Stochastic Radionuclide Distributions After a Basaltic Eruption for Performance Assessments of Yucca Mountain

Mark S. Jarzemba

The Center for Nuclear Waste Regulatory Analyses

Southwest Research Institute

6220 Culebra Road

San Antonio, TX 78238-5166

Telephone: (210) 522-6828

Fax: (210) 522-5155

Internet: mjarzemba@smtp.cnwra.swri.edu

ABSTRACT

The assessment of long-term isolation performance for a geologic repository requires the use of mathematical models that consider the probability and consequences of postulated disruptive scenarios. In the case of the proposed repository at Yucca Mountain, Nevada, volcanism is one of the important disruptive scenarios being considered in site evaluation. A stochastic modeling approach is developed for use in simulating the airborne release of radioactive particulates associated with the basaltic volcanism scenario. The modeling approach in this paper considers such factors as the eruption energetics, eruption duration, wind velocity, and particle properties to compute the activity areal density as a function of spatial location. Various components of the model are based on empirical relationships and data that are reported for observed and monitored cinder cone eruptions analogous to those that likely occurred in the Yucca Mountain region in the past. Illustrative applications of the stochastic model are presented for the cases of a single event realization and a multiple-event average realization.

INTRODUCTION

The proposed High-Level Radioactive Waste (HLW) repository at Yucca Mountain (YM), Nevada is located within an area of past volcanic activity. This volcanic field consists of eight basaltic cinder cones formed by volcanic activity within the last one million years, and numerous cinder cones formed within the last 5 million years (1,2,3,4,5,6). As is typical for volcanic fields of this kind located throughout western North America, volcanic activity in the YM region is best characterized by the formation of new cinder cones at a low recurrence rate. Recent estimates of the probability of a new basaltic cinder cone forming within the area of the proposed repository range from 0.0001 to 0.0005 for a 10,000-yr period (7,8,9,10,11). Although probability estimates will likely be refined, current estimates are large enough to be of regulatory concern and must be addressed in Performance Assessment (PA). Also, if recent recommendations for an environmental standard for YM are adopted (12), the period of regulatory concern may be extended to the order of a million years, and volcanic release mechanisms may become more important in PAs of YM.

Basaltic volcanism can encompass a variety of eruption styles, depending on the eruption energy. The energy of basaltic eruptions varies from effusive activity, in which the predominant product is lava flows, to explosive activity, which results in fragmentation of the magma into scoria fragments and transport of scoria in the atmosphere as pyroclasts. This latter style of activity generally results in the formation of cinder cones, such as those found in the YM region. Explosive volcanic activity of this kind has the potential to cause the dispersal of radionuclides through the biosphere. The dispersion of radionuclides resulting from volcanic activity can be modeled using approaches originally developed to model the dispersal of ash after volcanic eruptions (13).

BACKGROUND

To assess the hypothetical radiation doses that would occur after a basaltic eruption, the distribution of radionuclides in the biosphere after such an event needs to be estimated. To estimate

the distribution of radionuclides, it is assumed that the ash particles from the eruption are the carriers of the radionuclides. Methods used previously to estimate radionuclide dispersal by volcanism are based on the assumption that the ash cloud travels with a gaussian plume that is released at a stack height of one half of the volcanic column height (14). Application of the gaussian plume model is based on the assumption that a plume of contaminants travels in the same direction as the prevailing wind (x-direction), but may be somewhat depressed toward the earth surface due to gravitational settling. The contaminants in the plume follow a gaussian distribution in the dimensions perpendicular to the direction of travel (y and z directions). The gaussian plume model is suitable for modeling airborne and ground concentrations of contaminants for a point source release of contaminants at some point above the earth surface (the stack height). However, a point source approximation may not be appropriate for a volcanic eruption because a volcanic eruption column is a continuous source of contaminants in the upward direction. Also, the gaussian plume model does not accurately account for the effects of gravitational settling of volcanic particles with large diameters (on the order of centimeters). This shortcoming may lead to the gaussian plume model predicting much greater particle ranges than would be the case in reality, and hence wider radionuclide distributions than would normally be expected after a basaltic eruption. This wider distribution of radionuclides may tend to underestimate the radiation exposure of persons in a critical group. The critical group is defined as a small, homogenous group (generally ones to several tens of people) who are at the highest risk of incurring additional health effects from the proposed repository. This approach has recently been recommended as the standard of measuring compliance for YM (12).

Models to predict the distribution of ash after an eruption have been developed with the intention of relating eruption magnitude to ash dispersion (13,15,16). In this paper the model described in (13) that relates eruption magnitude to ash distribution is modified to relate eruption magnitude to radionuclide distribution for YM based on a few simple assumptions. The model

described in this paper uses Monte Carlo sampling to determine the power and duration of the eruption, along with other properties of the ash particulates, and develops a radionuclide distribution from those sampled parameters. The radionuclide distribution can then be used to model dose to man.

