Department of Energy

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QA: N/A
Project No. WM-00011

JUL 30 2004

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TRANSMITTAL OF KEY TECHNICAL ISSUE (KTI) AGREEMENT IGNEOUS ACTIVITY (IA) 2.17: *ASH REDISTRIBUTION BY EOLIAN AND FLUVIAL PROCESSES*

Reference: Ltr, Reamer to Brocoum, dtd 9/12/01 (NRC/DOE Technical Exchange and Management Meeting on Igneous Activity, September 5, 2001)

In the referenced letter, the U.S. Nuclear Regulatory Commission (NRC) documented an agreement (IA 2.17) between NRC and the U.S. Department of Energy (DOE). The wording of the agreement is as follows:

> IA 2.17
> "DOE will evaluate conclusions that the risk effects (i.e., effective annual dose) of eolian and fluvial remobilization are bounded by conservative modeling assumption in the TSPA-SR, Rev 00, ICN 1. DOE will examine rates of eolian and fluvial mobilization off slopes, rates of transport in Forty-mile Wash, and rates of deposition or removal at proposed critical group location. DOE will evaluate changes in grain size caused by these processes for effects on airborne particle concentrations. 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). DOE will document the results of investigations in the AMR, Eruptive Processes and Soil Redistribution ANL-MGR-GS-000002, expected to be available in fiscal year 2003 and in the AMR, *Input Parameter Values for External and Inhalation Radiation Exposure Analysis*, ANL-MGR-MD-000001, available FY 2003, or another appropriate technical document."

The enclosure to this letter, *Ash Redistribution by Eolian and Fluvial Processes*, provides a direct response to Agreement IA 2.17. This agreement relates to characterizing processes of eolian and fluvial remobilization, evaluating assumptions in the Total System Performance Assessment for the Site Recommendation model related to mass loading, and providing an evaluation of the risk effects (i.e., effective mean annual dose) of eolian and fluvial ash redistribution.

The DOE considers KTI Agreement IA 2.17 to be fully addressed by this transmittal, and pending review and acceptance by the NRC, it should be closed.

LIMSS07

There are no new regulatory commitments in the body or the enclosure to this letter. Please direct any questions concerning this letter and its enclosure to Timothy C. Gunter at (702) 794-1343 or e-mail at timothy_gunter@ymp.gov, or Eric T. Smistad at (702) 794-5703 or at e-mail eric_smistad@ymp.gov.

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OLA&S:TCG-1418

Enclosure:
Ash Redistribution by Eolian and Fluvial Processes, Revision 3

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ENCLOSURE

ASH REDISTRIBUTION BY EOLIAN AND FLUVIAL PROCESSES (RESPONSE TO IA 2.17)

Note Regarding the Status of Supporting Technical Information

This document was prepared using the most current information available at the time of its development. This Technical Basis Document and its appendices providing Key Technical Issue Agreement responses that were prepared using preliminary or draft information reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases this involved the use of draft Analysis and Model Reports (AMRs) and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the AMRs and other references will be reflected in the License Application as the approved analyses of record at the time of License Application submittal. Consequently, the Project will not routinely update either this Technical Basis Document or its Key Technical Issue Agreement appendices to reflect changes in the supporting references prior to submittal of the License Application.

ENCLOSURE

ASH REDISTRIBUTION BY EOLIAN AND FLUVIAL PROCESSES (RESPONSE TO IA 2.17)

This enclosure provides a response for Key Technical Issue (KTI) agreement Igneous Activity (IA) 2.17. This KTI agreement relates to characterizing processes of eolian and fluvial remobilization, evaluating assumptions in the total system performance assessment for the site recommendation (TSPA-SR) model related to mass loading, and providing an evaluation of the risk effects (i.e., effective annual dose) of eolian and fluvial ash redistribution.

KEY TECHNICAL ISSUE AGREEMENT

Agreement IA 2.17 was reached during the U.S. Nuclear Regulatory Commission (NRC)/U.S. Department of Energy (DOE) Technical Exchange and Management Meeting on IA, held September 5, 2001, in Las Vegas, Nevada (Reamer 2001).

The wording of the agreement is as follows:

IA 2.17

> 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, ICN1. DOE will examine rates of eolian and fluvial mobilization off slopes, rates of transport in Fortymile Wash, and rates of deposition or removal at proposed critical group location. DOE will evaluate changes in grain size caused by these processes for effects on airborne particle concentrations. 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). DOE will document the results of investigations in the AMR, *Eruptive Processes and Soil Redistribution* ANL-MGR-GS-000002, expected to be available in fiscal year 2003 and in the AMR, *Input Parameter Values for External and Inhalation Radiation Exposure Analysis*, ANL-MGR-MD-000001, available FY 2003, or another appropriate technical document.

BACKGROUND

Following deposition of a blanket of ash and waste from a volcanic eruption through the repository, wind-blown (eolian) and water-borne (fluvial) sedimentary processes would redistribute the waste-contaminated ash in the region. These processes would result in the erosion, transport, dilution, and redeposition of contaminated ash. Redistribution of volcanic ash could contribute to dose by transporting the contaminated ash to the reasonably maximally exposed individual (RMEI) location. Alternatively, these same sedimentary processes could reduce dose at the location of the RMEI by introducing nonash sediments during redistribution that would lead to a dilution in concentration of contaminated ash; however, underlying soils would most likely become contaminated over time.

The effects of ash redistribution and its contribution to dose in TSPA-SR was accounted for by fixing the wind direction toward the critical group to maximize the effects of wind-borne deposition where the ash thickness would be greatest. For TSPA for the license application (TSPA-LA), the human receptor considered is the RMEI location, rather than the critical group location, in accordance with 10 CFR 63.311.

For license application, an ash redistribution model has been developed and is abstracted into the TSPA-LA model as two bounding outcomes to evaluate the dose to the RMEI, located on the Fortymile Wash alluvial fan. The outcomes represent two locations for contaminated ash fall and the subsequent exposure potential when the ash is remobilized after primary deposition. The outcomes are defined as primary deposition of contaminated ash at the location of the RMEI (Outcome 1) and primary deposition within the Fortymile Wash drainage basin upstream from the location of the RMEI (Outcome 2). The criterion for selection of the outcome is based on minimum ash thickness at the location of the RMEI, which is defined as the diameter of one ash grain. Using the ASHPLUME code, the TSPA-LA model performs thousands of realizations that sample input values from distribution functions characterizing uncertainty in more than 30 parameters used to represent properties of a violent Strombolian eruption, including wind speed and direction. The TSPA-LA model produces a mean eruptive dose curve that contains contributions from both outcomes. The relative contribution of each outcome is largely determined by wind direction.

