioned and explore this possibility. Alternatively, the Project can generate 2-D ASHPLUME results and compare these to published 3-D forward models relevant to eruptions at Mount Vesuvius, Italy. My own guess is that for the purposes of the TSPA the 2-D model would suffice. Even with a sophisticated 3-D model, the lack of knowledge of the winds aloft at some time in the future 10000 years may translate into a larger uncertainty in ash thickness at a specific location than that associated with a 2-D rather than 3-D model. But this is speculation on my part.

5.1.2

This is a very conservative assumption. Inspection of volcanological data suggests the ratio of lava to proximate tephra (cone-building deposits) to distal ash (the deposition that ASHPLUME and like models compute) is of order 1:1:<<1. That is, for the sort of eruption 'expected' at Yucca Mountain, the distal ash will make up only a small portion of the total. Hence the assumption made by the Project, that the entire eruptive volume is processed through a Strombolian column, is conservative. For Lathrop Wells, if the entire eruptive volume of 0.06 km³ is identified with the ash volume (it clearly is not!), then according to

expressions used by the Project, the eruptive duration was ~ 11.5 days, the eruptive mass flow was 6×10^4 kg/s and the column height was $H \sim 3.6$ km.

5.1.3

Small ash particles can not host large fuel waste particles. This seems to be a very reasonable assumption in no further need of documentation or explanation.

5.2.1

Even if one knew the future climate, predicting winds aloft and their variation in time and space is most difficult. The present winds aloft structure is as good as any other and is consistent with the level of approximation in ASHPLUME.

5.2.2

Waste is assumed to be unaltered spent commercial fuel. This is an adequate approximation given other uncertainties.

5.2.3

The Project adopts a relationship from Wilson and Head (1981) between vent exit radius (r_e) and eruptive velocity (u_e), as input for ASHPLUME. Neither the derivation of this relationship nor a discussion of the assumptions upon which it is based are given in MDL-MGR-GS 000002 REV. It is noted here that this "correlation" is based on incompressible flow and assumes specific pressure gradients (based on a density differences between magma and host crust) and magma viscosities. *The conditions assumed to generate the values in Table 3 in Wilson and Head (1981) are not generally applicable to the highly compressible high-speed eruption of volatile-charged magma in the inertial regime.* Jarzempa (1997) also cites a relationship from Wilson and Head (1981) that provides a correlation amongst vent exit radius (r_e), mean density of ash particles (ρ_p) and eruption mass flow rate ($\dot{M}$) to determine the eruption velocity at the vent exit (u_e). It is important to insure that the Wilson and Head (WH) scaling relation does not implicitly or explicitly involve assumptions inconsistent with other assumed relations (e.g., eq (7a) on p.39 of MDL-MGR-GS 000002 REV). In particular, the last few sentences of section 5.2.3 on p. 26 of MDL-MGR-GS 000002 REV are puzzling. *Results plotted on fig. 6a in WH (1981) pertain to specific exsolved magma water contents which are less than those expected for basaltic volcanism at Yucca Mountain (see Final Report of the Igneous Consequences Peer Review Panel, February, 2003).*

From review of the documentation, it appears that the Project develops the input needed for ASHPLUME according to the following scheme. First, a value for the eruptive ash volume (V) is picked from a uniform distribution. Then using eq (7a) on p.39 of MDL-MGR-GS 000002 REV, the eruptive duration, t_d is calculated

(project literature calls this T_d ; to avoid confusion with the thermodynamic temperature used in some volcanic plume models, although not in ASHPUME, use is made of the symbol t_d here). Once t_d and V are known, then eq (7b) on p.39 of MDL-MGR-GS 000002 REV is used to compute the column height, H . Once V and t_d are known, $\dot{M}$ and M (eruptive mass) are easily computed given a density (based on particle size) of ash particles using $\dot{V}=\dot{M}/\rho_e$ and $V=M/\rho_e$, respectively. (Project uses symbol ψ_p for particle density). Then the Project uses the Wilson and Head (WH) scaling relation (discussed above) amongst r_e , $\dot{M}$ and ρ_e to obtain the vent exit radius, r_e and finally, from the continuity expression $\dot{M}=\rho_e\pi r_e^2 u_e$, the eruption velocity at vent exit (labeled W_0 by Project and u_e in this review).

It seems, unless this reviewer is mistaken, that this procedure is redundant. That is, once V and hence t_d are determined, then indeed H is easily determined. However, implicit in the correlation between V and t_d is the value of $\dot{M}$ and hence M , for an assumed ash density. It seems the vent exit velocity is uniquely determined once a value for r_e is chosen using the expression $\dot{M}=\rho_e\pi r_e^2 u_e$. In other words, why does the Project resort to the use of the WH correlation, presumably identical to or a closely related to the one given as eq (14) in Jarzempa (1997)?