Following the approach of (13), it is assumed that energy is released steadily for the duration of the eruption. This assumption is valid for high mass flow eruptions that are relatively brief in duration. Typically, basaltic cinder cones are active over periods of several months to years . During this period of activity, individual eruptions occur during which activity is well characterized by steady eruption columns. For example, during the nine-year eruption of Paricutin, Mexico, the volcano experienced a generally low-level of activity, punctuated by short periods of energetic, steady-state eruptive activity that lasted for hours to weeks, and during which an ash column continuously emanated from the cinder cone. Most of the ash dispersed by Paricutin erupted during these short intervals of steady eruption (17). Similar periods of energetic, steady-state activity are reported during most cinder cone eruptions (18,19,20). This type of activity is variously termed violent strombolian, plinian,or sub-plinian. Some eruptions at cinder cones are not well represented by steady-state eruption models. These include normal strombolian eruptions, phreatic and phreatomagmatic eruptions. Such eruptions are best represented as detonations or short explosions (21). In general, normal strombolian activity will produce a less dispersed ash blanket. The model in (13) does not capture ash dispersion related to this style of activity.

The model developed by (13) is appropriate for particles of mean diameter greater than about 15 to 30 micrometers. This cutoff is generally accepted to be the lower limit for the importance of gravitational settling of particles (22,23). For particle sizes less than about 15 micrometers, atmospheric turbulence is great enough to keep the particle aloft for a longer time than would be predicted by the model. Since the typical mean diameter of ash particles after an eruption is generally much larger than 15 micrometers (13), this model is useful for calculating the distribution for the vast

majority of ash, and hence radionuclides released. The ramifications of the health effects to the public of the smaller particles could be explored in future investigations.

MODEL

The model described in (13) can be summarized by the equation that describes the areal density of accumulated ash on the earth's surface after an eruption:

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

where:

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

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

ρ_{min} = The minimum value of ρ.

ρ_{max} = The maximum value of ρ.

z = The vertical distance from the ground surface, km.

H = The height of the eruption column above the vent, km.

x = The x coordinate on the earth's surface, cm. This coordinate is oriented in the same direction of the prevailing wind.

y = The y coordinate on the earth's surface, cm. This coordinate is oriented perpendicular to the direction of the prevailing wind.

Q = The total quantity of erupted material, g.

$P(z)$ = The probability density function for particle diffusion at height within dz about z.

$f(p)$ = The probability density function for particles with a log-diameter within dp about p.

C = A constant relating the eddy diffusivity and the particle fall time, cm^2 per $s^{5/2}$.

t = The particle fall time, s.

t_s = The particle diffusion time in the eruption column, s.

u = The wind speed, cm per s.

The assumptions that were used in (13) to derive Equation (1) are that; (i) the erupted material consists of a finite quality of volcanic particles, (ii) the distribution of the diameter of the released particles has a single mode, (iii) all of the particles fall at the terminal velocity and finally accumulate on the ground, and (iv) the particles have a probability to diffuse out of the eruption column during their upward travel in the column. These assumptions are more realistic for modeling volcanic releases of radionuclide than the assumptions used in the gaussian plume model (i.e. a point source of radionuclides released at a single height above the vent) provided that the ash particles are the carrier media for the released radionuclides.

The probability density distribution function $P(z)$ is given by (13):

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

where

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

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

β = A constant controlling the diffusion of particles in the eruption column.

W_0 = The volcanic eruption velocity at the vent exit, cm per s.

$W(z)$ = The particle velocity as a function of height.

$$= W_0 \left[1-\frac{Z}{H}\right]$$

V_0 is the particle terminal velocity at sea level. This quantity is given by (13):

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

where:

ψ_a, ψ_p = The density of the air and particles, respectively, g per cm^3.

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

η_a = The viscosity of air in g per cm-s.

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

The particle fall time is given by (13):

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

where t is in s, V_0 is in cm per s and z is in km above the vent. The size distribution of the logarithm of particle size is given by a gaussian distribution (13):

$$f(\rho) = \frac{1}{\sqrt{2\pi}\,\sigma_d} \exp\left[-\frac{(\rho - \rho_m)^2}{2\sigma_d^2} \right] \tag{5}$$

where σ_d is the standard deviation of ρ. For a physical derivation of Equations (1) through (5), the reader is referred to (13). Also, (13) recommends that his model be compared with field data to test its validity. This could be the subject of future investigations of the model.

In PAs, the necessary quantity to track is the radioactivity per unit area as a function of position on the earth surface after ash, released from the eruption that penetrates the proposed

repository, settles on the earth's surface. If one assumes that the total amount of activity released is uniformly concentrated per unit mass of ash, then the activity areal density on the earth surface is given by:

$$R(x,y) = X(x,y)\frac{A}{Q} \tag{6}$$

where:

$R(x,y)$ = The quantity of radioactivity per unit area accumulated at location (x,y), Ci per cm^2.

A = The total amount of radioactivity released, Ci.

The transformation given in Equation (6) could be performed on an individual radionuclide basis to provide radionuclide activity areal densities as well.

The distribution of radionuclides with the ash given in Equation (6) is based on the assumption that the radionuclides released in this event are "homogenized" with the ash particles that carry them to the biosphere, i.e. the radioactive waste is incorporated into the ash particulates without appreciably changing the properties of the particulates. Alternatively, one could think of this same assumption as if the radionuclides (i.e. spent fuel) were pulverized into particulate matter that had the same properties as the ash particles. It may also be possible to model the column as being composed of two types of ejected particles, pulverized waste particles of a given density and distribution and ash particles. As no data or reliable method exist to predict the characteristics of fragmented waste, the simple method outlined by Equation (6) is adopted in this paper. In any event, the distribution of radionuclides within the ash particles as given in Equation (6) could be revised as more information on this topic becomes available.