After primary deposition, normal sedimentary processes (eolian and fluvial) erode, dilute, transport, and redeposit the contaminated ash. The ash redistribution model is a numerical representation of these processes and the potential risk to the RMEI considering both outcomes. In Outcome 1, the ash is removed from the RMEI; however, due to radionuclide migration, the underlying soil is contaminated. In Outcome 2, the contaminated ash is transported to the location of the RMEI and subsequently contaminates the underlying soil. The TSPA-LA model then estimates the risk through inhalation and ingestion by the RMEI.

RESPONSE

To assess the potential consequences of dose from the redistribution of contaminated ash from a volcanic eruption through the repository at Yucca Mountain, a numerical model representing normal posteruption sedimentary processes and radionuclide concentrations in the redeposited ash and underlying soil has been developed for abstraction into the TSPA-LA model. The ash redistribution model implemented in TSPA-LA contributes to estimating the dose at the location of the RMEI. The following discussion addresses the elements of Key Technical Issue (KTI) IA 2.17.

Use of Conservative Modeling Assumptions Concerning Risk Effects of Contaminated Ash Remobilization–An ash redistribution model developed for TSPA-LA replaces the method used in TSPA-SR and includes the effects of redistribution of contaminated ash (waste combined with volcanic ash). The ash redistribution model considers two outcomes based on whether or not primary ash deposition occurs at the location of the RMEI. The model also considers waste concentrations and ash depth on two different landforms, interchannel divides and distributary channels that are features of the Fortymile Wash alluvial fan at the location of the RMEI. If primary contaminated ash deposition occurs at the location of the RMEI, the main sedimentary processes considered for the interchannel divides are eolian (wind-blown) and sheet wash (debris flow) deposition during infrequent flooding. The main sedimentary process for distributary channels is fluvial (including infrequent flooding). If primary contaminated ash deposition occurs in Fortymile wash instead of the location of the RMEI, redistribution of contaminated ash is accounted for by eolian and low-probability flooding processes on the interchannel divides, and by fluvial processes in the distributary channels (BSC 2004, Section 6.7.2). In both sedimentary processes and for both land forms, dilution of contaminated ash will occur. Radionuclide migration (infiltration) into the underlying soil is also a part of these sedimentary processes.

Sedimentary processes are accounted for in the ash redistribution model used in TSPA-LA; therefore, the conclusions that the risk effects (i.e., effective annual dose) from eolian and fluvial remobilization are bounded by conservative modeling assumptions used in TSPA-SR are no longer applicable.

Volcanic Ash Remobilization Off Slopes, Transport in Fortymile Wash, and Deposition or Removal at the RMEI Location–Generally, eolian and fluvial remobilization processes in the Yucca Mountain region would act to dilute the concentration of basaltic ash from a young ash layer (tephra sheet). When sufficient rainfall occurs upslope, basaltic ash particles are picked up and carried downslope, leaving behind an incipient channel. The moving water continues to acquire additional particles until the channel becomes overloaded with sediment; subsequently, the mixture floods over the leading edge as a debris flow and carries material downslope away from the channel. Successive debris flows transport additional basaltic ash material farther downslope. This repeating action results in the progressive movement of material to the base of the tephra sheet and to a drainage channel at the base of the slope. That drainage, which is commonly marginal to the tephra sheet, would also carry a sediment load that would include nonbasaltic ash material. In the Yucca Mountain region, these nonbasaltic ash sediments are dominantly clasts of silicic tuff and eolian quartz sand. When the two sediment types are combined in the drainage channel, mixing of the particles occurs, and the nonbasaltic ash sediment dilutes the basaltic ash component. The result is the contaminated basaltic ash becomes a progressively smaller proportion of the total sediment load as the mixture is transported down the drainage channel toward the location of the RMEI (BSC 2003a, Section 6.5.1.1).

Effects of Changes in Grain Size on Airborne Particle Concentrations–Parameter distributions of airborne particle concentrations are developed from analog measurements of mass loading taken following volcanic eruptions and in settings with no volcanic ash. These measurements are taken over a variety of conditions (BSC 2003b, Table 4.2) in order to encompass the effects of changes in ash and soil particle sizes over time. Uncertainty in soil particle size was considered in the selection of the parameter distributions of mass loading and the mass loading decrease constant (BSC 2003b, Sections 6.2 and 6.3). The distributions of those parameters reasonably incorporate uncertainty in the effects of changes in ash and waste particle sizes over time. The development of those distributions and the distributions are given in *Inhalation Exposure Input Parameters for the Biosphere Model* (BSC 2003b, Sections 6.1, 6.2, and 6.3 (development of distributions) and Tables 6.1.1-1, 6.1.2-1, 6.1.3-1, 6.1.4-1, 6.2.1-1, 6.2.2-1, B-1, B-2, D-1, D-2, and E-1 (distributions)).

Mass Loading Model Assumptions Concerning Radionuclide Concentration–The methods used to calculate mean annual exposure to airborne particulate matter have been substantially revised, and the TSPA models no longer assume that the concentration of radionuclides on soil in air is equal to the concentration of radionuclides in soil on the ground. The calculation of concentrations in the air due to particle resuspension now includes an enhancement factor parameter to account for differences between particle concentrations in the air and on soil (BSC 2003c, Section 6.5.2.1). The enhancement factor is defined as the ratio of the airborne particle activity concentration to the activity concentration in soil. For the volcanic ash exposure scenario, the distribution of this parameter ranges from 0.21 to 1.04 for inactive and indoor environments and from 2.8 to 8.4 for the active outdoor environments (BSC 2003d, Section 6.5).

The information in this report is responsive to agreement IA 2.17 made between DOE and NRC. This report contains the information that DOE considers necessary for NRC review for closure of this agreement.

BASIS FOR THE RESPONSE

Immediately following deposition, a tephra sheet would be unconsolidated material and would be subject to remobilization and redistribution by eolian and fluvial processes. As time passes, the tephra sheet would stabilize, and, in the absence of further disruption, it would eventually become a relatively stable soil that is less susceptible to these sedimentary processes. This sequence is consistent with posteruption observations in the vicinity of volcanoes. Both the amount of ash redistribution and the time required for stabilization of the tephra sheet are uncertain, and neither process was addressed explicitly in TSPA-SR.

Use of Conservative Modeling Assumptions Concerning Risk Effects of Contaminated Ash Remobilization–The TSPA model has been revised to include an ash redistribution model to replace the method used in TSPA-SR and to include effects of redistribution of contaminated ash. The model considers two outcomes based on whether or not primary ash deposition occurs at the RMEI location. The model also considers waste concentrations and ash depth on interchannel divides and in distributary channels. Interchannel divides are the land areas on the Fortymile Wash alluvial fan that have relatively stable surfaces and that separate distributary channels. Distributary channels are divergent streams that incise the land surface and are the primary erosional and depositional areas on the Fortymile Wash alluvial fan. Four modeling components are identified: interchannel divide areas with and without initial ash deposits and channel areas with and without initial ash deposits. These model components are shown in Table 1.

