EXPECTED DOSE FROM CH-TRU WASTE DURING AN ACCIDENT AT WIPP – A PROBABILISTIC APPROACH

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ABSTRACT

A probabilistic assessment of radioactive doses as consequences from accident scenarios was conducted to complement the deterministic assessment presented in the Waste isolation Pilot Plant (WIPP) Safety Analysis Report (SAR). The International Council of Radiation Protection (ICRP) recommends both assessments be conducted to ensure that "an adequate level of safety has been achieved and that no major contributors to risk are overlooked" (1). To that end, the probabilistic assessment for the WIPP accident scenarios addresses the wide range of assumptions that could possibly have been overlooked by the SAR.

The WIPP is located in southeastern New Mexico for the deep underground disposal of defense-generated transuranic (TRU) waste. It is expected that routine releases of radionuclides from the WIPP repository to the environment during the waste emplacement operations will be essentially zero.

In contrast, potential accidental releases from postulated accident scenarios during waste handling and emplacement could be substantial, which necessitates the need for radiological air monitoring and confinement barriers (2). The WIPP Safety Analysis Report (SAR) calculated doses from accidental releases to the on-site (at 100 m from the source) and off-site (at the Exclusive Use Boundary and Site Boundary) public by a deterministic approach. This approach, as demonstrated in the SAR, uses single-point values of key parameters to assess the 50-year, whole-body committed effective dose equivalent (CEDE).

The basic assumptions used in the SAR to formulate the CEDE are retained for the probabilistic assessment. However, for the probabilistic assessment, single-point parameter values were replaced with probability density functions (PDF) and were sampled over an expected range. A Monte Carlo simulation was then run, in which 10,000 iterations were performed by randomly selecting one value for each parameter and calculating the dose. Statistical information was then derived from the 10,000 iteration batch, which included 5%, 50%, and 95% dose likelihood, and the sensitivity of each assumption to the calculated doses.

As one would intuitively expect, the doses from the probabilistic assessment for most scenarios were found to be much less than the deterministic assessment. The lower dose of the probabilistic assessment can be attributed to a "smearing" of values from the high and low end of the PDF spectrum of the various input parameters. The analysis did, however, find a potential weakness in the deterministic analysis of the SAR; a small detail on drum loading was not taken into consideration. It has been the experience of waste emplacement operations thus far to handle drums from each shipment as a single unit, i.e. drums from each shipment are kept together. Shipments typically come from a single waste stream, and therefore the curie loading of each drum can be considered nearly identical to that of its neighbor. Calculations show that if

there are large number of drums used in the accident scenario assessment, e.g. CH5, then the probabilistic dose assessment calculations will diverge from those of the deterministically determined doses. As it is currently calculated, the deterministic dose assessment assumes one drum loaded to the maximum allowable (80 PE-Ci), and the remaining are 10% of the maximum. It is recommended that the WIPP SAR calculations be revisited and updated based on the conclusions of this paper.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a repository for disposal of defense transuranic waste owned and operated by the United States Department of Energy (DOE). It is located in southeastern New Mexico, approximately 42 kilometers east of Carlsbad in the Delaware Basin. The repository is a mined room and pillar construction 655 m below the surface in the Salado Formation, which consists mainly of halite (rock salt) with alternating thin layers of anhydrite with clay seams. The WIPP was approved by the United States Environmental Protection Agency (EPA) in May 1998 (3) as showing compliance with the EPA standards for long term disposal (4,5).

With the EPA final approval, WIPP has been receiving nonmixed transuranic waste (radioactive waste without a significant hazardous waste component) since March 1999. At the time of this writing, a RCRA Part B permit has been issued and will be effective in late November 1999. The permit is needed to allow the DOE to dispose of mixed transuranic waste. The hazardous waste constituent of the mixed waste is mainly volatile organic compounds (VOC) with trace amounts of heavy metals, solvents, and asbestos.

The CH-TRU waste will be shipped via truck on an open flat bed in specially designed, Nuclear Regulatory Commission (NRC) approved containers. The container, called the TRUPACT II, is a right circular cylinder with a screw-top lid. The TRUPACT II was designed with a double confinement philosophy, as opposed to the original TRUPACT I design, which had only single confinement. The TRUPACT I was opposed by EEG (6); it did not provide double confinement that is needed for shipment of plutonium in excess of 20 Curies.