Given values for the model parameters, one can calculate the distribution of radioactivity after an eruption by evaluating Equations (1) through (6). To incorporate this methodology into existing PAs, the parameter distributions and interrelationships must be sampled. The following section

describes the Monte Carlo parameter sampling incorporated with this model.

PARAMETER SAMPLING

WIND SPEED AND DIRECTION

The wind velocity (speed and direction) is an important parameter for predicting the distribution of ash after an eruption. This paper uses the data found in the *Site Characterization Plan* (24) to characterize the wind velocity distribution at YM. Furthermore, the cited report contains wind information at various altitudes. For simplicity, it is assumed that the data for wind vectors at a height of 5,000-ft is sufficient to characterize the wind velocity distribution to which the entire eruption column would be exposed.

The *Site Characterization Plan* shows the percent occurrences (of 1,922 total observations) of wind direction measured at 5,000 ft above the YM site. Direction is listed in 16 angles (e.g., NNW, SSW, ENE, etc.). In addition to the percent occurrences of wind direction, the *Site Characterization Plan* also shows the average wind speed as a function of direction. These data were summarized from (25) and were obtained from observations made from 1957 to 1964. These data form the basis of the Monte Carlo sampling of wind velocity for this paper.

A uniform deviate (r_1) on [0,1] is drawn to stochastically determine the wind velocity that a volcanic eruption column would experience at YM. Depending on the value of the uniform deviate, the wind direction and the average speed in that direction are determined. Table I shows the relationship between the uniform deviate and the wind direction and average speed. The "deviate range" column is determined by the fractional observations (of the total observations) of the wind direction from (24), where deviate range is the range of values that r_1 would have to be in to sample that wind direction for a particular realization.

To calculate the wind speed, it is assumed that the wind speeds follow an exponential distribution. The exponential distribution is used as an approximation to the Weibull distribution that

is recommended by (26). The exponential distribution for wind speed is assumed to have a parameter λ that is the inverse of the average wind speed from Table I. To statistically sample the wind speed given a particular direction, another uniform, random deviate (r_2) is drawn on [0,1]. The wind speed (u) in cm per s is given by:

$$u = \frac{-\ln(1-r_2)}{\lambda(r_1)} \tag{7}$$

ERUPTION PARAMETERS

Several relationships exist in the literature that describe how eruption parameters are correlated with each other. These correlations are described in this section. (21,17,19,18) all describe volcanic eruptions in terms of their power (P) and the time duration of the eruption (T). The data for small-volume basaltic eruptions similar to those that may have occurred in the YM region in the past are summarized in Table II. It is assumed that the data contained in Table II define the ranges of values of P and T for YM. For the purposes of this paper, it is assumed that a postulated volcanic event erupts at a constant power over the duration of the event. Figure 1 shows a plot of log (P) versus log (T) for data on observed eruptions. The volcanic eruptions included in Figure 1 were chosen because of their similarity to postulated volcanic eruptions at YM. The similarity is supported by the presence of ash deposits 3 km and 6 km north of Lathrop Wells cinder cone, and ash deposits in Solitario Canyon 10 km east of the Quaternary Crater Flat volcanoes (27).

It is noted that the duration of volcanic events is one of the most easily observed parameters for the event, as is, to a lesser extent, the height of the eruption column (a direct function of volcanic

power, 21). This fact means that driving the stochastic realization from these two parameters will likely lead to the most realistic simulations of volcanic events.

The procedure to stochastically sample P and T used in the paper is to first sample log (T) from a uniform probability distribution over the range:

$$\log(T) \in [3.25\ ,\ 6.83] \tag{8}$$

With log (T) determined, a mean value, used to sample log (P) from a normal distribution, is determined from the least squares fit shown in Figure 1. The variance of log(P) (i.e. σ_P^2) is determined from the sum of the squared distances of the data points from the linear fit of the data, and is found to be 0.5. The probability distribution function, f, used to determine log(P) is given by:

$$f[\log(P)] = \frac{1}{\sqrt{2\pi}\,\sigma_P} \exp\left[\frac{\left\{\log(P)-\left[16.73-0.962\log(T)\right]\right\}^2}{2\sigma_P^2}\right] \tag{9}$$

(21) describe the following relationship between the volcanic power (P) and volcanic column height (H):

$$H = 0.0082P^{0.25} \tag{10}$$

where H is in km and P is in watts. The Hekla, 1947 (21) eruption is assumed to be a maximum power event for this type of eruption style. The maximum eruption column height of this eruption was about 24 km. This maximum height corresponds to a P of 7×10^{13} W; therefore, log(P) is limited to a maximum of 13.8 in this paper.

The literature also contains other volcanic parameter interrelationships. Assuming that the volcanic power has been determined by the means described above, the mass ejection rate of material from the volcano (Q) in g per sec is given in (28) as

$$\dot{Q} = 1{,}000 \left[\frac{H}{0.24} \right]^4 \tag{11}$$

and therefore;

$$Q = \dot{Q}T \tag{12}$$

where it has been assumed that the mass ejection rate is constant over the duration of the event. The eruption velocity at the vent exit (W_0) is given by:

$$W_0 = \frac{\dot{Q}}{\psi_p \pi r_v^2} \tag{13}$$

where r_v is the vent radius in cm. An expression for the volcanic vent radius is extracted from (29) to be:

$$\log_{10}(r_v) = -0.069 + 2\log_{10}(\psi_p) + 0.274\log_{10}(\dot{Q}) \tag{14}$$

Equations (8) through (14) describe how to determine the important volcanic parameters for calculating ash distributions (and hence radionuclide distributions) after an basaltic eruption is assumed to occur. These parameters are determined from Monte Carlo sampling that stochastically samples the volcanic energy and time duration from the stated ranges and distributions.