The conceptual model for the distribution of radionuclides in soil (BSC 2004, Figure 6-2) conservatively overestimates the total mass of radionuclides present in the soil system by allocating the initial content of radionuclides simultaneously to both the ash layer (which, hypothetically, should contain the majority of radionuclides that reach the location of the RMEI in the interchannel divide areas) and the underlying soil layer. In the conceptual model, the radionuclides in the contaminated ash migrate into the underlying soil over time. For situations in which the primary ash layer is relatively thin (e.g., millimeters or less in thickness), the additional mass of radionuclides allocated to the 9-cm soil profile may be greater than the primary mass. This overestimate of total radionuclide mass could cause significant overestimation of doses from the 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 (BSC 2004, Figure 6-4) provides a reasonable approximation of the effects of possible infiltration processes that could keep surface concentrations relatively high, even as erosion exposes increasingly deeper horizons (BSC 2004, Section 6.7.2). This approach was selected because long-term inhalation is the dominant exposure pathway following a volcanic eruption for most radionuclides, as shown in *Disruptive Event Biosphere Dose Conversion Factor Analysis* (BSC 2003e, Table 6.2.7 and Section 7.5).

The ash redistribution model considers sedimentary processes in terms of whether or not primary contaminated ash deposition has occurred at the RMEI location, by sedimentary processes that occur on interchannel divides or distributary channels. If primary contaminated ash deposition has occurred at the location of the RMEI, the main sedimentary processes considered for interchannel divides are eolian deposition and infrequent sheet wash deposition during flooding. For distributary channels, the main sedimentary process considered is fluvial with infrequent flooding that transports contaminated ash to the RMEI (BSC 2004, Section 6.7.2). In both cases, dilution of contaminated ash results from the normal sedimentary processes. Radionuclide migration (infiltration) into the underlying soil is also a part of these processes as a result of water movement and sediment burial.

The ash redistribution model has two components that are bounding outcomes for primary ash deposition (see Table 1). The outcomes represent two locations for primary contaminated ash deposition and the subsequent exposure potential when the ash is remobilized after primary deposition. The outcomes are defined as primary deposition of contaminated ash at the location of the RMEI (Outcome 1) and primary deposition within the Fortymile Wash drainage basin upstream from the location of the RMEI (Outcome 2). The criterion for selection of the outcome is based on minimum ash thickness at the location of the RMEI, which is defined as the minimum median diameter of one ash grain (0.001 cm). After primary deposition, normal sedimentary processes (eolian and fluvial) erode, dilute, transport, and redeposit the contaminated ash. The ash redistribution model is a numerical representation of these processes and the potential risk to the RMEI considering both outcomes. In Outcome 1, the ash is removed from the RMEI; however, due to radionuclide migration, the underlying soil is contaminated. In Outcome 2, the contaminated ash is transported to the location of the RMEI and subsequently contaminates the underlying soil.

The output of the ash redistribution model is the variation with time of the concentration of radionuclides in soil and the depth of ash following a volcanic event. Separate time histories are calculated by the ash redistribution model for the two different outcomes, which includes the two landforms. This results in four cases. Soil concentrations are calculated separately for each of the four cases.

Outcome 1 represents a wind direction that results in deposition of ash at the location of the RMEI. For interchannel divides, which cover about 82% of the landscape 18 km south of Yucca Mountain, the initial tephra deposit thickness and waste concentration is that calculated by the

ASHPLUME model. The tephra (and associated waste) is eroded by principally eolian processes at a rate of 0.02 to 0.04 cm/yr (BSC 2003a, Table 7-1 and Section 6.6.3.1). This erosion rate of the tephra deposit is based on interpretation of ^{137}Cs data collected in the Yucca Mountain region (BSC 2003a, Figure 6-10 or Table 6-8). The model also considers that radionuclides in the initial deposit infiltrate (chemically or mechanically) into the underlying soil. The concentrations of those radionuclides are assumed to decrease linearly to a depth of 9 cm based upon the infiltration depth of ^{137}Cs. After removal of the 9-cm soil layer, a concentration equal to 1% of the initial concentration in the tephra is assumed to remain in the surface soil.

Table 1. Waste Concentrations in Soil for the Total System Performance Assessment Model

	Interchannel Divide	Distributary Channels
Areal Weighting	**0.82**	**0.18**
Outcome 1 Primary tephra (ash fall) at the location of the RMEI.	**Initial** 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 and 0.04 cm/yr. **Residual** 9-cm contaminated soil layer beneath initial ash. Volumetric concentration of the waste (see NOTE following table) in this layer decreases linearly from the initial value calculated in the ash to 1% of that value at 9 cm. This layer is removed at the same rate as the initial ash layer, consistent with ^{137}Cs observations. The linear volumetric concentration decrease is conservative with respect to the exponential decrease observed for ^{137}Cs. Below the 9-cm layer is an additional 1 to 2 cm (uniform distribution) layer with 1% of the initial volumetric concentration. Assumed to remain indefinitely. Represents migration 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 NOTE following table) 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% of its initial volumetric concentration within a time period uniformly distributed between 100 and 1,000 years. *This decrease in volumetric concentration represents dilution during removal and replacement of the initial sediment.* **Residual outcome** After removal of the initial volumetric concentration, a layer with the same initial thickness but with 1% 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 1. Waste Concentrations in Soil for the Total System Performance Assessment Model (Continued)

	Interchannel Divide	Distributary Channels
Areal Weighting	0.82	0.18
Outcome 2 No primary tephra fall on or near the RMEI location. *Primary tephra deposition in upper Fortymile Wash drainage basin.*	Possible contamination by eolian processes or major flood events is approximated by a 1 to 2 cm (uniform distribution) layer. 1% of the initial mean volumetric waste concentration from the 18-km ASHPLUME calculations is assumed to remain indefinitely.	**Initial condition** Initial ash-layer thickness: uniform distribution from 1 to 15 cm. Initial waste concentration: geometric mean 18-km ASHPLUME volumetric concentration (BSC 2004, Table 6-4). **Ash removal** Volumetric concentration of waste in the ash layer decreases linearly from its initial volumetric concentration to 1% of its initial volumetric concentration within a time period uniformly distributed between 100 and 1,000 years. *This decrease in volumetric concentration represents dilution during removal and replacement of the initial sediment.* **Residual outcome** After removal of the initial volumetric concentration, a layer with the same initial thickness but with 1% 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.

Source: DTN: LA0401CH831811.001.

NOTE: The term "fuel" is used synonymously with the term "waste" in this table.
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-year) erosion rates, the range provided is considered reasonable for the regulatory time frame.
Areal weights are developed by Turin and Ware (2003, p. 77).
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 and from the mean ash layer thickness at the same location (BSC 2004, Table 6-4). A value of 1.0 g/cm^3 should be used for ash settled density (BSC 2004, Table 7-1, DTN: LA0311DK831811.001). For example, ash areal concentration (g/cm^2) divided by ash settled density (g/cm^3) equals ash thickness (cm); waste areal concentration (g/cm^2) divided by ash (or deposit) thickness (cm) equals waste volumetric concentration (g/cm^3). 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.