The waste is currently stored in Department of Transportation (DOT) approved, Type A 55 gallon carbon steel drums or steel waste boxes and consists mainly of plutonium contaminated debris waste with minor amounts of respirable material and liquid sludge (<1%). The steel waste boxes are equivalent to 8.9 drum volumes and the WIPP repository was designed to dispose of approximately 850,000 drum-equivalents. In addition, WIPP will dispose remote-handled transuranic (RH-TRU) waste. A shipping container for RH TRU waste has yet to be certified by the NRC.

Once the truck arrives on site at WIPP, waste handling personnel unload the TRUPACT in the CH side of the Waste Handling Bay (WHB). Each truck can transport up to three TRUPACT IIs, with each TRUPACT II containing either 14 drums (two 7-drum arrays stacked vertically) or two standard waste boxes. After unloading, the operational procedures begin, and the waste is transported to the underground.

NORMAL OPERATIONAL PROCEDURES

Under normal operating procedures, the waste is unloaded from the TRUPACT II, placed on a palette, and lowered underground by way of a hoist. Once underground, the waste is moved to one of the eight panels where seven rooms have been carved in each panel. The 7-drum arrays (or standard waste box) are stacked three high in each room, with a room holding approximately 6180 drum-equivalents. Sacks of magnesium oxide, MgO, are placed atop each drum stack and logs of MgO are placed between each drum. The MgO is used as a backfill, based on its chemical characteristics that supports long-term disposal (7).

The WHB is equipped with two TRUDOCKS and two overhead bridge cranes for opening and unloading the TRUPACT II. Each TRUDOCK can accommodate two TRUPACT IIs (2). The TRUDOCK is a raised platform to allow access by personnel to conduct operations. The TRUPACT II is moved from the truck through a series of air locks into the TRUDOCK by a heavy-duty forklift. Above each TRUDOCK is an overhead bridge crane, which lowers an adjustable center-of-gravity lift fixture (ACGLF) to remove the outer containment vessel (OCV) lid and the inner containment vessel lid (ICV) of the TRUPACT II to their respective stands. The ACGLF is then used to balance the payload of waste containers and the overhead crane places the waste on a pallet for underground storage.

The waste pallet is lowered underground via the waste hoist in the waste handling shaft. The pallet is rated for a 11,364-kg load, which will typically hold the contents of two TRUPACT IIs. The maximum load for a TRUPACT II is 3,466 kgs, thus giving plenty of margin for safety. The waste hoist is an electrically driven friction hoist with a maximum speed of 2.5 m/s (2). Besides waste, the hoist was designed to transport machinery and personnel underground.

ABNORMAL OPERATIONS AND ACCIDENTS

Although waste-handling personnel are well trained on the equipment or duty that they will perform to ensure safe operating procedures, hazardous operability studies (8) suggest the potential for handling accidents that could breach containers and release radioactive material. An accident at WIPP could include dropping a drum from the waste facility pallet or the waste hoist failing and plummeting 655 m underground. Such accidents may result in possible worker exposure to radioactive material and that will be the focus of this report. Other accidents involving personal injury or equipment damage will not be investigated here.

Several accident scenarios have been postulated in the SAR, and probabilities have been assigned to their frequency of occurrence. Table I lists the possible accidents and the probability associated with each accident.

Table I. Listing of Accident Scenarios in the WIPP Safety Analysis Report.

