NAC-0021_R2

# Atmospheric Transport Modeling for the Clive DU PA

## Clive DU PA Model v1.4

5 November 2015

Prepared by

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|---|---|---|
| 1. Title: Atmospheric Transport Modeling for the Clive DU PA | | |
| 2. Filename: Atmospheric Modeling v1.4.docx | | |
| 3. Description: This white paper provides documentation of the development of parameter values and distributions used for atmospheric modeling for the Clive DU PA Model. | | |
| | Name | Date |
| 4. Originator | Dan Levitt | 5 November 2015 |
| 5. Reviewer | Paul Black | 5 November 2015 |
| 6. Remarks<br><br>Nov 5, 2015: D.Levitt: Updated from v1.2 to v1.4. Updated R313 information. | | |

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# 1.0 Summary of PA Model Inputs

A summary of parameter values and distributions employed in the atmospheric modeling component of the Clive Performance Assessment (PA) model is provided here. Additional information on the derivation and basis for these inputs is provided in subsequent sections of this report. With the exception of particulate resuspension flux, the PA model inputs related to atmospheric modeling are derived from AERMOD air dispersion modeling results. The term Chi/Q refers to the ratio of breathing-zone air concentration (*Chi*) to the emission rate (*Q*) used in the AERMOD simulations. The term $PM_{10}$ refers to particulates with a mean aerodynamic diameter of 10 μm and less, the size fraction employed in regulatory air modeling to represent respirable particles.

**Table 1. Summary input parameter values and distributions**

| *PA Model Parameter* | *Units* | *Value* | *Notes* |
|---|---|---|---|
| Chi / Q ratios for $PM_{10}$ | μg/m$^3$ per g/s | See Table 4 | Based on AERMOD modeling; see Section 10. |
| Chi / Q ratios for gases | μg/m$^3$ per g/s | See Table 5 | Based on AERMOD modeling; see Section 10. |
| Embankment $PM_{10}$ redeposition | g/m2-yr per g/yr | See Table 6 | Based on AERMOD modeling; see Section 15. |
| Resuspension flux of $PM_{10}$ | kg/m$^2$-yr | LogUniform ( 2.5e-7, 0.3 ) | Implementation of Cowherd et al (1985); see Section 17. |
| Fraction $PM_{10}$ deposition in off-site exposure area | — | See Table 6 | Based on AERMOD modeling; see Section 15. |

# 2.0 Introduction

The safe storage and disposal of depleted uranium (DU) waste is essential for mitigating releases of radioactive materials and reducing exposures to humans and the environment. Currently, a radioactive waste facility located in Clive, Utah (the "Clive facility") operated by the company Energy*Solutions* Inc. is being considered to receive and store DU waste that has been declared surplus from radiological facilities across the nation. The Clive facility has been tasked with disposing of the DU waste in a manner that protects humans from future radiological releases.

To assess whether the proposed Clive facility location and containment technologies are suitable for protection of human health, specific performance objectives for land disposal of radioactive waste set forth in Utah Administrative Code (UAC) Rule R313-25 *License Requirements for Land Disposal of Radioactive Waste - General Provisions* must be met—specifically R313-25-9 *Technical Analyses* (Utah 2015). In order to support the required radiological performance assessment (PA), a probabilistic computer model has been developed to evaluate the doses to human receptors that would result from the disposal of radioactive waste, and conversely to determine how much waste can be safely disposed at the Clive facility. The GoldSim systems analysis software (GTG 2011) was used to construct the probabilistic PA model.

The site conditions, chemical and radiological characteristics of the wastes, contaminant transport pathways, and potential human receptors and exposure routes at the Clive facility that are used to structure the quantitative PA model are described in the conceptual site model documented in *Conceptual Site Model for Disposal of Depleted Uranium at the Clive Facility* (Clive DU PA CSM.pdf). Based on current and reasonably anticipated future land uses, the two future use exposure scenarios described in the CSM for evaluation in the PA are ranching and recreation.

The Neptune and Company, Inc. (Neptune) white paper *Dose Assessment for the Clive PA* (Dose Assessment.pdf) details the assumptions and computational methods for estimating radiation doses to future human receptors associated with DU and its decay products. This present white paper focuses on one aspect of the exposure and radiation dose calculations; atmospheric modeling to support the calculation of breathing zone air concentrations of radionuclides for future human receptors. Specifically, this paper addresses the modeling of:

1. Rates of particle resuspension by aeolian (wind derived) processes;
2. Air concentrations of radionuclides above the disposal embankment and at specific locations of potential off-site exposure; and,
3. Deposition flux of resuspended embankment particles at locations beyond the embankment.

Particle resuspension related to mechanical disturbances from off-highway vehicle (OHV) use is also addressed in the PA model and is discussed in the white paper *Dose Assessment for the Clive PA*.

# 3.0 Overview and Framework

Atmospheric dispersion modeling was conducted using computer software outside of the GoldSim modeling environment, as the GoldSim PA model is a system-level model. An atmospheric dispersion model is a mathematical model that employs meteorological and terrain elevation data, in conjunction with information on the release of contamination from a source, to calculate breathing-zone air concentrations at locations above or downwind of the release. Some models may also be used to calculate surface deposition rates of contamination at locations downwind of the release.

Air dispersion models, including the AERMOD (EPA, 2011a) and CAP-88 (EPA, 2011b) models used in this exercise, commonly assume a Gaussian distribution for estimating vertical and horizontal dispersion of contamination away from the source. Factors affecting the amount of dispersion include atmospheric turbulence, the height of the release (e.g., a virtual stack versus ground level), the buoyancy of the plume, and terrain features. Although they employ different mathematical models for assessing horizontal and vertical dispersion, both AERMOD and CAP-88 ultimately calculate annual-average contaminant breathing zone air concentrations at various distances and in various directions from a source release.

The Clive facility waste disposal embankment will be a large-area emissions source with a gently sloping surface that will be raised approximately 15 m above the surrounding terrain. There are two types of future radioactive emissions associated with the embankment:

1. Particulate emissions of contaminated surface soil due to aeolian erosion; and,
2. Emissions of gas-phase radionuclides diffusing across the surface of the embankment into the atmosphere.

With respect to potential human receptors exposed upon the embankment itself (ranchers and recreationalists, including hunters, and OHV sport riders—see the *Dose Assessment* white paper), the surface of the embankment represents a ground-level (0-m height) emissions source. For estimating the annual dose to these individuals, the air modeling endpoint of interest is the annual-average breathing-zone concentration of respirable particles or gaseous radionuclides above the embankment. For individuals exposed at locations other than the embankment, the embankment represents a 15-m elevation emissions source, as transport by wind will be necessary for exposure at these locations. A second air modeling endpoint of interest for these “off-site” receptors is the same as for the “on-site” receptors; i.e., the annual-average breathing-zone concentration of respirable particles or gaseous radionuclides released from the embankment at some specific off-site location.