PARTICLE PROPERTIES

Mean Particle Diameter (d_m)

(13) gives a range of values for mean particle diameter that spans three orders of magnitude from 0.01 cm to 10 cm. In most of (13) examples, 0.1 cm is used for the mean particle diameter. Data from another source (30) for the terminal fall velocity of pyroclasts would seem to suggest that the mean particle diameter is on the order of 0.1 cm. For these reasons, it is assumed that the d_m for a volcanic event has a log-triangular distribution where the minimum common logarithm of d_m is -2.0 and the maximum common logarithm of d_m is 1.0. The median value for the common logarithm of d_m is assumed to be -1.0.

Standard Deviation of the Mean Particle Diameter (σ_d)

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

Constant Controlling Ash Dispersion (β)

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

ANALYSIS

For each Monte Carlo simulation, the right hand side of Equation (1) was evaluated numerically to calculate the distribution of the radioactive volcanic ash on the earth's surface resulting from a basaltic eruption that is assumed to disrupt the repository. The wind velocity (speed and

direction), energy of the volcanic event, and duration of the volcanic event were sampled according to the procedures outlined in the previous section. The other necessary parameters were also determined as described in the previous section. Figure 2 displays an example of the contour lines of the radionuclide areal distribution per unit radioactivity concentration in the ash [in (Ci/cm^2) per (Ci/g) or g/cm^2] on the earth surface after a basaltic eruption at the YM site occurs. Table III shows the volcanic parameters and wind velocity that were stochastically chosen in this example. Table IV shows properties that were used in this example and the example described in the following paragraph that were deterministically chosen along with the source of the information. The information shown in Figure 2 could be used to calculate the risk of additional health effects to a critical group located near the repository in Pas of YM.

The previous paragraph describes how the proposed volcanic release model would be used in a single realization of a PA code to predict areal radionuclide concentrations after a basaltic eruption. A more interesting example of the proposed model is shown when considering multiple volcanic events. Figure 3 displays the radionuclide distribution contours averaged over 200 volcanic realizations for a 140 km by 140 km square centered on the proposed repository. As one can see from Figure 3, the radionuclide contours are not circular, meaning that the critical group may not necessarily be the group located nearest the repository, if only volcanism were considered as a release mechanism. These "hot spots" would represent areas of elevated health risk to a postulated critical group from a basaltic eruption at YM. Figure 3, for example, could be helpful to an investigator attempting to determine the location of the critical group described previously.

CONCLUSION

This paper describes a method for stochastically determining the distribution of radioactive ash after an assumed eruption penetrates a proposed repository at YM. The method is intended to be used in PAs for the proposed repository to more realistically (than present methods) predict doses to a

critical group after the basaltic eruption. Calculating risks of additional health effects to the critical group is a concept that has been recently recommended as the compliance standard for YM (12). The model used in this paper is useful for calculating the distribution of radioactive particles whose mean diameter is larger than about 15 to 30 micrometers. For particles smaller than about 15 micrometers, gravitational settling is no longer the dominant mechanism in determining the distribution of ash, i.e., atmospheric turbulence is sufficient to keep the smaller particles aloft for a longer time than the model presented herein would predict. Since most ash particles have diameters that are larger than this cutoff, the model proposed in this paper should predict the radionuclide distribution for the vast majority of the radionuclides released from just such an event.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. Charles Connor, Center for Nuclear Waste Regulatory Analyses (CNWRA), and Mr. Robert Baca, CNWRA, for their technical reviews and Dr. Budhi Sagar, CNWRA, for his programmatic review of this manuscript.

This paper was prepared to document work performed by the CNWRA for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research (RES), Division of Regulatory Applications. This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory positions of the NRC.

REFERENCES

1. Bradshaw, T.K. and E.I. Smith. 1994. *Polygenetic Quaternary volcanism at Crater Flat, Nevada.* J. Volcanol. Geotherm. Res. **63**. pp. 165-182.

2. Champion, D.E. 1991. *Volcanic episodes near Yucca Mountain as determined by paleomagnetic studies at Lathrop Wells, Crater Flat, and Sleeping Butte, Nevada.* Second International Conference on High-Level Radioactive Waste Management. Las Vegas, NV, American Nuclear Society. pp. 61-67.

3. Faulds, J.E., J.W. Bell, D.L. Feuerbach, and A.R. Ramelli. 1994. *Geologic map of the Crater Flat Area, Nevada.* Nevada Bur. Mines Geol. Map **101**.

4. Heizler, M.T., W.C. McIntosh, F.V. Perry, and B.M. Crowe. 1994. *40Ar/39Ar results of incompletely degassed sanidine: age of Lathrop Wells volcanism.* U.S. Geol. Surv. Circular, **1107**, pp. 133.