First of all, it is not clear that eqs(7a) and (7b) on p.39 of MDL-MGR-GS 000002 REV are consistent with the WH relationship used by the Project. The density of the magmatic mixture depends on the pressure at the vent exit which in turn depends on the volatile content. Do these considerations affect the r_e - u_e scaling relationship assumed to obtain input parameters for ASHPUME? *Secondly, and most importantly, it is not clear why the WH scaling correlation is needed at all.* Straightforward manipulation of eq (7a) on p.39 of MDL-MGR-GS 000002 REV gives:

$$\frac{V}{t_d} = e^{-a} V^{1-b} \quad (6)$$

where a and b are constants. Hence eq (6) combined with continuity ($\dot{M}=\rho_e\pi r_e^2 u_e$) implies that

$$\pi r_e^2 u_e = e^{-a} V^{1-b} \quad (7)$$

From eq (7) it appears that given V , a unique relationship between r_e and u_e exists. A selected value for r_e completely determines u_e without need for an additional WH correlation.

Were all reasonable alternative models identified and adequately treated? If not, what are they, what are their capabilities, and what are their limitations?

The short answer to this question is "No". The Project uses the ASHPLUME model. There has been no systematic comparison of results generated by ASHPLUME with other models. On p.34 in MDL-MGR-GS 000002 REV 00B there is discussion of other models although no detailed comparisons have been made. The models briefly mentioned in MDL-MGR-GS 000002 REV 00B (Gaussian-Plume, PUFF and Gas-Thrust code) suffer limitations and cannot generate the quantitative output needed for the TSPA without modification. A model not mentioned in MDL-MGR-GS 000002 REV 00B called VAFTAD (Hefter and Stunder, 1993) has been found to accurately model the dispersion of volcanic ash in the atmosphere. That is, to predict the motion of airborne ash clouds. Unfortunately, VAFTAD like PUFF offers no prediction of ground-level ash accumulation and therefore unsuitable in its present form for TSPA purposes.

Fortunately, other volcanological ash dispersal models that provide quantitative results for ground-level ash accumulation exist and may be utilized by the Project to build confidence and discover the limitations of ASHPLUME. Perhaps the most cogent model is one developed by Hurst and co-workers (Hurst, 1994) based on the earlier model of G. Macedonio and co-workers (Armienti et al, 1988; Macedonio et al, 1988, 1990). The code developed by the Italian group implements a three-dimensional particle diffusion model with allowance for wind direction and speed as a function of height. The original code was somewhat unwieldy requiring large 3-D arrays and long run times. Motivated by the need for an easy-to-implement Civil Defense tool, Hurst and co-workers developed a code called ASHFALL. This is a 2-dimensional code that accounts for variations in wind speed and direction as a function of altitude and time. Vertical diffusion of ash is neglected (as in ASHPLUME). The output of ASHFALL is the ash thickness at points on a rectangular grid centered on the vent. Details of the model can be found in the report and users guide entitled "ASHFALL- A Computer Program for estimating Volcanic Ash Fallout" by T. Hurst (1994). The characteristics and performance of ASHFALL are documented in the studies of Hurst and Turner (1999). A comparison of ASHFALL predictions with observed ash distributions of three ash-producing events from Ruapehu volcano in the North Island of New Zealand shows that actual ash thickness at any location are generally within a factor of two of that forecast by ASHFALL. The accuracy of the forecast wind

direction is the main factor affecting quality of ASHFALL predicted tephra isopachs according to the study by Hurst and Turner (1999).

Finally, mention should be made of the Hybrid Particle and Concentration Transport Model (HYPACT) of Walko and Tremback (1985). HYPACT simulates the motion of atmospheric tracers under the influence of winds and turbulence. Its Lagrangian formulation enables representation of sources of any size and the maintenance of concentrated, narrow plumes until atmospheric dispersion dictates they should broaden. The Lagrangian particle plume can then be converted into a concentration field and advected using a Eulerian formulation. The Lagrangian particles are moved through space and time based on interpolated wind velocities plus a superimposed random motion scaled to the intensity of local turbulence. A spectrum of gravitational settling velocities related to particle size can be specified. The velocity field (all three components), the potential temperature and information regarding the scale of turbulence are necessary input for implementation of HYPACT. HYPACT is the most sophisticated model for following the trajectory of airborne particles known to this reviewer.