A third endpoint of interest is the off-site deposition rate of embankment particulates. As particulates eroding from the embankment are deposited on surrounding land, this surrounding area may become a secondary source of radionuclide exposure for ranchers and recreationists. The relative importance of exposure on-site and off-site depends in part on the fraction of total exposure time a rancher or recreationist spends in each area. However, the importance of on-site vs. off-site exposure also depends on the rate of aeolian particle erosion from the embankment and the rate at which contamination from the disposed waste is transported to the the surface of the embankment by processes such as biotic transport (see *Biological Modeling* white paper) and radon diffusion. If transport rates of radioactivity are much higher than the rate at which aeolian particle erosion removes radioactivity, then embankment surface soil radionuclide concentrations will steadily increase over time relative to off-site levels. However, if aeolian particle erosion rates are greater than the transport/accumulation rate of radioactivity in surface soil, then embankment soil radioactivity will be minimal throughout the modeling period. Because only a portion of wind-eroded particles remain within the overall receptor exposure area, and because receptor exposure intensity varies between the embankment and the off-site exposure area, this can have significant consequences for dose assessment results.

In summary, there are three air modeling endpoints:

1. Annual-average breathing-zone concentration of respirable particles and gaseous radionuclides above the embankment;
2. Annual-average breathing-zone concentration of respirable particles and gaseous radionuclides at specific off-site locations; and,
3. Off-site aeolian deposition rate of embankment particulates.

For gas-phase radionuclides, the contaminant transport component of the GoldSim PA model (see *Unsaturated Zone Modeling* white paper) provides the diffusive flux (activity per area per time, as in $Bq/m^2 \cdot s$) at the surface of the disposal embankment. A particulate resuspension model, described below, is employed to calculate the particle flux from the surface of the disposal embankment. The gas-phase radionuclide and particle fluxes are the site-specific inputs to the air dispersion model. The third endpoint, the off-site deposition rate of embankment particulates, is used as an input for modeling radionuclide soil concentrations over time in the off-site exposure area for ranchers and recreationists.

AERMOD, a United States Environmental Protection Agency (EPA)-recommended regulatory air modeling system that incorporates state-of-the-art modeling approaches (EPA, 2011a), is used for the air dispersion modeling to address the three endpoints. As a quality assurance measure, a second EPA regulatory air dispersion model (CAP-88; EPA, 2011b) is employed to confirm the AERMOD results (see Section 16).

# 4.0 Model Descriptions

The following subsections provide a summary of the particle resuspension and air dispersion models used to support the modeling endpoints described above.

## 4.1 Cowherd Particle Resuspension Model

Air dispersion models for estimating radionuclide concentrations above, or at some distance from, a release source require a radionuclide emission rate as an input. In the case of aeolian soil particulates in ambient air (e.g., dust), an area-averaged particulate resuspension rate is needed. For screening of potential inhalation risks at contaminated soil sites, EPA recommends a particulate emission factor (PEF) model to estimate annual average concentrations of respirable particulates (approximately 10 µm and less; i.e., $PM_{10}$) in ambient air above contaminated soil (EPA, 1996; EPA, 2002).

The PEF incorporates $PM_{10}$ emission models (Cowherd et al, 1985) related to wind erosion under one of two conditions. The particulate emission model for $PM_{10}$ used in EPA (1996; 2002) pertains to a surface with unlimited erosion potential. Cowherd et al (1985) also provide a model for estimating $PM_{10}$ particle emissions from surfaces with a limited reservoir of erodible particles. The decision criterion in choosing between these model types is provided in Figure 3-2 of Cowherd et al. (1985) as, “Is threshold friction velocity > 75 cm/s?” For surfaces not covered by continuous vegetation, including assumed future states of the disposal embankment (see *Biological Modeling* white paper), surfaces with a threshold friction velocity larger than 75 cm/s tend to be composed of elements too large to be eroded, or of erosion-resistant crusts. An erosion-resistant crust might be of cryptogamic nature (particles bound by a biological community consisting of one or more types of cyanobacteria, lichens, mosses, and fungi), or simply by aggregation of very fine silty-clay particles.

Methods for characterizing threshold friction velocity in Cowherd et al. (1985) rely on site inspection, which is problematic for this modeling because the future surface characteristics of the embankment are uncertain. The foreseeable future state of the cap surface likely includes a range of particle sizes due to contributions from windblown loess, from decaying plant material, and from degrading rip rap. A practical constraint on the use of the limited-reservoir model of soil erosion is that this model is dependent upon the frequency of disturbance of the surface. When a surface has limited erosion potential, disturbances to expose fresh surface material are considered necessary to restore erodibility. For the Clive PA model, a range of input parameter values are used with the unlimited-reservoir model to estimate possible $PM_{10}$ emission rates based on the presumption of dynamic steady-state conditions, where $PM_{10}$ emissions are presumed to be balanced by deposition of particles from upwind locations.

The equation for particle emissions from a surface with *unlimited* erosion potential, originally published as Equation 4-4 in Cowherd et al. (1985), has the form:

$$E_{10} = 0.036 \times (1 - V) \times ([u] / u_{t-7})^3 \times F(x) \tag{1}$$

where:

- $E_{10}$ is the annual-average $PM_{10}$ emission rate per unit area of contaminated soil ($g/m^2 \cdot hr$);
- $V$ is the fraction of vegetative cover (-);
- $[u]$ is the mean annual wind speed (m/s);
- $u_{t-7}$ is the threshold value of wind speed at 7 m (m/s); and,
- $F(x)$ is a function dependent on the ratio $u / u_t$ (-).

and, from Equation 4-3 in Cowherd et al. (1985):

$$u_{t-7} = (u_t \times F_{adj} / 0.4) \times \ln(700 \text{ cm} / z_0) \tag{2}$$

where:

- $u_t$ is the unadjusted threshold friction velocity (m/s);
- $F_{adj}$ is the threshold friction velocity adjustment factor; and,
- $z_0$ is the surface roughness height (cm).