5. Langenheim, V.E., K.S. Kirchoff-Stein, and H.W. Oliver 1993. *Geophysical investigations of buried volcanic centers near Yucca Mountain, southwestern Nevada.* Fourth International Conference on High-Level Radioactive Waste Management. Las Vegas, NV. American Nuclear Society. Pp. 1840-1846.

6. Sawyer, D.R., R.J. Fleck, M.A. Lanphere, R.G. Warren, D.E. Broxton, and M.R. Hudson. 1994. *Episodic caldera volcanism in the Miocene southwestern Nevada volcanic field: Revised stratigraphic framework, 40Ar/39Ar geochronology, and implications for magmatism and extension.* Geol. Soc. Am. Bull., **106**, pp. 1304-1318.

7. Crowe, B.M., and F.V. Perry. 1989. *Volcanic probability calculations for the Yucca Mountain site: estimation of volcanic rates.* Proceedings Nuclear Waste Isolation in the Unsaturated Zone, Focus '89. American Nuclear Society. pp. 326-334.

8. Connor, C.B. and B.E. Hill. 1995. *Three nonhomogeneous Poisson models for the probability of basaltic volcanism: application to the Yucca Mountain region, Nevada*. Journal of Geophysical Research **100**:10, pp. 107-10, 125.

9. Ho, C.H., E.I. Smith, D.L. Feuerbach, and T.R. Naumann. 1991. *Eruptive probability calculation for the Yucca Mountain site, USA: statistical estimation of recurrence r...* Bull. Volcanol., **54**. pp. 50-56.

10. Margulies, T., L. Lancaster, N. Eisenberg, and L. Abramson. 1992. *Probabilistic analysis of magma scenarios for assessing geologic waste repository performance*. 92-WA/SAF-11. American Society of Mechanical Engineers. New York, NY.

11. Smith, E.I., T.R. Naumann, D.L. Feuerbach, and J.E. Faulds. 1990. *The area of most recent volcanism near Yucca Mountain, Nevada: implications for volcanic risk assessment*. International Meeting on High-level Radioactive Waste Management. Las Vegas, NV. American Nuclear Society. pp. 81-90.

12. National Academy of Sciences. 1995. *Technical Bases for Yucca Mountain Standards*. National Academy Press: Washington: D.C.

13. Suzuki, T. *A Theoretical Model for Dispersion of Tephra*. 1983. Arc Volcanism: Physics and Tectonics. Terra Scientific Publishing: Tokyo, Japan, pp. 95-113.

14. Wescott, R.G., M.P. Lee, N.A. Eisenberg, and T.J. McCartin. 1995. *NRC Iterative Performance Assessment Phase 2: Development of Capabilities for Review of a Performance Assessment for a High-Level Waste Repository*. NUREG-1464. In preparation.

15. Hopkins, A.T. and C.J. Bridgeman. 1985. *A Volcanic Ash Transport Model and Analysis of Mount St. Helens Ashfall*. Journal of Geophysical Research. **90**, pp. 10,620-10,630.

16. Glaze L.S.and S. Self. 1991. *Ashfall Dispersal for the 16 September 1986 Eruption of Lascar, Chile, Calculated by a Turbulent Diffusion Model*. Geophysical Research Letters. **18**, pp. 1237-1240.

17. Luhr, J.F. and T. Simkin (eds.). 1993. *Paricutin- The Volcano Born in a Mexican Cornfield* . Geoscience Press Inc.: Phoenix: AZ.

18. Self, S., R.S.J. Sparks, B. Booth and G.P.L. Walker. 1974. *The 1973 Heimaey Strombolian Scoria deposit, Iceland* . Geol. Mag., **111**, No. 6, pp. 539-548.

19. Fedotov, S.A. and Ye.K. Markhinin (eds.). 1983. *The Great Tolbachik Fissure Eruption, Geological and Geophysical Data 1975-1976*. Cambridge University Press: New York, NY.

20. Connor, C.B., L. Powell, W. Strauch, M. Navarro, O. Urbina, and W.I. Rose. 1993. *The 1992 eruption of Cerro Negro, Nicaragua: An example of Plinian-style activity at a small basaltic cinder cone*. EOS, Transactions of the American Geophysical Union **74**:43. pp. 640.

21. Wilson, L. ,R. S. J. Sparks, T.C. Huang and N.D. Watkins. 1978. *The Control of Volcanic Column Heights by Eruption Energetics and Dynamics* , Journal of Geophysical Research, **83**:B4, pp. 1829-1836.

22. Cember, H. 1983. *Introduction to Health Physics- Second Edition*. Permagon Press: New York, NY.

23. Heffter, J.L. and B.J.B. Stunder. 1993. *Volcanic Ash Forecast Transport and Dispersion (VAFTAD) Model*. Weather and Forecasting. **8**, pp. 533-541.

24. Department of Energy. 1988. *Site Characterization Plan* ,Volume II Part A, Chapter 5, Climate and Meteorology. DOE/RW-0199. 1988. Washington D.C.

25. Quiring, R.F. 1968. *Climatological Data, Nevada Test Site and Nuclear Rocket Development Station*, ESSA Technical Memorandum ARL-7. Environmental Sciences Service Administration. U.S. Department of Commerce: Las Vegas, NV.

26. Curtis, D.C. and P.S. Eagleson. 1982. *Constrained Stochastic Climate Simulation*, Report Number 274. Massachusetts Institute of Technology: Cambridge, MA.