In the study of Turner and Hurst (2001) a comparison is made between HYPACT and ASHFALL using the Regional Atmospheric Modeling System (RAMS) for the winds aloft structure as input for both models (see Pielke et al, 1992 for details pertaining to RAMS). Comparison of the performance of RAMS/HYPACT with ASHFALL shows that RAMS/HYPACT provides more accurate spatial and temporal forecasts of ash transport. Although the HYPACT model is superior in reproducing the temporal and spatial movement of the ash cloud, it is not suitable in its current form for quantifying the depth of ash. The code would need to be modified in order to determine the distribution of isopachs.

In summary, a detailed comparison should be made between ASHFALL and ASHPLUME. This can be done in two ways. First, one can select representative eruption and winds aloft parameters and compare predictions made by ASHPLUME and ASHFALL. Secondly, one can apply ASHPLUME to the 1995 and 1996 Mount Ruapehu, New Zealand eruptions. These have already been modeled using ASHFALL and results are readily available in the literature. Based on the results of such comparisons, one will be able to develop confidence in the results from ASHPLUME. Because the ASHFALL code is not freely available, Project geoscientists may want to work with Dr. Tony Hurst (T.Hurst@gns.cri.nz). Hurst is the developer of ASHFALL and may be available to run some models in coordination with Project geologists. ASHFALL unlike ASHPLUME can handle a time-varying vertical profile of wind speed and direction perhaps more appropriate to conditions during an

eruption. It can also be used in the simpler ASHPLUME-like mode with constant wind speed and direction.

Do the outputs of the model represent the inputs, or are the limitations to the model such that the outputs are not representative of possible future states?

In general, the output of an ash dispersal model provides the type of information needed for the TSPA. The real issue is the quality of the forward model. Ash dispersal in all its complexity is a problem that has not been fully solved. However, for the purposes of the TSPA and given the state-of-the-art, a two-dimensional model such as ASHPLUME may suffice. However, further work should be accomplished to increase the confidence in ASHPLUME results. One way of doing this is to make a detailed comparison between ASHFALL and ASHPLUME. Another is to apply ASHPLUME to the 1995 and 1996 eruptions at Mount Ruapehu. Typically, these eruptions exhibit column heights $H \sim 10$ km consistent with eruptive mass flow $\dot{M} \sim 3 \times 10^6$ kg/s, eruptive volume $V \sim 0.08$ km³ and ~ 10 -hr eruption duration. This is within the range of possibility for Strombolian eruptions at Yucca Mountain. Recall that Strombolian mass flows are generally in the range 10^4 - 10^6 kg/s with very strong so-called 'violent' Strombolian eruptions having $\dot{M}$ up to $\sim 10^7$ kg/s. The main need is to compare ASHPLUME results to results from another method. This task can probably be accomplished by 3-5 weeks or less if outside expertise (e.g., Dr. Tony Hurst for ASHFALL) contributes to the effort.

Are the outputs of the model a reasonable representation of what may be expected from a volcanic eruption at Yucca Mountain?

Tentatively the answer to this question is "probably yes". Comparison of ASHPLUME results with other codes would enable one to more definitively answer this question. *An explanation of the issue raised in section labeled 5.2.3 in this review should be provided to insure self-consistency is maintained in application of ASHPLUME.*

Other Comments on MDL-MGR-GS 000002, REV 00B.

p.41. reference to 'Suzuki et al' should be to 'Jarzemba et al (1997)'.

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**ATTACHMENT VI:
INDEPENDENT TECHNICAL REVIEW OF MDL-MGR-GS 000002, REV 00H
ASH REDISTRIBUTION CONCEPTUAL MODEL**

Included in Attachment VI are the following:

**CRITERIA FOR TECHNICAL REVIEW OF THE ASH REDISTRIBUTION
CONCEPTUAL MODEL**

**INDEPENDENT TECHNICAL REVIEW: DR. DAVID BUESCH,
U.S. GEOLOGICAL SURVEY**

**INDEPENDENT TECHNICAL REVIEW: DR. DENNIS O'LEARY,
U.S. GEOLOGICAL SURVEY**

Criteria for Independent Review for the Ash Redistribution Conceptual Model

Model validation as stated in the model validation procedure (AP-SIII.10Q) is the process used to establish confidence that the mathematical model (if applicable) and its underlying conceptual model adequately represent with sufficient accuracy the system process, or phenomenon, in question. AP-SIII.10Q identifies a number of methods for validating models that range from simple documentation to peer review. For the ash redistribution conceptual model, the *Technical Work Plan (TWP) -- Igneous Activity Assessment for Disruptive Events* (TWP-WIS-MD-000007, REV 4), identifies the post development method to achieve the desired level of model validation (Level II):

"Technical review, planned in the applicable TWP, by reviewers independent of the development, checking, and interdisciplinary review of the model documentation (the Originator, Responsible Manager/Lead, Checker, QER, and interdisciplinary reviewers assigned to the model document/activity may not serve as an independent post-development model validation technical reviewer) (Section 5.4.1(c)(5))."