Values of $F(x)$ are estimated based on the function shown graphically in Figure 4-3 of Cowherd et al. (1985). The value of $x$ is calculated as defined in Equation 4-4 of Cowherd et al. (1985):

$$x = 0.886 \times (u_{t-7} / [u]) \tag{3}$$

and the function $F(x)$ is approximated using the following equations:

when $x < 1$, $F(x) = (6 - x^3)/\pi$

when $x \geq 1$ and $< 2$, $F(x) = (-1.3 \times x) + 2.89$
when $x \geq 2$, $F(x) = [(8 \times x^3) + (12 \times x)] \times e^{-(x^\wedge 2)}$.

With the exception of the case where $x \geq 2$, these equations were fit by Neptune and Company based on visual approximation to the graphic in Figure 4-3 of Cowherd et al. (1985). For the case $x \geq 2$, the equation is taken from Appendix B of Cowherd et al (1985).

## 4.2 AERMOD

AERMOD is EPA's recommended regulatory air modeling system for steady-state emissions. It is defined by EPA (2011a) as

> "A steady-state plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain."

AERMOD supports source characterization as an area of user-defined dimensions and elevation and is thus suitable for modeling the disposal embankment. AERMOD employs two pre-processors related to handling of meteorological data and terrain data. The AERMET pre-processor is used to estimate boundary layer parameter values such as mixing height and friction velocity needed for the air dispersion modeling. AERMET inputs include albedo (a measure of the reflectivity of the ground surface), surface roughness, and Bowen ratio (a measure of heat flux to the atmosphere), plus meteorological measurements such as wind speed and direction, temperature, and cloud cover. The AERMAP pre-processor uses gridded terrain elevation data to generate receptor grids for the air dispersion modeling.

In the stable boundary layer nearest the earth's surface, AERMOD assumes a Gaussian concentration distribution on the vertical and horizontal axes. In the convective boundary layer above, the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described using a linear combination of two separate Gaussian functions. In this manner AERMOD addresses heterogeneity in the planetary boundary layer where wind and associated mixing is influenced by friction with the earth's surface.

## 4.3 CAP-88

The Clean Air Assessment Package – 1988 (CAP-88) modeling program (EPA, 2011b) is recommended for demonstrating regulatory compliance with the requirements of Subpart H of 40 CFR Part 61 (NESHAPS; National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities). As described in 10 CFR 40 Part 61.93, 12-15-1989:

> "To determine compliance with the standard, radionuclide emissions shall be determined and effective dose equivalent values to members of the public calculated using EPA approved sampling procedures, computer models CAP–88 or AIRDOS-PC, or other procedures for which EPA has granted prior approval."

CAP-88 employs a modified Gaussian plume dispersion model to compute ground-level radionuclide air concentrations for a circular grid around an emission source. Meteorological data must be processed into STability ARray (STAR) files for CAP-88, which include assignments of atmospheric turbulence into one of six stability classes labeled A through F.

# 5.0 Meteorological and Terrain Elevation Data

Raw meteorological data from the the Energy*Solutions* monitoring station at Clive, Utah were collected (MSI, 2010). The monitoring station is at 1,306 m above sea level, and is equipped to measure horizontal wind speed, wind direction, 2-and 10-meter temperature, delta-temperature for the derivation of atmospheric stability class, solar radiation, precipitation, and evaporation (MSI, 2010).

Meteorological Solutions Inc. (MSI), processed the raw meteorological data to create AERMET files (for AERMOD air dispersion modeling) and STAR files (for CAP-88 air dispersion modeling). STAR files were created by MSI using two different methods. The sigma-theta method (STAR-ST) assigns an atmospheric stability class based on the standard deviation of the horizontal wind direction. A second method (STAR-SR) assigns an atmospheric stability class based on solar radiation and delta-temperature measurements. The processed meteorological data were then employed by Neptune for the air dispersion modeling. AERMET, STAR-ST, and STAR-SR input files for the years 2003, 2004, 2006, 2007, and 2009 were made available to Neptune by MSI. Composite STAR-SR and STAR-ST files integrating meteorological data for all five years were also created by MSI and provided to Neptune.

A Clive, Utah wind rose from MSI (2010), showing wind speed and direction for the period January 2009 through December 2009, is duplicated here as Figure 1. As shown in Figure 4.1 of MSI (2010), the wind rose integrating data for the period 1993 through 2009 is very similar to that for 2009 shown here. For example, average annual wind speed for both time periods is 7.2 mph and stability class variability for 1993-2009 and just 2009 is less than 5% (MSI, 2010).

Terrain elevation information for each grid cell was derived from the AERMAP interface within the AERMOD View™ (Version 6.7.1) software package (Lakes Environmental, 2010). AERMAP accesses digital elevation model (DEM) data from webGIS (http://www.webgis.com), which is then processed for input into AERMOD. For this project, DEM data from the United States Geological Survey (USGS) for Tooele County, Utah are employed. These data have a nominal resolution of 90 m and were interpolated to the uniform Cartesian grid (i.e., the modeling area) using the inverse distance weighting setting, which is the recommended setting in AERMAP. The nature of the AERMOD View™ interface, and the basis of the spatial receptor grid, are described in Section 8.

# 6.0 Implementation of Resuspension and Dispersion Models

Neptune implemented AERMOD within the graphical user interface AERMOD View™ (Lakes Environmental, 2010). This software package provides an interface for using base maps to define sources and receptors, importing digital elevation data from USGS, and producing graphical displays of results.