27. Hill, B.E., F.M. Conway, C.B. Connor and P. LaFemina. 1995. Field Volcanism Research. *NRC High-Level Radioactive Waste Research at CNWRA January through June 1995*. Budhi Sagar, ed. CNWRA 95-01S. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses: 77-1 to 7-22.

28. Walker, G.P.L., S. Self and L. Wilson. 1984. *Tarawera 1886, New Zealand- A Basaltic Plinian Fissure Eruption*. Journal of Volcanology and Geothermal Research, **21**, pp. 61-78.

29. Wilson L. and J.W. Head. 1981. *Ascent and Eruption of Basaltic Magma on the Earth and Moon*. Journal of Geophysical Research, **86**:B4, pp. 2971-3001.

30. Walker, G.P.L., L. Wilson and E.L.G. Bowell. 1970. *Explosive Volcanic Eruptions-I: The Rate of Fall of Pyroclasts*. Geophys. J. R. Astr. Soc., **22**, pp. 377-383.

31. Sears F.W., M.W. Zemansky, and H.D.Young. 1983. *University Physics - Sixth Edition*. Addison-Wesley Publishing: Reading, MA.

Table I. The range of the uniform deviate corresponding to wind direction

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

Table II. A list of the volcanic events used to extrapolate the relationship between log(*P*) and log(*T*) along with the sources of the data

Event	Information Source	log(*T*) (*T* in s)	log(*P*) (*P* in W)
Cerro Negro, 1992	Connor, et al., 1992	4.8	12.0
Hekla, 1970	Wilson et al., 1978	3.9	12.8
Tolbachik, 1975	Fedotov and Markhinin, 1983	6.1	11.7
Paricutin, 1944 I	Luhr and Simkin, 1993	5.6	9.0
Paricutin, 1944 II	Luhr and Simkin, 1993	6.8	11.5
Paricutin, 1946	Luhr and Simkin, 1993	6.8	9.0
Hekla, 1947	Wilson et al., 1978	3.3	13.8
Heimaey, 1973	Self et al., 1974	6.4	9.9

Table III. The stochastically sampled parameter values in the simulation shown in Figure 2

Parameter Description	Sampled Value
Common Logarithm of Event Time duration [Time duration (T in s)]	4.81 (6.5×10^4)
Event Power (P in W)	1×10^{12}
Vent radius (r_v in cm)	240
Mass ejection rate ($\dot{Q}$ in g/s)	1.4×10^9
Column height (H in km)	8.2
Beta (β)	0.01127
Total ash mass (q in g)	9.1×10^{13}
Mean particle diameter (d_m in cm)	0.1356
Standard deviation of particle diameter (σ_d in cm)	0.3683
Eruption velocity (W_0 in cm/s)	9670.9
Wind velocity (u in cm/s)	665.1111
Wind direction (degrees-with respect to due east)	-67.5

Table IV. The deterministically chosen parameter values used in the simulations shown in Figure 2 and Figure 3

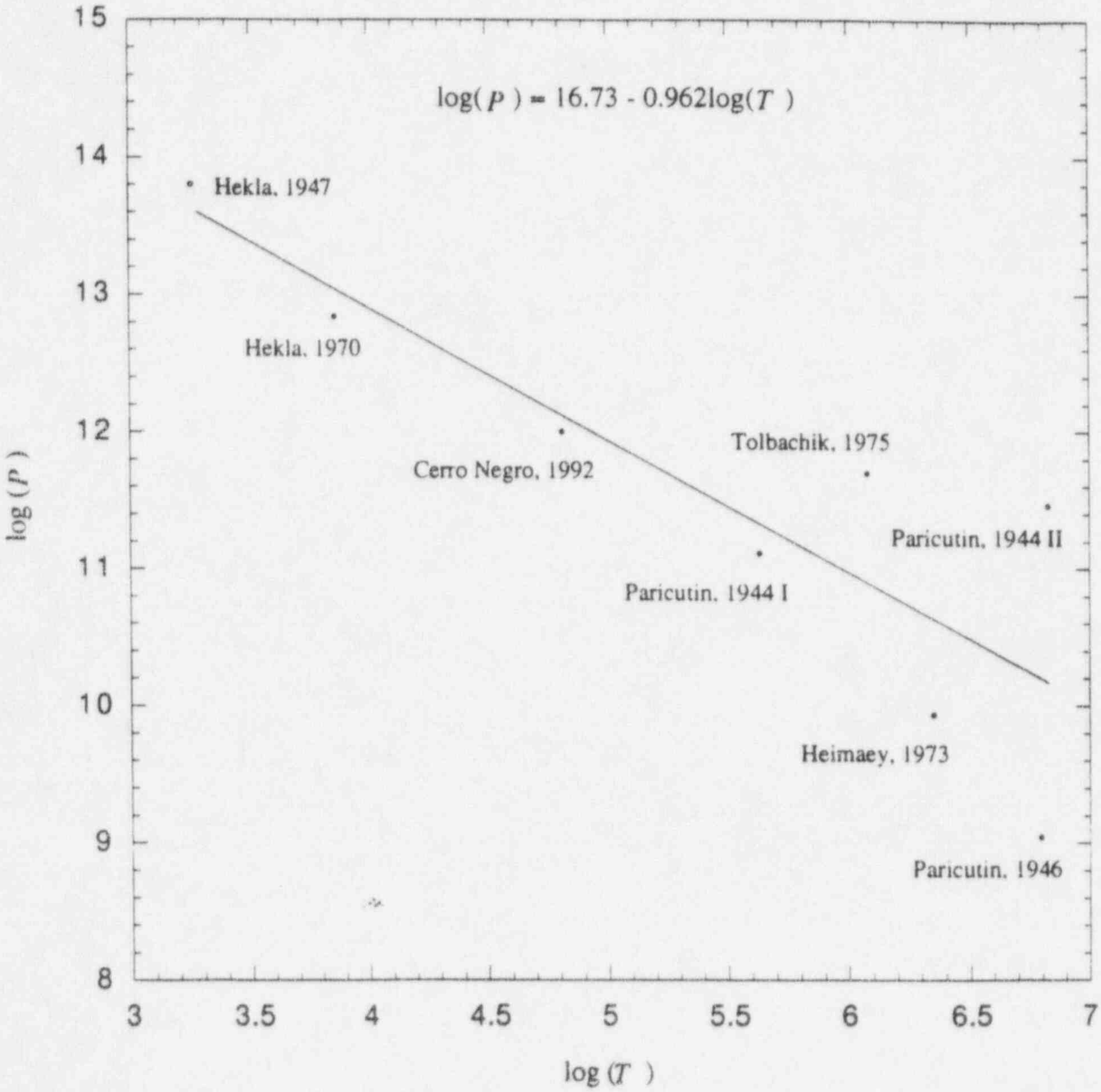
Parameter Description	Value	Source
Ash density (g/cc)	0.8	Suzuki (1983)
Shape factor	0.5	Suzuki (1983)
Air density (g/cc)	0.00129	Sears et al. (1983)
Air viscosity (g/cm-s)	0.00018	Sears, et al. (1983)
C ($cm^2/s^{5/2}$)	400	Suzuki (1983)