The TWP states that the conceptual model, developed specifically for the Yucca Mountain Project, will be validated under AP-SIII.10Q to develop confidence in its intended use. The draft model report describes the conceptual aspects of the ash redistribution conceptual model. This independent review will focus on the unique application of this model on the Yucca Mountain Project. The intended use of the model is to describe erosion and dilution of contaminated ash as it may affect the RMEI after an eruption of a hypothetical volcanic event intersecting the repository for two end-member scenarios.

The criteria for this independent review are as follows:

1. Is the conceptual model reasonable and appropriate for its intended use?
2. For given inputs, are the outputs of the model reasonable?
3. Are limitations of field and analytical data as well as the conceptual model adequately described?
4. Are there other approaches that may enhance the confidence in use of this model?
5. Are there other alternative models that should be considered?

Independent Technical Review of the Ash Redistribution Conceptual Model

The “Ash Redistribution Model” is a conceptual component of the “Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada” AMR. The document on which Dr. David Buesch (USGS) conducted the technical review has a Document Indicator (DI) of “MDL-MGR-GS-000002, REV 00H”, and only those parts of the document related to the “Ash Redistribution Model” were reviewed. This part of the independent technical review lists responses to the review criteria and major comments and concerns regarding the data and conceptual model. Comments pertaining to logic flow of the text, presentation and consistency of text and figures, and text editing (or lack thereof) are as annotations on the manuscript.

The criteria for this independent review are as follows:

1. Is the conceptual model reasonable and appropriate for its intended use?
The model lays out several detailed and “big picture” ideas that are based on some data, and in the end it provides some values for input into Total System Performance Analysis (TSPA) models. So, in that respect the model is appropriate for its intended use (i.e., TSPA gets some parameters). Having said that, the model is largely conceptual, so many of the components are not well developed and this diminishes the final intended use of the model (note the use of the word “diminishes”, not “excludes”).
2. For given inputs, are the outputs or the model reasonable?
The current version of the model is mostly conceptual, but there are a few examples that are based on input data to develop values that are in turn generalized into values for TSPA models. One can follow (possibly even better with a little additional information and editing) the authors ideas for the detailed examples. So for these detailed examples, one can see the logic from input to reasonable output, even though the amount of data is probably less than what one might like to have in order to make solid and defensible arguments for model results.
3. Are limitations of the model adequately described?
Most of the model manuscript is used to explain the conceptual model and present and develop supporting data and ideas, so there is very little explicit discussion on the limitations and uncertainty of the model and results. There are some limitations on the data directed toward the use by TSPA models.

4. Are there other validation approaches that may enhance the confidence in use of this model?
The current model is mostly conceptual and is pretty sparse on data, so one technique for validation is to acquire additional data to test several of the hypotheses or components of the model. The current model focuses on dilution of ash (and waste) by mechanical erosion and mixing of the sediment during transportation and deposition, and it briefly discusses the possible mechanical process of infiltration into deposits. The data used to evaluate these processes are few and localized, but are used to extrapolate to “full model” conclusion. The authors have shown some interesting initiative using the radionuclide Cs-137 as a tracer (however, the appropriateness of this application must be better understood and described), and there are numerous possibilities of using other radionuclide and non-radionuclide tracers to quantify physical and chemical process. Collection of data that better quantify the processes of erosion, local storage, and flushing of the material through (or farther down) the system would greatly enhance these components of the model and thereby reduce (or at least quantify) uncertainty and enhance confidence. There are atmospheric wind velocity and direction data from numerous sites near Yucca Mountain and Fortymile Wash in addition to regional data, typically from 10 m above the ground surface (Fransioli and Ambros, 1997). These wind data might be used in conjunction with the distributions of sediment types to determine (calculate) potential for erosion by eolian deflation processes that is part of the Cesium (Cs)-137 study, and that might occur at many locations affected by the potential tephra sheets in the model. Having said all this, one must acknowledge that quantifying wind- and water-related processes in a desert such as at Yucca Mountain is challenging because events are few and far between; therefore, collecting appropriate data and developing it into conceptual and numerical models will probably be one of the few avenues upon which rational discussion and evaluation can take place.

Fransioli, P.M., and Ambros, D.S., 1997, Regional and Local Wind Patterns Near Yucca Mountain: Civilian Radioactive Waste Management System Management & Operating Contractor, Las Vegas, NV, 200 p. November 20, B000000000-01717-5705-00081 REVISION 00, MOL.19980204.0319.