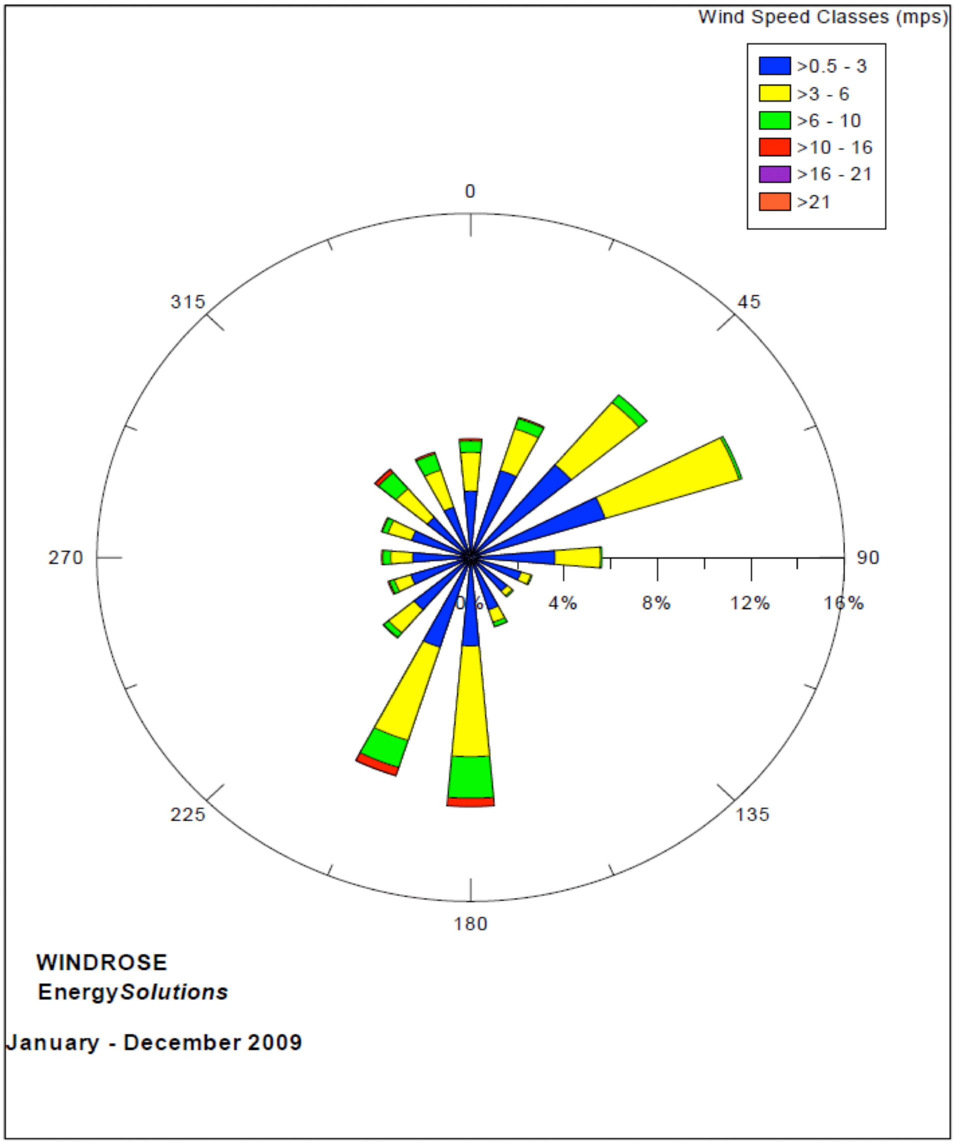


**Figure 1. Wind Rose for Clive, Utah (courtesy of Meteorological Solutions, Inc.)**

## 6.1 Spatial Attributes of Air Dispersion Modeling

As described in Section 1, the intent of the air dispersion modeling was to estimate air concentrations of radionuclides above the disposal embankment, and for receptors at specific locations of potential off-site exposure. These receptors and off-site locations, described in the Dose Assessment white paper, include:

- Travelers on Interstate-80 which passes 4 km to the north of the site;
- Travelers on the main east-west rail line which passes 2 km to the north of the site;
- The resident caretaker present at the east-bound Grassy Mountain (Aragonite) Interstate-80 rest area 12 km to the northeast of the site;
- Recreational users of the Knolls OHV area (BLM land that is specifically managed for OHV recreation) 12 km to the west of the site; and,
- Workers at the Utah Test and Training Range (UTTR, a military facility) to the south of the Clive facility, who may occasionally drive on an access road immediately to the west of the Energy*Solutions* fenceline.

These five locations are shown in Figure 2. A uniform Cartesian grid using 1-km$^2$ resolution grid cells was employed in the AERMOD air dispersion modeling to support calculation of air concentrations at the first four locations. This grid was constructed of 299 grid cells (23 grid cells longitudinally by 14 grid cells latitudinally).

To support the estimation of air concentrations above the disposal embankment and particle deposition onto the embankment, AERMOD was also run with a smaller 0.3-km$^2$ grid size, which corresponds to the area of the disposal embankment. In this AERMOD simulation, one grid cell was centered directly above the 0.3-km$^2$ area emissions source representing the embankment. The results for this grid cell were also applied to the UTTR access road, which is in close proximity to the disposal embankment.

## 6.2 AERMOD Results for Air Concentrations and Off-Site Deposition

Two sets of simulations were conducted using AERMOD; one to estimate air concentrations and total deposition of particulates, and a second to estimate gas concentrations at the specified receptor locations in Section 8. The air concentration outputs (particulate and gas) from AERMOD were then used to calculate $\chi/Q$ ratios, which are the ratio of breathing-zone air concentration ($\chi$) to the emission rate ($Q$) used in the AERMOD simulations (Section 10). These $\chi/Q$ ratios are then employed in the GoldSim model for each receptor location by multiplying $\chi/Q$ by the gas or particle emission rate generated in the model. Particle deposition rates from AERMOD were used to calculate the fraction of particulates that are redeposited on the embankment (Section 15). This off-site deposition fraction was used in conjunction with the particle emission rate generated in the model to calculate the mass of embankment particles deposited onto the off-site air dispersion area over time.


**Figure 2. Off-site air dispersion locations (Note: red line is the rail; green line is UTTR access road).**

### 6.2.1 AERMOD Simulated Air Concentrations and Chi/Q Values

As described in Section 8, AERMOD was run using either a 0.3-km$^2$ or a 1.0-km$^2$ resolution grid, depending on whether the air concentrations above the embankment or at distant off-site locations were simulated. A consideration in the air dispersion modeling is the elevation of the area source. For modeling air concentrations in the breathing zone above an area source, it is necessary to define a zero meter-elevation release height in AERMOD. For modeling air concentrations at the locations of distant off-site receptors, however, the disposal embankment is more accurately represented as an area source with a 15-m release height (where 15 m is the approximate height of the gently sloping top of the embankment).

An assumed $PM_{10}$ emission rate of 0.25 g/sec was used for all AERMOD simulations. This value corresponds to an area flux of approximately 0.025 kg/m$^2$-yr, which is near the upper end of $PM_{10}$ emission rates derived using Cowherd et al (1985) (see Section 17). The AERMOD results are used to develop $\chi/Q$ ratios, which in principle are independent of the specific emission rate used in the simulations. The emission rate input to AERMOD was varied over several orders-of-magnitude, and it was confirmed that the ratio $\chi/Q$ is independent of emission rate.