Scenario Description	Scenario Name	Accidents Probability
Spontaneous Ignition of Drum in WHB	CH1	1.3×10^{-8} /yr
Crane Failure in WHB	CH2	9.8×10^{-3} /yr
Puncture of Waste Container in WHB	CH3	8.0×10^{-3} /yr
Waste Container Drop in WHB	CH4	1.5×10^{-2} /yr
Waste Hoist Failure	CH5	1.9×10^{-9} /yr
Seismic Event	CH6	N.A.
Spontaneous Ignition of Drum Underground	CH7	4.8×10^{-7} /yr
Aircraft Crash	CH8	N.A.
Waste Container Drop Underground	CH9	2×10^{-2}
Tornado Event	CH10	N.A.
Underground Roof Fall	CH11	4.7×10^{-7} /yr

ACCIDENT CONSEQUENCES AND MITIGATION

The consequence of each accident was calculated in the SAR by estimating the radioactive dose from potential uptake of airborne radioactivity into the body. The worker is subjected to a radioactive plume on the surface, outside of the WHB. The plume is a result of an accident above or underground and is released through the exhaust shaft or WHB ventilation. The calculations considered the source of each accident and how much material could be respirable, the breathing rate, and wind speed and plume dispersion at the site. Together, these terms form the committed effective dose equivalent (CEDE), which is calculated by

$$CEDE = D = Q * \chi/Q * BR * DCF \qquad (1)$$

where D is dose in rem[i], Q is the source term in plutonium-equivalent Curies (PE-Ci)[ii], χ/Q is the site-specific air dispersion factor in s/m^3, BR is breathing rate (equal to 20 l/min as stipulated in IRCP-23 (9)), and DCF is the dose conversion factor for converting the source activity of Pu-239 to rem (assumed W[iii] class, consistent with the SAR - 5.1×10^8 rem/Ci).

Table II lists the consequence calculations reported in the SAR for each of the scenarios listed above. The table also shows the source term assumptions used in formulating the dose, and any effects of mitigation. Mitigation for the aboveground WHB facility includes continuous on-line High Efficiency Particulate (HEPA) filtration of ventilation, and underground mitigation includes switching the underground exhaust flow to HEPA filtration in the case of an accident. HEPA filtration for the underground exhaust cannot be continuously on-line due to the extreme pressure drop in underground airflow, which falls far below standards for miners working with diesel equipment. For calculations of a mitigated release, the leakpath factor is considered to be

Table II. Dose calculations for an above ground worker from each accident scenario.

Accident Scenario	Number of Drums Used in Source Term	Drum Loading in PE-Ci	Unmitigated Dose (rem) at 100 m	Mitigated Dose (rem) at 100 m
CH1	1	80	33	$3.3x10^{-5}$
CH2	7	1@80, 6@8	2.7	$2.7x10^{-6}$
CH2 *	1 (damaged)	1100	0.16	$1.6x10^{-7}$
CH2 **	7 (damaged)	7@80	12	$1.2x10^{-5}$
CH3	4	1@80, 3@8	3.8	$3.8x10^{-6}$
CH3 *	1 (damaged)	1100	0.15	$1.5x10^{-7}$
CH3 **	4 (damaged)	4@80	8	$8x10^{-6}$
CH4	4	1@80, 3@8	0.86	$8.6x10^{-7}$
CH4 *	1 (damaged)	1100	0.0091	$9.1x10^{-9}$
CH4 **	4 (damaged)	4@80	2.7	$2.7x10^{-6}$
CH5	28	1@80, 27@8	61	$6.1x10^{-5}$
CH7	1	80	33	-
CH9	7	1@80, 6@8	2.7	-
CH9 *	1 (damaged)	1100	0.23	-
CH9 **	7 (damaged)	7@80	1.2	-
CH11	21	1@80, 20@8	5.2	-

* Dose consequences are calculated by estimating the effects of a damaged drum with a loading of 1100 PE-Ci. Drum loading above 80 PE-Ci are usually placed in a 85-gallon drum overpack or reprocessed for safer confinement.

** Dose consequences are calculated by assuming a worst case scenario. Drums above 80 PE-Ci are usually overpacked or reprocessed and it is postulated that the source from this drum load would represent the largest dose possible.

$1x10^{-6}$ for an above ground release, i.e., a reduction of dose by 10^6 is expected. No credit for mitigation is taken for a release underground.

PROBABILISTIC DOSE MODELING

The use of probabilistic modeling has gained much attention in the last several years, especially in the nuclear industry in regards to radiation safety and potential exposure. The International Commission on Radiation Protection (ICRP) identified two complimentary techniques to assess the potential exposure to individuals: deterministic and probabilistic assessment methods (1).