5. Are there other alternative models that should be considered?
There are many details on the physical processes that can be included and considered for other models. These processes include refinements to eolian, colluvial, fluvial, pedogenic, mechanical, and chemical processes that result in determining better (and hopefully more realistic) estimates of amounts of materials on the landscape and time during which processes are active. It is the interaction and sum of these processes that can emerge as a model and, which in turn, can be discussed and tested using numerical modeling techniques. The long and short answer to this question is that by focusing more on the diversity of physical processes, collecting appropriate data to evaluate these processes, and integrating them into full-basin and sub-basin models, then another “new” model will emerge, and that model is what should be considered for the redistribution of ash and waste.

In summary, the conceptual model and the semi-qualitative (semi-quantitative?) results can probably be used for the intended use as input into TSPA models. However, the model should probably be considered as a starting point upon which refinements and enhancements will result in a more rigorous and defensible model.

Major comments and concerns

There are five major comments and concerns regarding the “Ash Redistribution Model”, and although individually none of the concerns result in invalidating the model, together the comments point out some of the gaps in the current model. [Note: the word is “gaps”, not “invalidate”.] Several of these comments and concerns can probably be initially addressed with additions to the existing document, but others might require additional work to more thoroughly document and substantiate components of the conceptual (and possibly future quantitative and numerical) model. As with many products for the Yucca Mountain Project (AMRs, etc.), there are numerous citations of other reports or data sources rather than providing and developing data with the report so a reader does not have to jump around from product to product.

1. Most of the supporting and component parts of the model focus on two small (scoping?) studies, and these studies are the basis for “scaling up” to the current conceptual model. The Lathrop Wells Cone “ash dilution” consists of nine samples along two transects that are 1 and 2.5 km long. Additionally, the drainage basin that includes Lathrop Wells Cone has an upstream drainage basin (relative to the tephra sheet) compared to the downstream drainage area that is expressed as a ratio of 6:1. Several (pertinent) reasons are listed for why the Lathrop Wells data should not be directly developed as a simple scaling factor for the ash-dilution values; however, shortly after these statements are made, the Fortymile Wash drainage is expressed in the same type of ratio and a dilution distance is quoted. Observations at Sunset Crater, Arizona, are only briefly described in a scientific notebook; therefore, relations are of limited scope and detail. The Cesium Study for surficial processes consists of 51 samples in approximately a 12 km² area south of Highway 95 on the distributary fan of Fortymile Wash. Each of these studies has merit, especially because the Lathrop Wells Cone and the distributary fan of Fortymile Wash are near the typically cited “reasonably maximum exposed individual” (RMEI). However, using these studies as the sole basis for “scaling up” to complete ash redistribution model is, in my opinion, a stretch.
2. The Cesium Study for Surficial Processes in the Fortymile Wash alluvial fan is an interesting use of a radionuclide tracer; however, it is not clear that Cesium (Cs)-137 is an appropriate tracer for the mechanical and possibly chemical processes described or inferred. According to the U.S. Environmental Protection Agency (<http://www.epa.gov/radiation/radionuclides/cesium.htm>), Cesium (including Cs-137) is one of only three metals that is liquid at about 83° F and has a half-life of 30.17 years. These properties raise several issues that need to be addressed.
 - a. Is Cs-137 transported to the site and deposit as atoms, complexed into molecules, or attached to (or entrained in) particles, and if with particles, then what size are these particles? The physical form of Cs-137 at the time of deposition (or “shortly” thereafter) might influence the susceptibility to mechanical erosion or chemical reaction.
 - b. It is proposed that Cs-137 infiltration can be used as a general proxy for the depth to which fine particles (clay, silt, and ash or sand-sized grains) might transported into the soil. It seems that this proposal assumes mechanical infiltration; however, with a Cs-137 liquidus of about 83° F the potential of mechanical and chemical processes must be evaluated and explained.