For distributary channels, the initial tephra deposit thickness is either calculated by the ASHPLUME model or a value selected from a uniform distribution (ranging from 1 to 15 cm), whichever is larger. The upper value for this range is chosen on the basis of channel depths; sediments thicker than 15 cm would likely overtop the channel margins in this area of the alluvial fan. The initial waste concentration is either that calculated by the ASHPLUME model (if the tephra deposit thickness from ASHPLUME is also selected) or the geometric mean concentration calculated for a location 18 km downwind from the repository (BSC 2004, Table 6-4). This value was selected to represent a substantial, reasonable amount of waste redistributed through Fortymile Wash. Although the ash dilution information (BSC 2004, Section 6.6.3) indicates that tephra would be diluted by other sediments, it is conservatively assumed that the initial tephra deposit thickness in distributary channels would not be diluted. After initial deposition of undiluted tephra in the channels, new tephra-bearing sediment deposited at the location of the RMEI is increasingly diluted. This process is modeled by decreasing the volumetric concentration of waste in the ash layer linearly from the initial value to 1% of that value over time periods whose parameter values are uniformly distributed between 100 and 1,000 years. This 1% of the initial waste concentration is then considered to remain indefinitely.

Outcome 2 represents ash that is upstream of the location of the RMEI in the Fortymile Wash drainage and available for redistribution by eolian or fluvial processes. It is assumed that radionuclide-bearing tephra can be delivered to interchannel divides at the RMEI location by wind transport (in a north to south direction) or by flood events that fill the channels and spill onto the divides (see Table 1). In both cases, there is likely to be substantial dilution of tephra. It is assumed that interchannel 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 (BSC 2004, Table 6-4). Tephra can be subsequently redistributed to distributary channels at the RMEI location by fluvial processes. As with Outcome 1, Outcome 2 assumes that initial fluvial redistribution produces a 1- to 15-cm-thick layer of undiluted tephra to the channels. Over the following 100 to 1,000 years, this concentration is modeled to decrease in a linear fashion until the tephra volume concentration reaches 1%, after which no further decrease in concentration occurs (BSC 2004, Section 6.7.2).

The redistribution model calculates concentrations separately for each area (interchannel divide and distributary channels) and then combines them, weighted by their areal frequency, to achieve a total concentration from the redistributed contaminated ash. These areal weights for the interchannel divides and distributary channels (0.82 and 0.18, respectively) were developed by systematically estimating the relative percentage of the area of the alluvial fan occupied by the two landforms (BSC 2004, Section 6.6.3.1). The erosion rate (0.02 to 0.04 cm/yr) for eolian removal of ash and soil from the interchannel divides was developed in an analysis of ^{137}Cs concentration profiles in desert soils in the Yucca Mountain region (BSC 2004, Section 6.6.3.1), and they are corroborated by regional studies of soil loss in the Amargosa Valley and in Nevada as a whole (BSC 2003d, Section 6.4.2; USDA 2000, Table 11). The thickness of waste-contaminated ash and sediment in the distributary channels (up to 15 cm) is bounded by the typical depth of the channels in the upper part of the Fortymile Wash alluvial fan (BSC 2004, Section 6.3.4). The depth of migration of radionuclides into the soil (9 cm) and the persistent residual concentration of radionuclides in the soil (1% of initial concentration) are derived from the ^{137}Cs studies in Yucca Mountain region soils (BSC 2004, Section 6.7.2).

For TSPA, the output of the soil redistribution model provides direct input for the calculation of the probability-weighted eruptive dose. The relationship between ash redistribution model outputs and eruptive dose is not linear, but no simple method exists to evaluate the effect on eruptive dose of an incremental change in the output of the ash redistribution model. The information suggests that if concentrations of radionuclides in ash remain high for long periods of time following an eruption, the probability-weighted dose would increase. Conversely, if concentrations of radionuclides in ash decrease rapidly following an eruption, the probability-weighted dose would be less.

The soil concentrations are multiplied by BDCFs in each of these cases, yielding dose estimates for each case. Those dose results are then weighted by the areal frequency of the divide and channel areas, 82% and 18%, respectively (BSC 2004, Figure 6-3) (Table 1). The appropriate weighting for wind direction is included directly within the GoldSim model, and wind direction is sampled from a wind rose. The sampling determines the fraction of realizations in the initial – ash deposit and no –initial –ash deposit categories.

The largest contribution to eruptive dose is expected to come from the case for the interchannel divide areas in which wind is such that there is an initial ash deposit (Outcome 1, Table 1). Therefore, dose sensitivity to the redistribution effects would be greatest for the contribution from interchannel divide areas.

The feature, event, or process (FEP) related to the redistribution of contaminated ash is FEP 1.2.04.07.0C, Ash Redistribution Via Soil and Sediment Transport. Descriptions in *Atmospheric Dispersal and Deposition of Tephra from a Potential Volcanic Eruption at Yucca Mountain, Nevada* (BSC 2004, Table 6-1) identify an element of the FEP that is considered in the rate of erosion and deposition of sediments on the Fortymile Wash alluvial fan. The parameter related to the FEP is the site erosion and aggradation rate.

Volcanic Ash Remobilization off Slopes, Transport in Fortymile Wash, and Deposition or Removal at the RMEI Location–Dilution studies were undertaken to characterize the sedimentological processes that redistribute contaminated ash from points of primary deposition to points downstream and to the location of the RMEI. This section includes data from samples collected from the Lathrop Wells Cone tephra sheet and presents the results of a qualitative scoping analysis to assess the potential particle mixing and dilution of basaltic ash. The section also presents results of ^{137}Cs studies used to characterize landform stability and radionuclide infiltration (BSC 2003a, Section 6.5.1) over a period of 50 years.

Information about the erosion of the tephra sheet exposed northwest of the Lathrop Wells Cone was used to understand how the process of ash dilution occurs when primary ash is mixed with diluting sediments consisting of silicic tuffs and eolian sand (BSC 2003a, Section 6.5.1; BSC 2004, Section 6.3.4).

Table 2 presents the ^{137}Cs values and their interpretations. When sufficient rainfall occurs upslope and a small stream runs onto a basaltic tephra deposit, ash particles are picked up and carried downslope, leaving behind an incipient channel. The moving water continues to acquire additional particles until the stream becomes overloaded with sediment; subsequently, the mixture floods over the leading edge of the sediment wedge as a debris flow and carries material downslope away from the channel. Successive debris flows transport additional tephra material farther downslope. This repeating action results in the progressive movement of material to the base of the tephra sheet and, in this outcome, to a drainage channel at the base of the slope. That drainage, which is commonly marginal to the tephra, would also carry a sediment load, the majority of which is nonbasaltic ash material. In the Yucca Mountain region, these nonbasaltic ash sediments are dominantly clasts of silicic tuff and eolian sand. When the two sediment types are combined in the drainage channel, mixing of the particles occurs rapidly, and the more abundant sediment dilutes the basaltic ash component. The result is the basaltic ash becomes a progressively smaller proportion of the total sediment load as the mixture is transported down the drainage (BSC 2003a, Section 6.5.1.1).