The relative mass associated with two particle size fractions within the $PM_{10}$ category can be distinguished in AERMOD: 0 to 2.5 micron particle diameter, and 2.5 to 10 micron particle diameter. The actual particle size distribution of future $PM_{10}$ emissions from the embankment is unknown. To explore the influence of particle size fraction on on-site and off-site $PM_{10}$ air concentrations, the mass of particles in the two categories for a series of eight simulations was varied as presented in Table 2:

**Table 2. Allocation of particle mass in particle size fraction bins for PM10 emissions.**

| Simulation | 0 to 2.5 microns | 2.5 to 10 microns |
|---|---|---|
| 1 | 0% | 100% |
| 2 | 5% | 95% |
| 3 | 10% | 90% |
| 4 | 20% | 80% |
| 5 | 40% | 60% |
| 6 | 60% | 40% |
| 7 | 80% | 20% |
| 8 | 100% | 0% |

Note that these fractions represent fine particle fractions only, and assume that less than 10% of the particle emissions is composed of dust greater than or equal to 10 microns in diameter.

The AERMOD particulate simulations in Table 2 were conducted using meteorological input data for year 2009, as previously discussed. Additional simulations were conducted using meteorological data from 2003, 2004, 2006, and 2007. The differences in modeled air concentrations among the five data sets was minimal. Uncertainty related to meteorological conditions is overwhelmingly due to extrapolating current conditions (as represented by any of these five years) to the 10,000-year performance period, which is not possible to quantify at this time. Therefore, uncertainty related to the slight differences in AERMOD results based upon the five data sets has not been propagated in the GoldSim PA model.

As described above, two sets of simulations were conducted at different spatial resolutions (0.3-$km^2$ and 1.0-$km^2$) for the particle size fractions outlined in Table 2. The outputs from these simulations are summarized in Table 3.

The AERMOD input emission rate and the air concentration outputs from AERMOD were then used to construct $\chi/Q$ ratios for each receptor, as shown in Table 4. The $Q$ term for this ratio is 0.25 g/sec, as described above. The $\chi$ term ($\mu g/m^3$) is from Table 3. These $\chi/Q$ ratios were then directly imported into the GoldSim PA model. For each model realization, one of the eight simulations is selected and the associated $\chi/Q$ ratios are used in the dose calculations. Differences among the eight sets of $\chi/Q$ ratios represent uncertainty in the particle size distribution of future $PM_{10}$ emissions from the embankment.

**Table 3. Air concentration estimates (ug/m3 of PM10) by location and particle diameter fraction; 0.25 g/s emission rate.**

| Simulation | Knolls OHV Area | Grassy Mt. (Aragonite) Rest Area | I-80 | Railroad | Embankment | UTTR Access Road |
|---|---|---|---|---|---|---|
| 1 | 0.011 | 0.0017 | 0.065 | 0.11 | 56 | 56 |
| 2 | 0.011 | 0.0017 | 0.066 | 0.11 | 56 | 56 |
| 3 | 0.011 | 0.0017 | 0.066 | 0.11 | 56 | 56 |
| 4 | 0.011 | 0.0017 | 0.067 | 0.11 | 56 | 56 |
| 5 | 0.012 | 0.0018 | 0.068 | 0.11 | 57 | 57 |
| 6 | 0.013 | 0.0018 | 0.069 | 0.11 | 58 | 58 |
| 7 | 0.014 | 0.0018 | 0.070 | 0.11 | 59 | 59 |
| 8 | 0.015 | 0.0019 | 0.071 | 0.11 | 59 | 59 |

Concentration estimates for the Embankment and UTTR Access Road receptors are based on simulations conducted at 0.3-km$^2$ resolution. All other concentrations correspond to simulations conducted at 1.0-km$^2$ resolution. Values for I-80 and Railroad are the largest values for any grid cell containing these features (i.e. at points close to the Clive facility). Note that the simulation numbers in this table correspond to the particle diameter fractions in Table 2.

**Table 4. Receptor-specific $\chi/Q$ ratios for PM10 particulates.**

| Simulation | Knolls OHV Area | Grassy Mt. (Aragonite) Rest Area | I-80 | Railroad | Embankment | UTTR Access Road |
|---|---|---|---|---|---|---|
| 1 | 0.043 | 0.0069 | 0.26 | 0.43 | 222 | 222 |
| 2 | 0.044 | 0.0069 | 0.26 | 0.43 | 223 | 223 |
| 3 | 0.044 | 0.0069 | 0.26 | 0.43 | 224 | 224 |
| 4 | 0.046 | 0.0070 | 0.27 | 0.43 | 225 | 225 |
| 5 | 0.049 | 0.0071 | 0.27 | 0.43 | 228 | 228 |
| 6 | 0.052 | 0.0072 | 0.28 | 0.44 | 231 | 231 |
| 7 | 0.055 | 0.0073 | 0.28 | 0.44 | 234 | 234 |
| 8 | 0.058 | 0.0074 | 0.28 | 0.44 | 238 | 238 |

$\chi/Q$ ratios for the Embankment and UTTR Access Road receptors are based on simulations conducted at 0.3-km$^2$ resolution. All other off-site receptors correspond to simulations conducted at 1.0-km$^2$ resolution. Values for I-80 and Railroad are the largest values for any grid cell containing these features. Note that the simulation numbers in this table correspond to the particle diameter fractions in Table 2.

As described in Section 2, air concentrations of gases in the off-site air dispersion area are based on air dispersion of gas emissions from the cap. The size and basis of the off-site air dispersion