The more familiar of the two is the deterministic method, where an outcome is calculated based on one set of input values. This technique was used in the WIPP SAR, shown above in Table II, where the dose was calculated with one value for the source, breathing rate, dose conversion factor, and site-specific meteorological conditions. In addition, sensitivity of certain variables was tested to evaluate the outcome to various conditions. For example, the drum loading parameter was changed to assess the doses that could be expected from the different drum loading values. The drum loading was increased to calculate the effect of a worst case release, if there were an accident. Although the sensitivity of variables in Eq. 1 is rather intuitive, these 'What if' scenarios allow the modeler to bound the range of doses that could be expected. Probabilistic dose modeling is very similar to the deterministic modeling; the variables are still linked in the equations by addition or multiplication. However, the probabilistic modeling addresses the 'What if' scenario automatically by generating a number of scenarios based on the probability of the input variables. Each input variable inherently has uncertainty in the measurement, and it is the goal of probabilistic modeling to give weight to a variable by its probability of occurrence, which is characterized by a probability distribution.

The technique used here for assessing the probability distribution of each variable is the Monte Carlo simulation. The Monte Carlo simulation randomly selects (or samples) a value from the probability distribution of each variable to produce a multitude of scenarios (or iterations). The probability distribution is sampled in a manner that best reproduces the shape of the distribution (10), with the purpose of the distribution to capture the uncertainty of each variable. The greater number of iterations chosen, the higher the accuracy of that distribution.

Modeling the dose using Eq. 1 was quite simple, and was set up using a Microsoft Excel spreadsheet and an after-market plug-in called Crystal Ball (11). Crystal Ball allows the user to specify a probability distribution for each input variable and the number of iterations to be performed. The result of modeling Eq. 1 was a forecast of doses with a confidence associated with those doses. Confidence allows one to gauge the accuracy of the results, and is usually displayed as a percentage. If, for example, the dose was calculated to be 3 rem for a set of Monte Carlo simulations with a confidence of 95%, one could be assured that 95% of the calculated doses fell at or below 3 rem. Described differently, one could be 95% certain (confident) that the dose would fall at or below 3 rem, assuming the input probability distributions are reasonable.

The precision of probabilistic modeling relies heavily on the choice of probability distribution chosen to represent the uncertainty of each variable (10). Care must be used in formulating the function that best represents the empirical data in the model. The probability density function (PDF) therefore, must be adequately understood if the model results are to have any meaning.

WIPP DOSE MODEL

The WIPP dose model, predicated on Eq. 1, was assigned PDFs for site specific meteorological conditions for the air dispersion factor (χ/Q) and source term (Q), but left the breathing rate (BR) and dose conversion factor (DCF) as constant values. The breathing rate for a worker under light activity was established in ICRP-23 (15) and is retained for consistency with the WIPP SAR. The DCF of 5.1×10^{8} rem/Pu-239 Ci (12) was also retained for consistency.

Site-Specific Meteorological Conditions

In September, 1996 DOE established a well-sited meteorological tower for measuring the atmospheric conditions at WIPP. The meteorological conditions will dictate the speed and direction of a contaminated, aerosolized particulate plume. According to the draft ANSI standard, ANSI/ANS-3.11 (13), a well-sited meteorological tower should be in compliance with the design objectives stated in the standard. The main design objectives of the standard for a meteorological tower includes the measurements of wind speed, wind direction, any combination of methods to calculate wind stability class, and precipitation as a minimum; a redundant or backup data recording system; installed lightning protection to minimize data loss; located at a sufficient distant as to minimize the effects of local topographic obstructions (including buildings, trees, parking lots, etc.); periodic review of the meteorological program; and the data should be reviewed and validated by qualified personnel. This review should include comparisons with the expected ranges of each measured parameter and inter-parameter checks. In addition, the tower's basic meteorological measurement sensors need to operate continuously, meeting accuracy and resolution values stipulated in the standard and data recovery rates should be at least 90% for all measured parameters.

WIPP has two meteorological towers: a primary Meteorological Station and the WIPP Far Field (secondary meteorological monitoring station) (14). The primary station is located 500 m to the northeast of the Exhaust Shaft and houses a 50-meter instrument station. The secondary station is located 1000 m to the northwest of the Exhaust Shaft and houses a 10-meter instrument station.