If the area were subject to high wind velocities, eolian sand and coarse silt would be intermixed with the fluvially transported ash and other material in the channel. Eolian material carried onto the tephra sheet over time would result in deposition of medium to fine sand in the ash interstices, and the sand concentration would increase in the near-surface part of the ash sheet. As the material is transported downslope and along channels, more nonash eolian material would be incorporated. When a channel joins larger-order channels that carry mainly nonbasaltic material, the dilution continues, resulting in the proportion of basaltic ash within the sediment decreasing with transport distance (BSC 2003a, Section 6.5.1.1).

Table 2. ^{137}Cs Values and Their Interpretation for the Fortymile Wash Fan

Sample Number	Depth	^{137}Cs 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	1.5 to 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 2. ^{137}Cs Values and Their Interpretation for the Fortymile Wash Fan (Continued)

Sample Number	Depth	^{137}Cs in Layer (pCi/g)	Topographic Feature	Interpretation of Cesium and Topography
Cs-071802-P1	0–3 cm	0.231 ±0.040	Interstream divide	At least 1 cm of removal by wind
Cs-071802-P2	3–6 cm	0.014 ±0.013		
Cs-071802-Q1	0–3 cm	0.204 ±0.037	Interstream divide with eolian winnowing/lag	At least 2 cm of removal by wind
Cs-071802-Q2	3–6 cm	0.001 ±0.012		
Cs-071802-R1	0–3 cm	0.227 ±0.042	Interstream divide with pebbly lag/eolian removal	At least 1 cm removal by wind
Cs-071802-R2	3–6 cm	0.010 ±0.012		
Cs-071802-S2	0–3 cm	0.251 ±0.043	Old fan with poorly developed pavement	Stable fan surface, 1/2 cm removed
Cs-071802-S2	3–6 cm	0.034 ±0.010		
Cs-071802-T1	0–6 cm	0.104 ±0.022	Coppice	An active dune with sand held only temporary
Cs-071802-U1	0–3 cm	0.073 ±0.018	Sand surface near big dune; active sand movement	Active sand movement on this surface
Cs-071802-U2	3–6 cm	0.060 ±0.018		
Cs-0071802-V1	0–3 cm	0.322 ±0.056	Interstream divide with well-developed pavement	Stable surface, almost no infiltration of cesium
Cs-0071802-V2	3–6 cm	0.002 ±0.011		
Cs-071802-W1	0–3 cm	0.097 ±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 ±0.014		
Cs-071802-X1	0–3 cm	0.200 ±0.035	Old fan surface/divide; pebble lag indicates eolian	1 to 1.5 cm of removal by eolian processes
Cs-071802-X2	3–6 cm	0.028 ±0.012		
Cs-071802-Y1	0–3 cm	0.088 ±0.020	Active fan surface but seldom flooded	Sediment mixed
Cs-071802-Y2	3–6 cm	0.045 ±0.014		
Cs-071802-Z1	0–3 cm	0.240 ±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 ±0.016		
Cs-071802-AA1	0–3 cm	0.275 ±0.047	Interstream divide area with pebble lag/eolian removal	Surface has 1 cm of removal
Cs-071802-AA2	3–6 cm	0.016 ±0.011		
Cs-071802-BB1	0–2 cm	0.255 ±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 ±0.015		

Source: BSC 2004, Table 9.

NOTE: The term "interstream divide" used in this table is synonymous with the term "interchannel divide" used throughout the rest of the response.

Results of Ash Redistribution Study–The Lathrop Wells Cone study includes results from the two drainages adjacent to the cone (BSC 2003a, Table 35). Five samples covering a distance of 1,000 m were collected from the western drainage through three confluences with larger channels; the latter channels drain progressively larger areas that do not contain Lathrop Wells Cone tephra at the surface. The results (BSC 2003a, Figure 61) show that after only 1,000 m of transport, significant dilution to approximately 40 wt % ash by addition of other tuffaceous sediments has occurred, thus reducing the basaltic ash component by nearly two-thirds over a distance of 1 km. Dilution occurs by the addition of tuffaceous sediments from adjoining drainages and by incorporation of a large eolian sand load. Data from the eastern drainage are more complex but also show a general diminution of basaltic ash content with transport distance (BSC 2003a, Figure 62).

The dilution studies at Lathrop Wells Cone demonstrate that significant reduction of weight of basaltic ash per weight of sediment occurs over short distances during transport due to the continuous addition of nonbasaltic tuffaceous material to the drainage systems (BSC 2003a, Section 6.5.1.4).

^{137}Cs Study of the Fortymile Wash Alluvial Fan–A study was directed at describing the processes associated with concentration of ^{137}Cs in soils as a method of establishing a time-marker for sediments deposited since the initiation of atmospheric nuclear tests. Radioactive ^{137}Cs was distributed worldwide as a result of atmospheric nuclear tests beginning around 1950 (Ely et al. 1992, p. 196). As cesium accumulated on ground surfaces, it was incorporated into any sediments subsequently formed by transport and deposition. Therefore, ^{137}Cs provides a time-marker for sediments formed during the last 50 years. As such, the measurement of the concentration of ^{137}Cs with depth in the soil can be used to examine erosion and deposition rates over this short time period. Uncertainties are associated with relating processes and rates acting over a short time period (approximately 50 years) to erosion and deposition over much longer time periods (greater than 1,000 years) (BSC 2003a, Section 6.5.2.1).

^{137}Cs preferentially attaches to silt- and clay-size particles in normal sedimentary profiles but also to dune sand as, for example, in the sands of Big Dune (Amargosa Valley) (BSC 2003a, Figure 60) and to sand grains in small coppice dunes that traverse surfaces of alluvial fans. The cesium analyses discussed below show some of the highest cesium values from these dune materials, which possess almost no fine-grained material (BSC 2003a, Table 36).

In the study area, most stable alluvial surfaces contain a prominent vesicular A-horizon (A_v) composed of silt with minor amounts of clay, often directly beneath a desert pavement. Desert pavements develop over thousands of years and are characteristic of very stable surfaces. Stability of alluvial surfaces is necessary for the development of the A_v horizon prior to the influx of ^{137}Cs. Part of this study (the reference sample suite) was designed to verify that ^{137}Cs does not infiltrate rapidly into the deeper sediments so that depth profiles among sites could be compared confidently. The remainder of the study examined the cesium quantities in the material, vertical cesium profile, and particle-size composition of the upper 6 to 10 cm of sediments to help determine erosion and deposition sites on the Fortymile Wash alluvial fan surfaces (BSC 2003a, Section 6.5.2.1).