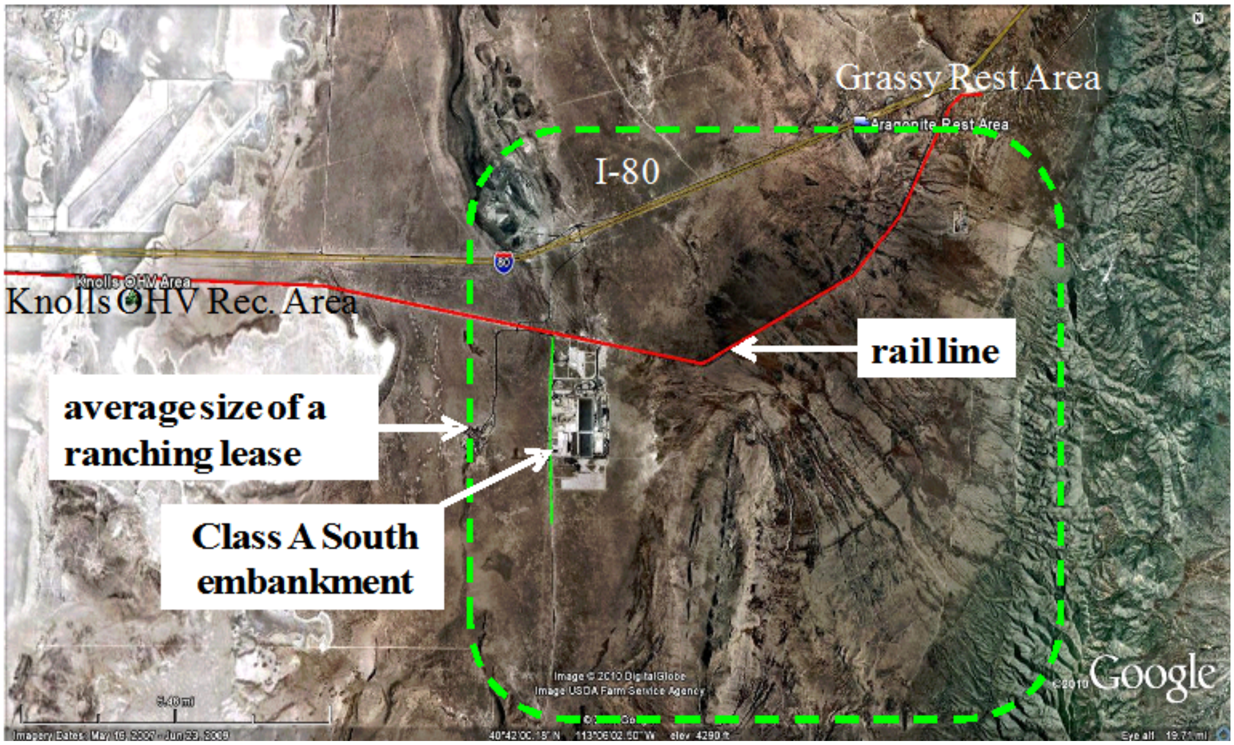


Figure 3) is discussed in the *Dose Assessment* white paper, and is that area surrounding the embankment in which ranchers and recreationists may be exposed to contaminants originating from the embankment.

Radon-222 is the only gas-phase radionuclide evaluated in the Clive PA model. Breathing zone concentrations of radon-222 in the off-site air dispersion area are based on releases from the cap, rather than evolution from any radium-226 deposited with particulates in dispersion area surface soil, because the former will be by far the more significant source. Radon transport in the embankment is discussed in the *Unsaturated Zone Modeling for the Clive PA* white paper.

Radon-222 air concentrations in the off-site air dispersion area have been calculated based on the smallest potential size of this area (16,000 acres, or approximately 65 $km^2$). The gas concentration in air for this area was calculated as the arithmetic average of the gas concentrations in the 65 AERMOD 1-km grid areas with the highest concentrations.

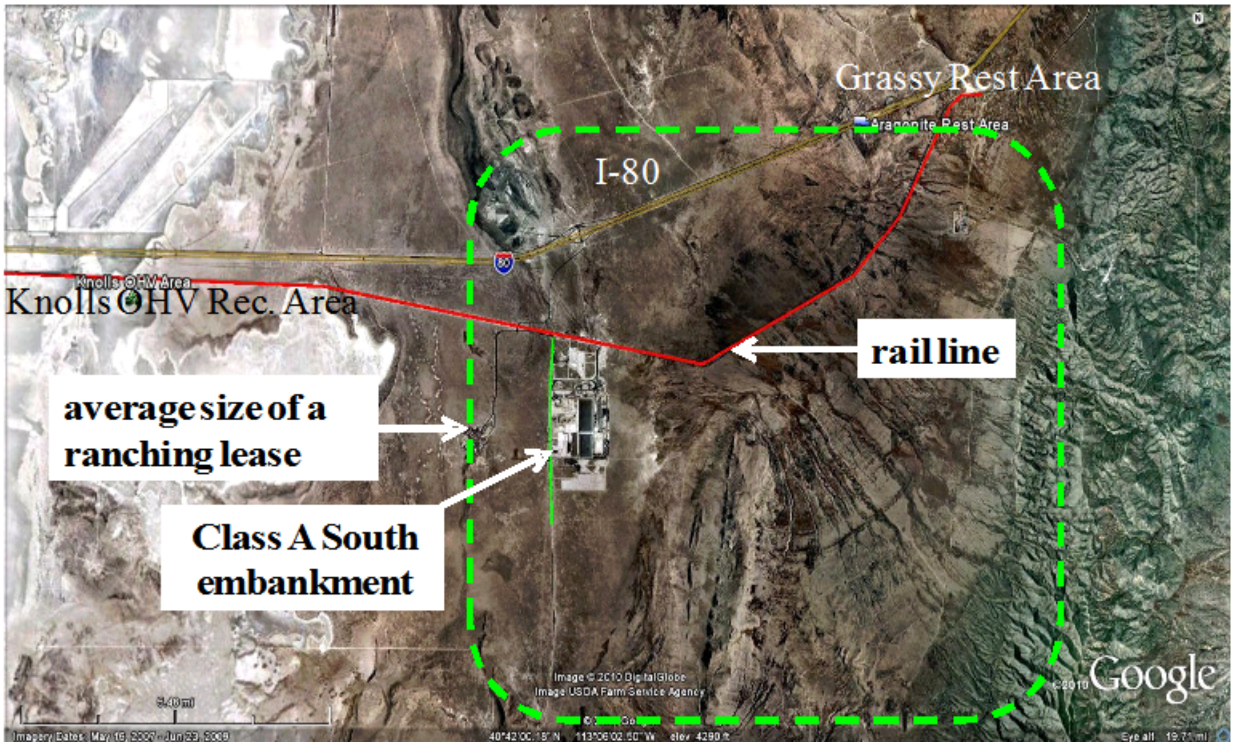


**Figure 3. Off-site air dispersion area (approximate dimensions of largest receptor exposure area shown as dashed green line).**

Radon-222 air concentrations were estimated using the gas deposition module in AERMOD for the embankment and the 5 other receptor locations described in Section 8. Similar to estimating air concentrations for $PM_{10}$ dust, these simulations were conducted with a 0-m elevation source for a 0.3-km$^2$ grid size (over the embankment and for the adjacent UTTR access road) and a 15-m elevation source with a 1.0-km$^2$ grid size (all other receptor locations). However, only one simulation each was conducted for radon gas dispersion because uncertainty related to particle size fraction is inapplicable to gases.

The input parameters required by AERMOD include diffusivity of the modeled gas in air and water, cuticular resistance, and Henry's Law constant. For radon diffusivity in air, a value of 0.11 cm$^2$/sec was assumed (Rogers and Nielson, 1991; Nielson and Sandquist, 2011). For radon diffusivity in water, a value of 100,000 cm$^2$/sec was assumed (Volkovitsky, 2004), while Henry's Law constant was assumed to be 0.0093 mol/kg-bar (NIST, 2011). The landcover properties were assigned the default values from AERMOD corresponding to category 8, or "barren land, mostly desert". Cuticular resistance, a measure of gas uptake by plants, was set to an arbitrarily low value of 0.1 sec/cm because this parameter was expected to have little influence for AERMOD simulations in a desert environment. The low influence of the value of cuticular resistance on modeled gas concentrations was confirmed by setting the value to 100 sec/cm and observing no change in radon air concentrations. As with particulates, radon air concentrations were simulated using meteorological data for year 2009.