- c. With Cs-137 potentially being deposited during several periods in the 20 years from the mid-1940s to the mid-1960s and a half-life of about 30 years, how might these competing processes of accumulation and decay be manifest in the data? For example, material deposited in the mid-1940s (about 57 years ago) will have undergone almost 2 half-life cycles, so only about 27 percent of the original material is still in the system.
3. On the basis of model results of “ASHPLUME”, establishment of two tephra sheets is a good use of end-member distributions where, relative to Yucca Mountain, one sheet is deposited south and the other sheet is deposited to the east. However, how and in what depth these two models are discussed differs greatly.
 - a. A figure (or two) illustrating these two model distributions should be included early in the Ash Redistribution section of the in the report so the reader can visualize the distribution, thickness, and even grain size in the tephra sheets. Location of the RMEI should be included (as it is, partially, on Figure 5).
 - b. The tephra sheet deposited to the south of Yucca Mountain would deposit ash on the RMEI area. Although the current model appears to emphasizes only eolian processes, this area contains numerous ridges and basins, including the one in which Lathrop Wells Cone is located, the Fortymile Wash alluvial fan, and both of these sites are described in detail for the fluvial redeposition of material. So, the emphasis on eolian processes in this model distribution under represents the fluvial processes in the area.
 - c. The tephra sheet deposited to the east of Yucca Mountain would deposit ash across Jackass Flats and in the drainage basin between the Calico Hills and Shoshone Mountain that is drained by Topopah Wash. The current model focuses on the fluvial redistribution of ash along Fortymile Wash. However, after introduction of this model end member, it is rarely described except through inference of colluvial and fluvial processes, in which most of this discussion is associated with the Lathrop Well Cone and Fortymile Wash alluvial fan studies. The discussions on short-duration, intense thunderstorms and the more aerially extensive, long-duration storms are apparently provided in support of the sediment transport into and through Fortymile Wash, but these same storm conditions are applicable throughout the area, including for the south-directed tephra sheet.
 - d. The RMEI is typically identified in the area of the Lathrop Wells Cone and Fortymile Wash; however, if the 18-km distance from the proposed repository site is the fundamental criteria, then an arc can be drawn to the east-northeast to where it intersects the southwestern edge of Little Skull Mountain. This minor eastward continuation of the 18-km arc intersects Topopah Wash just north of where this wash transitions into a distributary fan similar to the Fortymile Wash fan. So, the east-directed end-member model should probably include redeposition from the drainage of Topopah Wash and Jackass Flats because most of the tephra sheet would be deposited across these areas. According to Christensen and Spahr (1980), significant parts of Jackass Flats would be affected in 100-year storms, and especially 500-year and maximum flood events. So, eroded ash from the Jackass Flats area and the drainage near Calico Hills might be a contributing source of material to the RMEI area.

Christensen, R.C., and Spahr, N.E., 1980, Flood Potential of Topopah Wash and Tributaries, Eastern Part of Jackass Flats, Nevada Test Site, Southern Nevada: U.S. Geological Survey, Lakewood, CO, Open-File Report 80-963, 22 p. [TIC Catalog Number 203211]

4. Erosion, transportation, and deposition of ash from different types of slopes (orientation and inclination) and substrates (Miocene, densely welded ignimbrite versus colluvial and old or young alluvial surfaces) can differ greatly, but these variations are not discussed. Here are two aspects of how these conditions and processes might be applied to the model.
 - a. There are some minor discussions of material being eroded from steeper slopes and accumulating in the washes at the base of these slope (possibly during thunderstorms), and at later times (during long-duration regional storms) being flushed farther out into the fluvial system. These processes and times for each process to be active are challenging to quantify, especially in desert environments where there is sparse runoff data; however, estimates of thickness and rates of erosion are provided as “soil redistribution factors” for the TSPA model (Table 12). So, there are a few examples of attempts at quantifying amounts and processes, and there are many that have not been addressed.
 - b. In the discussion on tephra deposits on the RMEI in northern Amargosa Valley (paragraph 2 on page 64) it is stated that because of the strong eolian action in this area, it is “highly unlikely a that tephra deposit ... would remain in place and/or undiluted for more than a few decades”. There are other places in the text that complete (or near complete) removal of the tephra deposits is described as part of the model. It is hard to judge if complete (or near complete) removal of the ash in “a few decades” has positive or negative affects on the concentration of ash and waste materials, but it is not clear that these conditions are even appropriate. For example, consider the amount of ash deposited on the highly varied topography near Mount St. Helens, Washington, in 1980, and how much of this ash has been eroded off the slopes in the last 23 years. It is true that Mount St. Helens is in a different climate and environment. It is also true that there are no specific measurements that can be cited (just some oral communication estimates from some of those who have worked extensively in the area), but estimates of the amount of eroded 1980 ash vary from about 10 to 20 percent, and this means that 80 to 90 percent of the primary deposit is still on the hillsides. Erosion of the ash is primarily by the formation of rills, and once the rills are established, there is very little lateral cutting to strip of the material that remains on the interfluvial ridges. Coming back to the Yucca Mountain area, rills and interfluvial ridges are pretty common on many types of slopes and substrates. All this means is that more of the primarily deposited ash might not be eroded in the short time frame inferred in the current model.
5. There is an assumption from the ASHPLUME model that “waste” is incorporated into the ash and the two form individual grains that are deposited to form the tephra sheets; however, this “mixed grain of ash and waste” might not be appropriate for the Ash Redistribution model. I understand that the “mixed grain of ash and waste” has been an assumption in ASHPLUME model for quite a while, and that this is not part of the tasked technical review. However, from a fragmentation process-based mechanistic point of view, I think formation of