Results of ^{137}Cs Study–The results show that most of the ^{137}Cs is present within the upper 3 cm of the A-horizon in the stable environments near Yucca Mountain (BSC 2003a, Figure 65). There is little evidence in the Yucca Mountain region of any significant cesium infiltration below 6 cm into the deeper sediments during the last 50 years (BSC 2003a, Section 6.5.2.3).

Depth profiles for ^{137}Cs show similar trends among the suite of reference samples. A typical profile has a maximum value of about 0.325 pCi/g (range 0.251 to 0.421 pCi/g) in the upper 3 cm of soil, a lower average value of approximately 0.050 pCi/g in the 3- to 6-cm layer, and ^{137}Cs concentrations in the 6- to 9-cm depth layer 1 less than the uncertainties associated with the measurements (BSC 2003a, Figure 65). The reference samples retain almost their entire inventories of ^{137}Cs within 4 cm of soil because the ^{137}Cs attaches to fine-grained material in the upper part of the soil profile A_v horizon soon after deposition and remains relatively immobile. The typical depth profile used for comparison to the fan samples is a composite derived from the reference samples (BSC 2003a, Figure 65). This typical depth profile for the reference suite provides a tool for comparing other samples, and characteristics of the Fortymile Wash alluvial fan samples can be evaluated. The whole profile at each sample location is used in the comparison process (BSC 2003a, Section 6.5.2.3).

Sample locations whose ^{137}Cs profiles most resemble the reference-sample (stable surface) profiles are located on interchannel divide areas between distributary channels. Interchannel divide areas have the least likelihood of having been eroded during floods over the last 50 years. These profiles are similar to the reference profiles that have low ^{137}Cs values (in the range of 0.02 to 0.08 pCi/g) in the 3- to 6-cm layers. However, the surface layers (1 to 3 cm depth) typically have values much less than the reference samples from equivalent depths, which range from 0.251 to 0.421 pCi/g. It appears, then, that many of these interchannel divide areas have had part of the upper layer removed. The amount of material removed is estimated by comparing the ^{137}Cs value of the upper 3-cm layer to that of the reference value and calculating the thickness of the layer that would have to be removed to obtain the lower value. Application of this estimating method across the interchannel divide sample locations shows that most of the interchannel divide areas have had 1 to 3 cm of material removed from their surfaces in the last 50 years. Overbank deposits on the divide areas that would suggest periodic flooding are uncommon and restricted to narrow strips along the channel banks. The overbank and channel deposit samples have similar ^{137}Cs signatures; the 3- to 6-cm layers and the 6- to 9-cm layers also have nearly the same values (in the 0.100 to 0.200 pCi/g range), indicating that the material was mixed during transport and deposited as a homogeneous sediment (BSC 2003a, Section 6.5.2.5).

Fluvial processes are unlikely to have produced the erosion of the interchannel divides on the fan over the last 50 years (and probably much longer). Rather, the loss of material from these otherwise stable surfaces appears to be due to eolian processes. Evidence for wind playing a predominant role in erosion of the interchannel divide areas includes the lack of new or developing stream channels and the presence of modern coppice dunes near channels on interchannel divides. Erosion of a divide area with little evidence of recent water movement across the surface is most easily explained by eolian removal. The presence of nearby Big Dune and other eolian deposits provides strong support for eolian erosion and transport (BSC 2003a, Section 6.5.2.5).

Ash Dispersal from an Eruption through the Repository: Conceptual Model–In the unlikely event that a future basaltic eruption through the repository were to occur, the ash plume would most likely be transported in the direction of the prevailing winds, and, although transport could be any direction, the most probable direction would be from southwest to northeast (NOAA n.d.). The ash redistribution outcome that would result in delivery of the most basaltic ash through the Fortymile Wash system would be an ash plume that was deposited north-northeast along the axis of upper Fortymile Wash. In this outcome, tephra would be thickest near the vent above the repository and would cover the eastern flank of Yucca Mountain and much of the upper Fortymile Wash drainage basin (BSC 2003a, Section 6.5.3.1).

On the upper hillslopes at Yucca Mountain, a future eruption through the repository would cause scoria and ash to fill the heads of small valleys. Because this material would be largely situated on greater than 30° slopes, precipitation on these hillslopes would flow into or over the tephra and incise into it. The drainages would not be hydraulically plugged because of the slope steepness and the loose, permeable nature of the tephra. The process of removal of the material would begin immediately, as illustrated at Parícutin, Mexico, for loose, nonwelded ash and lapilli fallout (Luhr and Simkin 1993, Figure 171). However, the incision process could be slowed if the permeability of the tephra were sufficiently high. For example, at Sunset Crater, Arizona, observations show that tephra deposits have not been incised to produce a drainage system in a thousand years (since the cone was formed). On steep, tephra-covered slopes, no material has been carried to the base of the hillslopes. On the upper slopes of Yucca Mountain, the parallel drainages would act like flumes and steadily move the tephra through drainages as often as storms occurred that provided sufficient precipitation to move the tephra to the floors of adjacent valleys. This transport water and finer sediment would continue until reaching Fortymile Wash (BSC 2003a, Section 6.5.3.1).

Effects of Storms and Climate Change–Rainstorms at Yucca Mountain can be classed into two types: local, infrequent, high-intensity storms (summer monsoonal thunderstorms) and larger, lower-intensity regional storms, which cover very broad areas on scales larger than entire drainage basins (Coe et al. 1997, 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 during winter, although they can occur at any time of the year (BSC 2003a, Section 6.5.3.2). In general, storms that could cause material to move from the slopes into adjacent valleys are typically summer monsoonal thunderstorms, whereas storms that produce sediment transport throughout the Fortymile Wash drainage system are the broad, regional (typically winter) storms. However, the regional storms move little, if any, material off the hillslopes.

The flood of 1969 (probably the most severe in recent times) had an estimated peak flow in Fortymile Wash of about 20,000 ft^3/s (Squires and Young 1984, p. 12). During this flood, water flowed through the length of the wash, across the alluvial fan, into the Amargosa River, and ultimately into Death Valley, where a shallow lake was impounded over an area of 80 mi^2 (Hunt 1975, p. 15). These long-duration regional storm systems rain on entire drainage basins, flush the valley sediments, and might move large quantities of sediment through the drainage. If transport of erupted ash began in the upper watershed of Fortymile Wash, mixing of materials would occur along the entire length of transport, up to 70 km (BSC 2003a, Section 6.5.3.2).

If overall climate in the Yucca Mountain region were to change to wetter weather patterns, changes in the dominant storm type could result, which, in turn, could impact surface landscape conditions. During wetter conditions, long-duration regional storms would become more frequent and summer monsoon storms would become less frequent or possibly disappear. Landscape vegetation would become more abundant and in situ weathering would decrease overall particle sizes and enhance development of deeper soil. This change would result in a greater capacity to retain sediments on the hillsides and reduce the sediment load in streams, while due to the increase in rainfall, there would be more water in the system. When the sediments were put in transport, mixing would still be an effective agent in the dilution of contaminated sediment along the journey to the Fortymile Wash alluvial fan (BSC 2003a, Section 6.5.3.2).