The most significant use of WIPP meteorological data is modeling a plume release from the exhaust shaft during an underground accident and release of aerosolized radioactive particles. The models used in estimating the concentration of a contaminant at a given point typically employ the Gaussian straight-line continuous plume transport equation for air dispersion. The equation (below) assumes the site-specific, air dispersion factor (χ/Q) is governed by the wind speed and wind stability class exclusively.

$$\frac{\chi}{Q} = \frac{f(y)\,g(z)}{2\pi\sigma_y\sigma_z u} \qquad (2)$$

where u is the wind speed [L/T], σ_y is the lateral dispersion factor [L], σ_z is the vertical dispersion factor [L], and f(y) and g(z) are horizontal and vertical correction factors, respectively. f(y) and g(z) are represented by

$$f(y) = \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (3)$$

$$g(z) = \exp\left[-\frac{1}{2}\left(\frac{h_e - z}{\sigma_z}\right)^2\right] \qquad (4)$$

where h_e is the effective plume height. The effective plume height is equal to the stack height, h_s, plus any change in height, Δh, due either to plume rise, stack downwash or gravitational settling. Fig. 1. shows a graphical model of Gaussian plume dispersion.

The Gaussian nature of the plume spread in either lateral or vertical direction is represented by a dispersion factor, σ. This dispersion factor accounts for plume spread by mechanical and/or chemical mixing from empirical fitting formulae based on Pasquill-Gifford-Turner curves (15). The curves for dispersion factors σ_y and σ_z are represented by the equations below.

$$\sigma_y = A_y x^{0.9031} \quad (5)$$

$$\sigma_z = A_z x^{B_z} + C_z \quad (6)$$

where A,B,C are fitting coefficients and x is the downwind distance. The fitting coefficients are given in Table III for three distances: less than 100 m, 100 to 1000 m, and greater than 1000 m.

Table III. Fitting Coefficients for Dispersion Factors

Stability Class	**A_y**	**A_z**			**B_z**			**C_z**		
		<100	**100 to 1000 m**	**>1000m**	**<100m**	**100 to 1000 m**	**>1000m**	**<100m**	**100 to 1000 m**	**>1000m**
A	0.3658	0.192	0.00066	0.00024	0.936	1.941	2.094	0	9.27	-9.6
B	0.2751	0.156	0.0382	0.055	0.922	1.149	1.098	0	3.3	2
C	0.2089	0.116	0.113	0.133	0.905	0.911	0.911	0	0	0
D	0.1471	0.079	0.222	1.26	0.881	0.725	0.516	0	-1.7	-13
E	0.1046	0.063	0.211	6.73	0.871	0.678	0.305	0	-1.3	-34
F	0.0722	0.053	0.086	18.05	0.814	0.74	0.18	0	-0.35	-48.6
G	0.0481	0.032	0.052	10.83	0.814	0.74	0.18	0	-0.21	-29.2

Several numerical codes use these equations or similar equations (which may account for building wake effects, plume meander, etc.) to compute the concentration of a contaminant to a receptor downwind from the release point. As shown, Eqs. 3 and 4 do not incorporate plume meander or building wake effects.

The dispersion calculations conducted in the SAR for non-routine, accident release scenarios followed the format suggested in Nuclear Regulatory Guide (NRG) 1.145, 14 "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," Revision 1, November 1982 (16). This a slight modification of the Gaussian model described above. The guide suggests a site-specific relative concentration (χ/Q) be determined based on atmospheric conditions of the site. For neutral (D) or stable (E, F, or G) atmospheric stability conditions for windspeeds less than 6 m/s (3.1 knots) the χ/Q value should follow the procedure described below.