mingled and mixed grains it is difficult to do and it is very likely that the majority of waste and ash would be erupted as mostly individual particles (this complicates the calculations). If particles deposited in the tephra sheets are mostly individual grains of ash and waste, then each would have very different hydrodynamic and possibly chemical properties. These different properties would affect the erosion, transportation, deposition, and fractionation potential of the particles.

Finally, the intended use of the Ash Redistribution model is to provide some parameters to the TSPA, and that is what the (conceptual-semiquantitative-semiquantitative) model does. However, although the current model is a reasonable start, it only contains a few localized aspects of the physical processes that are likely to affect the redistribution of ash (and waste). Because processes that affect the redistribution of ash and waste operate at a wide variety of scales, a more integrated model is probably in order. For example, there are eolian and aqueous processes, localized processes of erosion on a slope, small drainage basin scales processes of erosion, transportation, and deposition, and full drainage basin scale processes of erosion, transportation, and deposition. Most of the basaltic eruptive (disruptive) processes, including the redistribution of ash and waste materials, are typically considered as post-closure events and there has not been a clear link between these issues and pre-closure issues such as potential flood events. The importance of fluvial and eolian processes described in the current model, and hopefully emphasized in this review, indicates that an integrated, full-basin model of potential flooding and sediment transport (including a few sub-basin models) would be important for evaluating both potential pre- and post-closure events. Such a quantitative model (or submodels) could provide a powerful tool in evaluating the redistribution of ash and waste material.

Independent Technical Review of the Ash Redistribution Conceptual Model

I reviewed sections 6.6: Ash Redistribution Conceptual Model, 6.7: Model Results, and 7: Model Validation, in Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada. I found no fatal flaws or other lapses. The constraints identified from field observations and from analytical data are considered in the report as fully relevant factors in the deposition and redistribution processes of tephra. The conceptual model is appropriate and the discussions and reasoning are presented in adequate detail to support the conclusions and inferences in these sections. Application of ASHPLUME is well reasoned and is appropriate for its intended use. The outputs of the model are reasonable with respect to the given inputs; the outputs adequately explain the distribution of tephra as a basis for analyzing its fate by erosion, fluvial and eolian transport, as described in the text. The limitations of the model are adequately described. I do not know of other validation approaches that may enhance the confidence in the use of the model, and I do not know of other alternative models that should be considered.

The following comments are suggestions pertaining to technical details in the interest of providing a more complete presentation.

1. To give an accurate impression of the distribution of tephra outfall, it should not be described as a sheet; it is actually an attenuated apron deposit continuous with the cone itself, distinguished mainly by the variation in particle size with distance from the vent. The scenarios implicitly assume a tephra dispersion profile based on size-related weight distribution. I think more should be said about the presumed waste particle distribution within the single eruption tephra deposit. Namely, will the waste content distribution mimic the tephra particle size distribution or is there a particle size waste adherence limit, as implied in Sec. 6.5.1? I suspect the nature of the waste particle distribution within the tephra distribution might have some bearing on the erosional dispersion of contaminated tephra by wind or water over time. Is windborn volcanic dust, then, ever a hazard?

2. Note that a single flood event in Fortymile Wash (and there have been a couple of bank-to-bank flows within the time I have been on the project) will distribute tephra from A to D (Fig. 2) instantaneously (i.e. within a day). The time lapse will be insignificant in this case but the tephra concentration downstream will probably be as shown in Fig 2. Note also that the amount of tephra contributed to bedload from the slopes of Yucca Mountain may be trivial if the flood event is a result of cloudburst/snowmelt from the Timber Mountain part of the drainage basin. It would seem that Timber Mountain weather would be a much bigger contributor to runoff in the channel

than the relatively infrequent Yucca Mountain-wide flank storms. Therefore, the amount of contaminated waste fed to Fortymile Wash may be metered by local storms and fed to a channel that is repeatedly cleared of tephra. It may be correct to think of relatively small slugs of contaminated tephra fed to the channel on an infrequent basis but sluiced down to Amargosa Valley in large, relatively frequent homogenizing flood events. If this is true, it would tend to decrease the rate of tephra delivery to RMEI. Fig 5 (p. 76) would be more useful if you could show on it the inferred area of a tephra deposit that would form from a violent strombolian eruption through the repository. Just a glance at Red and Black and Lathrop Wells Cones suggests that a tephra deposit(s) would occupy a small part of the Fortymile Wash drainage basin and that the tributary systems that dominate its delivery to Fortymile Wash would be Yucca, Midway and Dune Washes. Has any study been done to estimate the sediment contribution these tributaries made to Fortymile Wash in late Pleistocene -Holocene? I recommend you adjust fig. 5 to show the entire Fortymile Wash watershed to the north at Timber Mountain; this will make clear the enormous potential diluting effect available from upstream.