Table 5 presents the output air concentrations for radon for each receptor location and their associated $\chi/Q$ ratios that are input into the GoldSim model.

**Table 5. Radon air concentrations (0.25 g/s emissions) and χ/Q ratios for each receptor location.**

| Receptor Location | Air Concentration (μg/m$^3$) | $\chi/Q$ ratio (μg/m$^3$ per g/s) |
|---|---|---|
| Embankment (OnSite) | 59 | 234 |
| Knolls OHV Area | 0.013 | 0.053 |
| Grassy Mt. (Aragonite) Rest Area | 0.0022 | 0.0088 |
| I-80 | 0.070 | 0.28 |
| Railroad | 0.11 | 0.44 |
| UTTR Access Road | 59 | 234 |
| Off-Site Exposure Area | 0.096 | 0.38 |

χ/Q ratios for the Embankment and UTTR Access Road receptors are based on simulations conducted at 0.3-km$^2$ resolution. All other off-site receptors correspond to simulations conducted at 1.0-km$^2$ resolution. Values for I-80 and Railroad are the largest values for any grid cell containing these features.

### 6.2.2 AERMOD Off-Site Particulate Deposition

In addition to calculating air concentrations of gases and particulates, AERMOD was used to calculate the fraction of annual mass deposition (g/yr) of resuspended embankment particles outside the perimeter of the embankment. The total mass of deposited particulates within AERMOD is a function of the size of the grid area, and is therefore only approximated with a finite grid area. However, suspended particle re-deposition on the embankment is available as an output of AERMOD using the 0.3-km$^2$ grid size described in Section 8. The fraction of total particulate mass deposited outside the embankment area can be calculated by mass balance as:

$$Dep_{off\text{-}site} = 1 - (Dep_{site} / E_{site}) \tag{4}$$

where:

$Dep_{off\text{-}site}$ is the fraction of annual $PM_{10}$ emissions deposited beyond the embankment;

$E_{site}$ is the annual-average $PM_{10}$ emission rate per unit area of contaminated soil (g/m$^2$·yr); and,

$Dep_{site}$ is the annual deposition rate of resuspended site $PM_{10}$ within the site perimeter per unit area of contaminated soil ($g/m^2 \cdot yr$).

The majority of $PM_{10}$ particulates deposited outside the embankment are carried by atmospheric transport to regions far beyond the vicinity of the embankment. The fraction of all $PM_{10}$ emissions that is deposited within the combined area of the embankment and the largest potential size of the off-site dispersion area (64,000 acres, or 260 $km^2$; see the *Dose Assessment* white paper) varies depending on $PM_{10}$ particle size fraction (see Table 2) between approximately 4% and 11%.

The remaining $PM_{10}$ mass (89% to 96%) can be expected to be deposited over some very large region outside the receptor grid at rates no greater than the low values that were calculated with AERMOD near the receptor grid boundaries. The exact size of this region is influenced by regional atmospheric conditions and terrain features. At distances beyond approximately 20 to 50 km, AERMOD is unsuitable for air dispersion modeling and a long-range regional model would be required for quantifying concentrations and deposition rates. The fraction of total particulate mass deposited within the off-site exposure area is calculated as:

$$Dep_{\textit{off-site dispersion area}} = f_{local} \times Dep_{\textit{off-site}} \tag{5}$$

where:

$f_{local}$ is the fraction of annual $PM_{10}$ deposition occurring within the off-site dispersion area (see Table 6, Column 4); and ,

$Dep_{\textit{off-site}}$ is the fraction of annual $PM_{10}$ emissions deposited beyond the embankment from Equation 4.

To estimate the total amount of particulate matter deposited on the disposal embankment ($Dep_{site}$) for Equation 4, AERMOD simulations were performed using the 0.3-$km^2$ resolution grid for each of the eight particle size fraction combinations given in Table 2. Table 6 presents the AERMOD output for total deposition over the disposal embankment. To estimate the amount of redeposited material, the total mass emitted on an annual basis was calculated based on the AERMOD input emission rate of 0.25 g/sec. The total annual mass of particulates emitted each year from the source area is therefore 7,884,000 g. The total mass of particulate matter deposited per square meter over the embankment (Table 6, Column 2) was then divided by the annual mass emitted to give an estimate of on-site redeposition of particulate matter (Table 6, Column 3) for each of the eight simulations. These results were integrated into the GoldSim PA model in a manner analogous to that described for particle air concentrations in Section 10.

**Table 6. Total deposition of PM10 particulate matter on the disposal embankment.**

| *Simulation* | *Total Deposition ($g/m^2$-yr)* | *On-site redeposition ($g/m^2$-yr per g/yr)* | *Fraction off-site deposition occurring in off-site exposure area* |
|---|---|---|---|
| 1 | 3.3 | 4.2E-07 | 0.11 |
| 2 | 3.2 | 4.1E-07 | 0.11 |

| | | | |
|---|---|---|---|
| 3 | 3.2 | 4.0E-07 | 0.11 |
| 4 | 3.0 | 3.8E-07 | 0.099 |
| 5 | 2.6 | 3.3E-07 | 0.086 |
| 6 | 2.2 | 2.8E-07 | 0.072 |
| 7 | 1.8 | 2.3E-07 | 0.057 |
| 8 | 1.4 | 1.8E-07 | 0.041 |

## 6.3 Confirmation of AERMOD Results with CAP-88

Version 3 of the CAP-88 air dispersion model was used to confirm the results of the AERMOD simulations. The purpose of this comparison was to perform a quality assurance check on AERMOD data preparation. As described in Section 7, two types of STAR files for input of meteorological data to CAP-88 were prepared by MSI. The variability in CAP-88 results using STAR-ST vs STAR-SR files was about 10-20%, and a number of user input variables (such as the height of the tropospheric “lid” on mixing) were set at default values. On the AERMOD side, air concentrations and particle depositions varied by up to a factor of two depending on the particle size fractions assumed for emissions (see Table 3). Particle size fraction for the emission rate is not a variable input in the CAP-88 model. These sources of variance are in addition to the underlying differences in the model frameworks. AERMOD does not employ atmospheric stability class categories and troposhere "lid" inputs but instead implements planetary boundary layer methods of estimating atmospheric mixing. Therefore, comparison of AERMOD results with CAP-88 results is considered on an order-of-magnitude scale, where results within a factor of 10 or less of each other may be considered nominally equivalent.