$$\chi / Q = \frac{1}{\overline{U_{10}}(\pi \sigma_y \sigma_z + A/2)} \quad (7)$$

$$\chi / Q = \frac{1}{\overline{U_{10}}(3\pi \sigma_y \sigma_z)} \quad (8)$$

$$\chi / Q = \frac{1}{\overline{U_{10}}(\pi \Sigma_y \sigma_z)} \quad (9)$$

where,

> χ/Q = relative concentration (s/m^3)
> U_{10} = windspeed (m/s) at 10 m above the ground
> σ_y = lateral plume spread (m), a function of atmospheric stability and distance
> σ_z = vertical plume spread (m), a function of atmospheric stability and distance
> Σ_y = lateral plume spread with meander and building wake effects (m), a function of atmospheric stability and distance. For 800 m and less: $\Sigma_y = M\sigma_y$, where M is a correction factor determined from a lookup chart (16). For greater than 800 m: $\Sigma_y = (M-1)\sigma_{y800m} + \sigma_y$.
> A = vertical plane cross-sectional area of release vent (m^2).

χ/Q should be calculated using all three equations. The values from Eq. 7 should be compared to Eq. 8, and the largest value selected. The result is then compared to Eq. 9 and the smallest value selected.

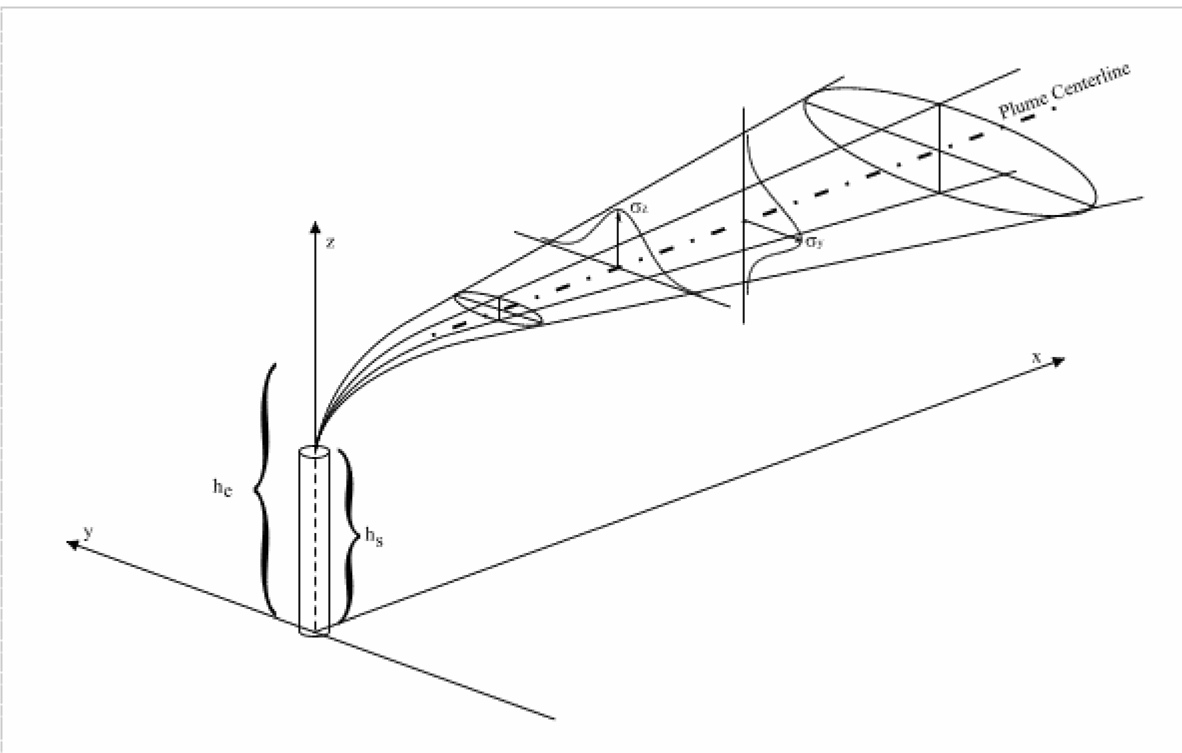

Fig. 1. Gaussian plume dispersion model

Intuitively, it is easy to see that the conditional use of Eqs. 7-9 is not the most conservative combination; using the largest value of the three would always insure conservatism in the calculation of the site-specific air dispersion factor. However, the NRC RG 1.145 gives rational for the selection of the most appropriate equation, citing 1) horizontal plume meander tends to dominate dispersion during light wind and stable or neutral conditions, and 2) building wake mixing becomes more effective in dispersing effluents than meander effects as the windspeed increases and the atmosphere becomes less stable (16).