Basis for Ash Redistribution Model–Field studies of tephra in drainages around the Lathrop Wells Cone, surficial erosion and deposition rates based on ^{137}Cs, analog observations in other volcanic settings, and general considerations of the sediment transport systems around Yucca Mountain are the basis for the ash redistribution model. This model and its output parameters for use in TSPA are summarized (Table 1) (BSC 2004, Table 6-5) in terms of the two tephra fall and redistribution outcomes (BSC 2004, Section 6.7.2), as well as the two main geomorphic features at the RMEI location (interchannel divides and distributary channels). For the purposes of TSPA, the distinction between Outcomes 1 and 2 was made on the basis of the presence of nonnegligible ash thickness at the RMEI location. Nonnegligible ash thickness was defined as greater than or equal to the minimum median ash particle diameter of 0.001 cm. This thickness, or greater, of ash constitutes ash fall at the RMEI location (Outcome 1), while less than 0.001 cm constitutes Outcome 2.

The analyses of ^{137}Cs concentrations in the samples (BSC 2003a, Table 6-8) from the upper fan support a conclusion that the upper-fan interchannel 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 primarily the result of wind erosion (BSC 2003a). The surface erosion in 50+ years equates to erosion rates of approximately 0.02 to 0.04 cm/yr. The erosion rates of 0.02 to 0.04 cm/yr are similar to the lower soil loss (erosion) rate of 0.19 $kg/m^2 \cdot yr$, equivalent to 0.019 cm/yr, predicted to occur on farmland in Amargosa Valley (BSC 2003d, Section 6.4). This 0.19 $kg/m^2 \cdot yr$ value is used in the biosphere model (BSC 2003d, Section 6.4.2) (converted to centimeters per year using an ash bulk density of 1 g/cm^3 (DTN: LA0311DK831811.001), 0.19 $kg/m^2 \cdot yr$ 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 noncultivated cropland and pastureland in Nevada (USDA 2000, Table 11) (1 ton/acre·yr $\times$ 907 kg/ton $\times$ 2.47 $\times$ 10^{-4} acre/m $\times$ 0.001 m^3/kg [bulk density] $\times$ 100 cm/m = 0.02 cm/yr).

Although the effects of erosion by surface winds (BSC 2004, Section 6.3.4) can be inferred from the ^{137}Cs data (BSC 2003a, Table 6-8), evidence of eolian deposition on some surfaces also exists. The presence of coppice dunes along the edges of the interchannel divide areas indicates that vegetation traps some of the eroded materials before the eolian materials can be carried off the divide area. Supporting data for wind transport and deposition of material throughout the Yucca Mountain region include the presence of stratified eolian horizons of fine sand and silt marked by the presence of gas bubble vesicles (A_v horizons) (CRWMS M&O 2000, Sections

4.4.3.2 and 4.4.3.3.2.1; Wells et al. 1990, Figure 3; Lundstrom et al. 1995, Table 1). Such vesicular soil horizons are found on most geomorphic surfaces that have been stable for several hundred years. Studies of the potential for erosion in the Yucca Mountain region have shown that the geomorphic surfaces around Yucca Mountain are generally very stable (YMP 1993, Sections 3.3 and 3.3.1.4). The presence of Big Dune in close proximity to the Fortymile Wash fan, from which material is being removed and deposited almost continuously, 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 (BSC 2004, Section 6.3.4).

Effects of Changes in Grain Size on Airborne Particle Concentrations–Redistribution of ash and waste over time may result in the deposition of particles at the location of the RMEI that differ in size from the tephra initially deposited following an eruption. Those differences in particle size may be caused by differential settling of smaller or larger particles during fluvial and eolian transport, or from the breakdown of ash and waste into smaller particles as it is transported. These changes over time in the size of deposited particles may result in changes in the concentrations of resuspended particles.

Concentrations of resuspended particles and estimates of airborne activity concentrations are calculated in the biosphere model. The primary outputs of that model for the volcanic ash exposure outcome are sets of BDCFs, which are equivalent to the dose per unit concentration of radionuclides deposited in the soil following a volcanic eruption. To evaluate changes in resuspended particle concentrations over time, the biosphere model calculates BDCFs for the first year following a volcanic eruption and for the period after resuspended particle concentrations have returned to preeruption levels. It also includes a time function to model the effects of decreases in resuspended particle concentrations following an eruption. The mass loading decrease constant controls the rate at which mass loading and, therefore, the dose from inhalation are predicted to return to preeruption levels. These methods are described in detail in *Biosphere Model Report* (BSC 2003c, Section 6.4).

Estimates of airborne activity concentrations are calculated in the biosphere model as a function of radionuclide concentrations in soil, an enhancement factor, and mass loading in four environments (BSC 2003c, Section 6.5.2), as shown in the following equation for the volcanic ash exposure outcome (BSC 2003c, Section 6.5.2.1).

$$Ca_{h,i,n}(d_a,t) = f_{enhance}\ Cs_{mc,i}(d_a)\ S_n(t) \qquad \text{(Eq. 1)}$$

where

$Ca_{h,i,n}(d_a,t)$ = activity concentration of radionuclide i in the air for environment n at time t and ash thickness d_a (Bq/m^3)

n = index of the environments, $n = 1$ for active outdoors; 2 for inactive outdoors; 3 for active indoors; 4 for asleep indoors;

and 5 for away from the contaminated area

$f_{enhance}$ = enhancement factor for the activity concentration of resuspended particles (dimensionless)

$Cs_{mc,i}(d_a)$ = activity concentration of radionuclide i in volcanic ash or in the mix of ash and dust of noncultivated land (Bq/kg)

d_a = thickness of ash deposited on the ground (m)

$S_n(t)$ = total average annual mass loading (the concentration of total resuspended particulates in the air) in environment n at time t following a volcanic eruption (kg/m^3).

Mass loading is the average annual concentration of resuspended particles in an environment. Because the majority of the inhalation dose would come from the active outdoor environment (BSC 2003b, Appendix A), the following discussion focuses on that environment.

Distributions of mass loading for postvolcanic conditions and the mass loading decrease constant were developed from analog measurements of airborne particle concentrations taken following the eruptions of Mount St. Helens (Washington), Mount Spurr (Alaska), Mount Sakurajima (Japan), Soufriere Hills (Montserrat, British West Indies), and Cerro Negro (Nicaragua). Those measurements were taken over a variety of conditions and likely encompass the effects of differences in ash particle size. However, the size distribution of ash and soil particles was not measured in most of those studies; therefore, the bounds of the mass loading distributions and time constant were selected to account for uncertainty in the use of those analog measurements and the effects that different grain sizes would have on concentrations of resuspended particles (BSC 2003b, Sections 6.2 and 6.3).