FIGURE CAPTIONS

Figure 1 - A plot of Log(P) versus Log(T) for several volcanoes of composition similar to that expected at Yucca Mountain.

Figure 2 - An example of the radionuclide distribution after a particular realization of the computer module.

Figure 3 - The average radionuclide distribution averaged over 200 realizations.


log(P) = 16.73 - 0.962log(T)
Hekla, 1947
Hekla, 1970
Cerro Negro, 1992
Tolbachik, 1975
Paricutin, 1944 II
Paricutin, 1944 I
Heimaey, 1973
Paricutin, 1946
log (P)
log (T)
15
14
13
12
11
10
9
8
3
3.5
4
4.5
5
5.5
6
6.5
7

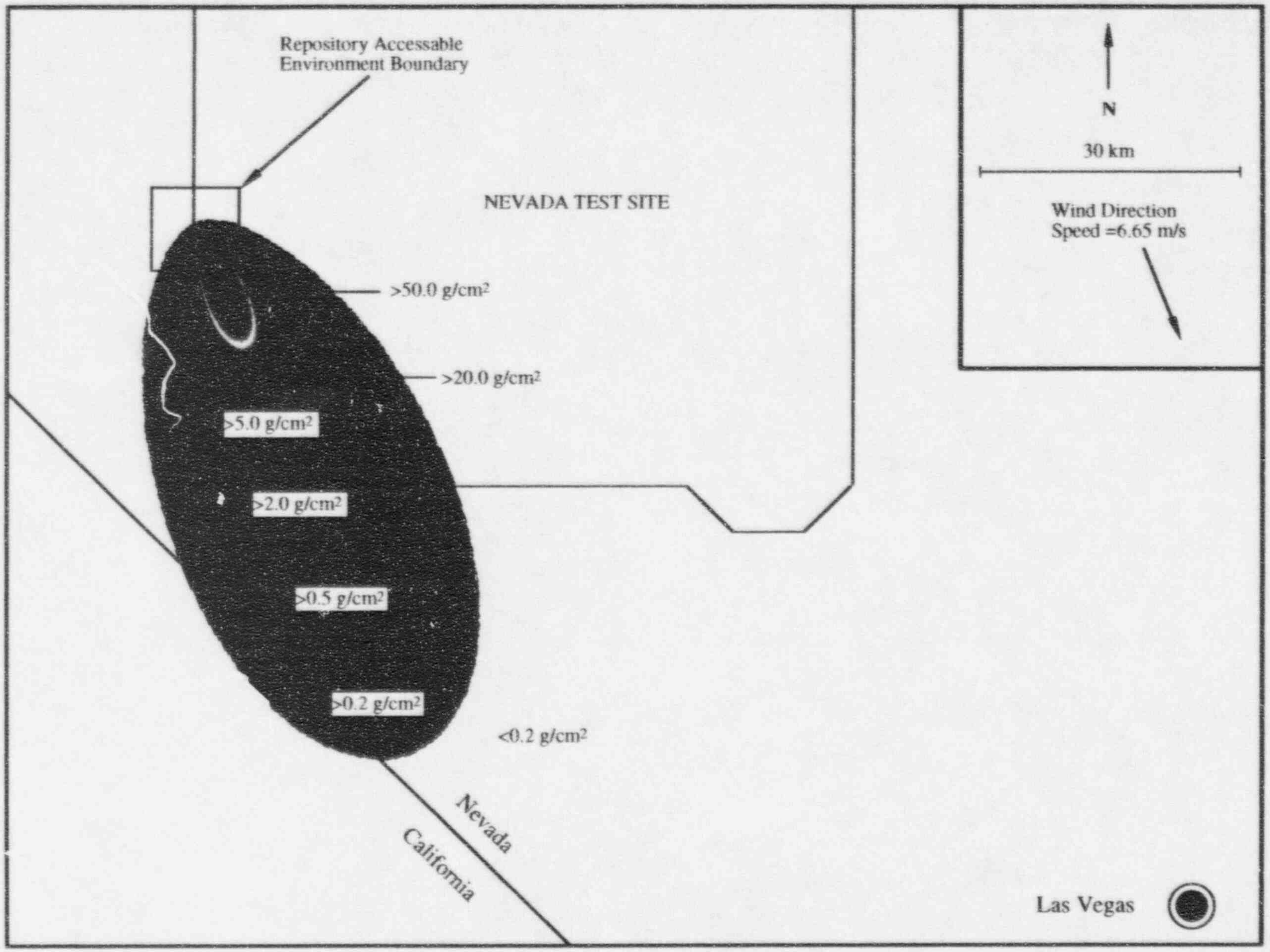


Figure 2. An example of the radionuclide distribution after a particular realization of the computer module

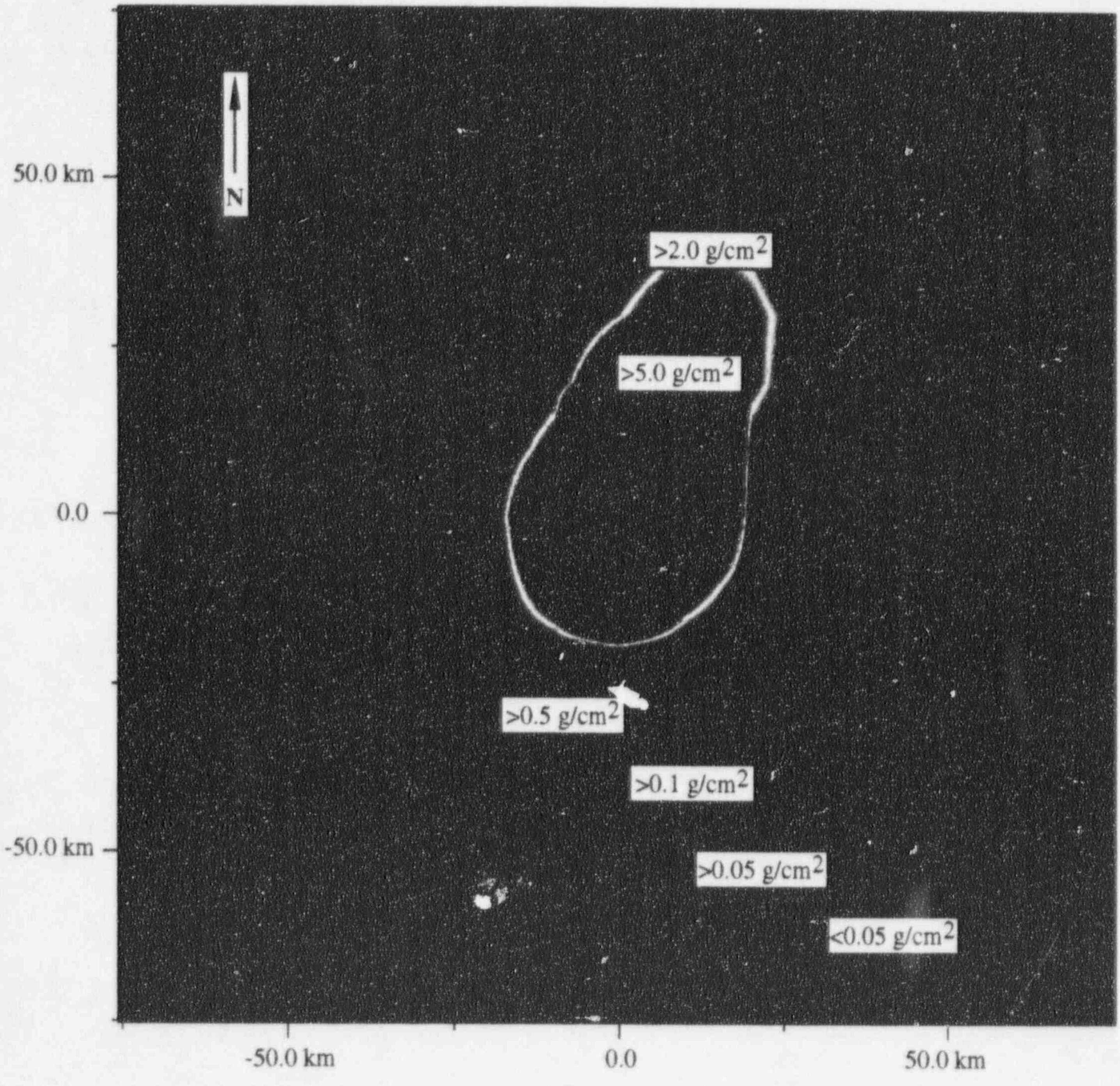


Figure 3. The average radionuclide distribution averaged over 200 realizations