Fig. 2 shows the concentration of tephra in the channel decreasing as a non-linear concave decay curve, notably at A. Is there a basis for this? I would assume a linear decrease incrementally stepped down to the right, each step representing a flood/erosion event (the slope could reflect tributary input of tephra, so I guess the curve would flatten with time as the tephra source becomes depleted or otherwise stabilized upslope). Is there a basis for having the concentrations at B, C, and D build to a maximum concentration and then begin to decrease? Since each subsequent flood through A brings down an increasingly diluted tephra load, shouldn't there be a net decrease in tephra at B and C after the first flood event (B and C also suffer erosion during each flood so I don't expect much of an incremental increase in tephra at those points.) D is harder to understand because it is more clearly an aggrading environment than C and B. The text says that the plots in fig. 2 are purely conceptual; perhaps some simple flume experiments would help support this concept.

3. Page 73 presents data on a tephra transport and redeposition study. It would be helpful to know the tephra grain size with distance from head of input. Can such data be added to Table 9? The text mentions ash and microscopic analysis, which suggests a fine sand size. How does the ash size in channel samples compare to tephra size at the presumed source (margin of intact tephra deposit)? Has there been appreciable size sorting by stream/erosion transport? Some estimates should be given to the size distribution and agglomeration of fragmented waste to the overall tephra distribution. I suspect that waste particle sizes will form a leptokurtic subpopulation of large particles, and more important, be discriminated by high density. If so, this suggests that contaminated tephra or waste particles will be relatively large and form a distribution of placer deposits and perhaps be strung out as lag deposits within Fortymile Wash rather than being uniformly fed to Amargosa Valley with a light fraction of sediment. Seems to me some large-scale flume experiments are in order. Or were such already performed by you? Another factor that probably should be mentioned is bedload transport abrasion. Most clasts of stream-bed basalt look fairly well-rounded. Has any work been done on rounding with transport distance and mixing? My guess is that the vesicular tephra are susceptible to comminution

during stream transport. Does grain fining by abrasion have an effect on your waste travel calculations? I suspect it is insignificant, but we probably should give the impression of having thought of every contingency. Note that this point is relevant to statements in Sec 6.7.2.4. On p. 88 (Sec. 6.7.2.4) there is a good discussion of ash removal with time. There is mention of "residual contamination that may have leached into the underlying sediments". This statement implies that there can be significant dissolution of ash during its time in the stream bed, allowing adhered waste particles to either dissolve and precipitate in the substrate, or migrate downward as very fine particles released from the dissolved ash host grains. Should the solubility of ash be discussed here? Is it a significant factor in the migration of waste?

4. I disagree that sediment mixing occurs at higher rates on steeper hillslopes (p. 70) and that drainage channels that form and flow across newly deposited tephra have well-mixed sediment loads after small transport distances (last sentence, first ¶, p. 70). Unless these streams cut into pre-tephra substrate, no mixing with other sediment types occurs. Drainage on steeper slopes is restricted to relatively narrow rill or gully incisions, and if the slopes are well-graded to the axial channels, upper slope tephra contributions should progressively diminish with time. Higher order channels gather a larger volume of more compositionally heterogeneous sediment, hence mixing is increased with channel size on lower slopes.

5. Sec. 6.7.2.3 p. 87 informs that "a layer of contaminated ash . . . appears immediately following eruption . . ." This contradicts the redistribution scenario presented in Sec. 6.6.1.2. You might want to make some appropriate qualification to mitigate this apparent discrepancy.

6. Sec. 7.3.1 Why did you use Cerro Negro as an analog instead of Paricutin? I would have chosen Paricutin because of: 1. its monogenetic eruption behavior is more analogous to the Yucca Mountain volcanoes, 2. It would be a worst-case scenario compared to Yucca Mountain eruptions, 3. the time since eruption ceased is sufficient to give some indication of how ash is being redistributed from a pristine state by erosion in an arid climate comparable to that of the Yucca Mountain area. In light of F. Spera's comment in Sec. 7.4 I would add Paricutin to your analogs.