Most of the analog measurements of airborne particle concentrations that were considered to develop mass loading distributions and the mass loading decrease constant were taken following the eruption of nonbasaltic volcanoes (Mount St. Helens, Mt. Spurr, Soufriere Hills). All of the following measurements of particle size distributions are presented as percent mass. About 10% or less of the ash from Mount St. Helens was less than 10 μm (Craighead et al. 1983, p. 6; Buist et al. 1986, p. 40). Ash at two sites 30 to 35 km east of Anchorage from the August 1992 eruption of Mt. Spurr had about 30% to 35% of particles less than or equal to 63 μm, 8% to 15% less than 15 μm, and 5% to 10% less than or equal to 7.5 μm (McGimsey et al. 2001, Figure 12). However, ash collected at a site about 25 km west of Anchorage (closer to Mt. Spurr) had few or no particles less than or equal to 63 μm. Ash from Soufriere Hills had 13% to 20% weight of particles less than or equal to10 μm and 60% to 70% weight of particles 10 to 125 μm (Baxter et al. 1999, p. 1142). Hill and Connor (2000, p. 71) reported that ash 21 km from the vent of the basaltic Cerro Negro volcano had about 2% of particles by weight less than 10 μm, 10% less than 60 μm, and 50% less than 200 μm. They report that other fall deposits from larger basaltic cinder cone eruptions (Paricutin, Tolbachik, Sunset Crater) may contain 2% to 5% weight of particles less than 10 μm at 20 km. Thus, ash from the volcanoes used as analogs in this analysis appears to have had higher concentrations of fine particles than that from basaltic volcanoes. In addition, for exposure estimates, the results obtained from Mount St. Helens and Montserrat will almost certainly need to be reduced by a factor to allow for the coarser material emitted at Cerro Negro (McKague 1998, Enclosure 3, Item 17). Thus, ash particles from the analog volcanoes used in this analysis generally were similar in size or smaller than those from basaltic volcanoes (BSC 2003b, Section 6.3.3).

Average resuspended particle concentrations measured over tephra while people were active outdoors range from less than 1 to about 10 mg/m^3 (BSC 2003b, Section 6.2.1.1). This is similar to resuspended particle concentrations measured while people were active outdoors in nonvolcanic conditions. It is also similar to the mass loading distribution for the active outdoor environment used in the biosphere model for the long-term period after mass loading has returned to preeruption conditions (triangular distribution with a minimum of 1 mg/m^3, mode of 5 mg/m^3, and maximum of 10 mg/m^3) (BSC 2003b, Section 6.2.1). To account for uncertainty in the effects of soil and ash particle size distributions on the concentrations of airborne particles, the mode and upper bound of the mass loading distribution for the first year following a volcanic eruption for the active outdoor environment is 50% higher than the concentrations used for long-term mass loading (BSC 2003b, Section 6.2.1.2). Thus, a maximum mass loading of 15 mg/m^3 is possible for the active outdoor environment for the period following a volcanic eruption. This bound, which is 50% higher than average values measured over tephra deposits, reasonably accounts for any uncertainty from the lack of information on soil and ash particle sizes associated with analog measurements of mass loading.

Airborne particle concentrations following the eruption of Mount St. Helens and other volcanoes returned to preeruption levels in 1 year or less (BSC 2003b, Section 6.3). To account for uncertainty in the influence of changes in particle size distributions and other factors on that rate of change, a modal value for the distribution of the mass loading decrease constant was selected that would result in a decrease in mass loading to preeruption levels over 10 years. The minimum value (i.e., slowest rate of change) selected would result in a decrease over 20 to 30 years (BSC 2003b, Section 6.3.3). These values incorporate uncertainties associated with changes in grain size resulting from fluvial and eolian redistribution and, therefore, will not result in the underestimation of risk.

Mass Loading Model Assumptions Concerning Radionuclide Concentration–To account for differences between the concentrations of radionuclides on soil and in air, the biosphere model now includes an enhancement factor in the calculation of concentrations of radionuclides in air due to resuspension of soil and ash particles, as shown in Equation 1.

The enhancement factor is defined as the ratio of the airborne particle activity concentration to the activity concentration in soil (Shinn 1992, p. 1183; NCRP 1999, Section 4.2.2). Differences in activity concentrations between airborne particles and soil may be the result of differential resuspendability of contaminated and uncontaminated particles, difference in concentrations of radionuclides on large and small particles (e.g., radionuclides preferentially attaching to small particles), or other factors.

The distributions of enhancement factors used in the biosphere model were developed from information summarized by the National Council on Radiation Protection and Measurements (NCRP 1999, p. 66). That report presents ranges and median values measured on disturbed and undisturbed soils.

A distribution of enhancement factors ranging from 0.21 to 1.04, with a median of 0.7, was selected for the indoor environments and inactive outdoor environments considered in the biosphere model. This distribution is used for the groundwater and volcanic ash exposure outcomes (BSC 2003d, Section 6.5). It is based on measurements of enhancement factors taken on undisturbed desert soil at the Nevada Test Site and undisturbed, bare cultivated fields at Bikini Island, South Carolina, and California. The sources of contaminants were safety shots (Nevada) (safety shots consisted of assembling a quantity of plutonium around a mass of explosive and detonating the combination.), nuclear fallout (Bikini), a processing facility smokestack ^{239}Pu release (South Carolina), and sewage sludge (California) (Shinn 1992; NCRP 1999, p. 66). Because these measurements were taken on desert soils or undisturbed cultivated fields, they are analogous to, and account for uncertainty in, conditions likely to occur in the Yucca Mountain region. All measurements were less than or equal to about 1; therefore, using this distribution will not result in the underestimation of risk from inhalation of resuspended particles in the indoor or inactive outdoor environments.

A higher range of enhancement-factor values was used for the active outdoor environment. For the groundwater exposure outcome, a distribution ranging from 2.2 to 6.5, with a median of 4.0, was selected (BSC 2003d, Section 6.5). The distribution was based on measurements of enhancement factors on soils recently disturbed by soil thawing, bulldozer blading, vacuum removal of soil, wildfire, and raking. (Note that the groundwater exposure outcome is not addressed in agreement IA 2.17. The information is provided only to show that values used in the volcanic ash exposure outcome are greater than the values used in the groundwater exposure outcome.) A distribution of 2.8 to 8.4, with a median of 4.4, was selected for the volcanic ash exposure outcome. This distribution was developed from measurements of enhancement factors taken during agricultural tractor operations on medium to highly contaminated soils near Chernobyl. The results of this study are analogous to conditions likely to occur following an eruption at Yucca Mountain because nuclear fuel particles were released from the Chernobyl accident. Similarly, granular waste particles would be released from an eruption at Yucca Mountain and deposited on agricultural fields (BSC 2003d, Section 6.5). These distributions adequately encompass uncertainty and variation in enhancement factors because they encompass the range of measurements taken over a variety of conditions. They are not likely to underestimate risk in the inhalation of resuspended particles because they are bounded by the maximum enhancement values reported for disturbed conditions.

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