Both AERMOD and CAP-88 output air concentrations and ground deposition rates, although with AERMOD these results are integrated over a receptor grid cell while in CAP-88 they are associated with specific x,y coordinates. Particle deposition rates were selected as the output for this comparison. CAP-88 results were obtained for distances of 1 km, 5 km, and 10 km from the embankment at each of 16 orientations (N, NNW, NW, WNW, etc). Particle deposition results from AERMOD grid cells overlapping these coordinates were identified. A comparison of these results for the four cardinal directions is shown in Table 7.

**Table 7. Comparison of CAP-88 and AERMOD particle deposition results (g/m2-yr).**

| Direction | Distance (km) | CAP-88 deposition | AERMOD deposition | Ratio CAP-88 / AERMOD |
|---|---|---|---|---|
| N | 1 | 0.14 | 0.11 | 1.2 |
| N | 5 | 0.015 | 0.016 | 0.92 |
| N | 10 | 0.0054 | 0.0047 | 1.2 |
| W | 1 | 0.13 | 0.097 | 1.3 |
| W | 5 | 0.013 | 0.0037 | 3.5 |

| | | | | |
|---|---|---|---|---|
| W | 10 | 0.0045 | 0.00084 | 5.3 |
| S | 1 | 0.082 | 0.099 | 0.83 |
| S | 5 | 0.0081 | 0.0096 | 0.85 |
| S | 10 | 0.0029 | 0.0033 | 0.89 |
| E | 1 | 0.042 | 0.21 | 0.20 |
| E | 5 | 0.0042 | 0.0045 | 0.93 |
| E | 10 | 0.0015 | 0.00056 | 2.7 |

Of the 12 comparisons shown in Table 7, CAP-88 and AERMOD particle deposition results were within a factor of two for all but four results. The largest discrepancies were approximately a factor of five, for the 10-km distance to the west and the 1-km distance to the east. This comparison indicates that that there is relatively low variability between the CAP-88 and AERMOD results considering the differences between these models, and suggests that the AERMOD results are reliable.

## 6.4 Implementation of Cowherd Unlimited-Reservoir Resuspension Model

A range of input parameter values for the unlimited-reservoir particle resuspension model were employed to evaluate the possible particle emission rates. Input parameters include fraction of vegetative cover ($V$), average annual wind speed ($u$), surface roughness height ($z_0$), the unadjusted threshold friction velocity ($u_t$), and the friction velocity adjustment factor. The range of potential adjustment factors is shown in Figure 3-5 of Cowherd et al (1985). High-end, middle, and low-end estimates (based on impact to the calculated emission rate ($E_{10}$) are shown in Table 8 and discussed in the following paragraphs.

**Table 8. Range of input parameter values for particle resuspension modeling.**

| Parameter | units | High $E_{10}$ | Middle $E_{10}$ | Low $E_{10}$ |
|---|---|---|---|---|
| vegetative cover ($V$) | – | 0.058 | 0.172 | 0.318 |
| average annual wind speed ($u$) | m/s | 3.20 | 3.14 | 3.10 |
| surface roughness height ($z_0$) | cm | 5 | 3.5 | 2 |
| unadjusted threshold friction velocity ($u_t$) | m/s | 0.1 | 0.25 | 0.7 |
| Friction velocity adjustment factor | – | 3 | 4 | 5 |

Values for the range of $V$ are based on means for each of the five plant communities evaluated in test plots near the disposal facility site. The range of $u$ is based on review of five years of Clive meteorological data. High-end and low-end values are approximate. Values of $z_0$ are based on Figure 3-6 of Cowherd et al (1985). The value for High $E_{10}$ is a slightly larger $z_0$ than that of a wheat field and comparable to "suburban dwellings". This is possibly analogous to widely spaced shrubs. The $z_0$ of 2 is the lower part of the range for "grassland".

Estimates for $u_t$ are the most critical for calculating particle erosion. The range of other parameters can be estimated, whereas the outcome of soil development on the cap after many millenia (with respect to particle size distribution, formation of soil crust, amount of projecting rip rap, etc) is essentially unknown. However, based upon professional judgment, the values used here are based on examination of Figure 3-4 of Cowherd et al (1985). The value of High $E_{10}$ is a factor of 10 below the lowest value for aggregate size distribution (100 µm) shown on the scale, or 10 µm. This corresponds, by extending the linear function in Figure 3-4, to a $u_t$ value of 0.1 m/s. The value of Low $E_{10}$ corresponds to an aggregate erodible particle size distribution mode of ~1 mm (1,000 µm). The middle value equates to a 100 µm size. The High $E_{10}$ value equates to an aggregate particle diameter smaller than that of silt-size particles (0.05 mm), below which one may presume a more crusted surface that is not associated with an unlimited-reservoir erosion model. For the Low $E_{10}$ value, an aggregate diameter of 1 mm suggests a relatively large contribution from weathering of rip rap and particle aggregation.

The $u_t$ adjustment factor estimates were developed based on correlation of expected cap conditions with photographs in Appendix A of Cowherd et al (1985). Figure A-3, was selected as the best representation of the likely future cap surface. The associated value of 5 for Figure A-3, however, is approximately equal to the upper end of the range of adjustment factors shown in Figure 3-5 of Cowherd et al (1985). Therefore, to capture some range of possible values, factors of 3, 4, and 5 were used for High $E_{10}$, Mid $E_{10}$, and Low $E_{10}$ calculations, respectively. Adjustment factors shown in Figure 3-5 span a range between 1 and 7, with the function steepening rapidly between values of 2 and 7.

The average-annual $PM_{10}$ emission rates ($E_{10}$) calculated using Equation 1 are as follows:

- High $E_{10}$: 0.30 kg/m$^2$-yr;
- Mid $E_{10}$: 2.5E-07 kg/m$^2$-yr; and,
- Low $E_{10}$: 1.4E-94 kg/m$^2$-yr.

Because the middle value is effectively zero, these results were represented in the GoldSim PA model using a log-uniform distribution with boundaries of 2.5E-07 and 0.30 kg/m$^2$-yr.

# 7.0 Electronic Reference

Atmospheric Modeling Appendix.pdf

This file contains graphical output of air concentrations and particulate deposition related to the AERMOD simulations described in this white paper.

# 8.0 References

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