The SAR reported a χ/Q value of 5.11×10^{-3} s/m^3 at 100 m for conditions of stability class F, windspeed =1.5 m/s, σ_y = 4.6 m, σ_z = 2.3 m, M = 4, and A=117 m^2. At the time of the SAR update, sufficient meteorological data did not exist. However, since 1996, over three years of quality meteorological data exists and that data was used in formulating a PDF for windspeeds of the six stability classes. Fig. 2a shows the PDF for stability class A used in formulating the dose. Wind stability class was incorporated into the dose formulation by a weighting factor developed from each class. The weighting factor was established through observing the number of 15-minute occurrences for each class in the meteorological data and normalizing them to the total number of observations. For example, stability class A was observed 22.4% of the time, B=5.3%, C=5%, D=16.8%, E=18.5%, F=13.5%, and G=18.5%.

The lateral distance from the source was incorporated into the calculations by discretizing a 1-D grid by 50 m increments, starting at 100 m from the source to 500 m. The final results show dose versus distance.

Source Term

The formulation of the source term for the probabilistic dose assessment remained consistent with the SAR. The only change was the use of a PDF to represent the actual drum loading expected from each generator site as reported in the Baseline Inventory Report (BIR), Rev. 3 (17). The source term, Q in Ci, was calculated by

$$Q = MAR * DR * ARF * RF * LPF \qquad (10)$$

where MAR is the material at risk (Ci) and is calculated by the Curie content of a drum multiplied by the number of drums involved in the accident. DR is the damage ratio and is the fraction of the MAR that is impacted by the accident. ARF is the airborne release fraction and is the fraction of radioactive material that is suspended in air resulting from the accident. RF is the respirable fraction, which relates to the fraction of particles that are in the respirable range (less than 10 μm AMAD). LPF is the leakpath factor and is the fraction of material that is not filtered out of the air after the accident. Filtering for an above ground accident occurs in permanently installed, continuous on-line two-stage HEPA filtration system. Filtering for an underground accident is only engaged during an accident. LPF is assumed to be 1×10^{-6} for the mitigating case (filtered) and 1.0 for unmitigated release (2). It is assumed that all accidents for the probabilistic dose assessment is unmitigated for comparison with the SAR.

The waste form of each drum and type of accident dictates the values for DR, ARF, and RF and are referenced from DOE-HDBK-3010-94 (18). Table IV lists some examples of values used in the three parameters and the product of the three. The values from Table IV were used in formulating the source term for the dose calculations.

Table IV. Example DR, ARF, and RFs used in formulating the source term.

Waste Form	DR	ARF	RF	Overall Product
Combustible Solids(95%) drops less than 5 ft (drum)	$1x10^{-2}$	$1x10^{-3}$	$1x10^{-1}$	$1x10^{-6}$
Noncombustible Solids(95%) drops less than 10 ft (SWBs/overpacks)	$1x10^{-2}$	$1x10^{-3}$	1.0	$1x10^{-5}$
Solidified Solids, Vehicle Impact and Puncture	$1x10^{-2}$	$2x10^{-5}$	N.A.	$2x10^{-7}$
Noncombustible Solids(95%) drops 2000 ft (waste hoist)	$2.5x10^{-1}$	$1x10^{-3}$	1.0	$2.5x10^{-4}$

The Curie content of each drum from all major generator sites was evaluated and a PDF was assigned respectively. Fig. 2b-2d shows example PDFs of 3 generator sites' expected drum loading. For the dose assessment, a total of nine generator sites were evaluated, including Idaho National Laboratory (IN), Los Alamos National Laboratory (LA), Lawrence Livermore National Laboratory (LL), Mound Site (MD), Nevada Test Site (NT), Oak Ridge National Laboratory (OR), Rocky Flats (RF), Richland Site in Hanford (RL), and Savanna River Site (SR). The PDFs shown in Fig. 2 are for the entire expected population of drums to arrive at WIPP as reported in the BIR (17). Fig. 2 was created from the observed frequency normalized to the total population.

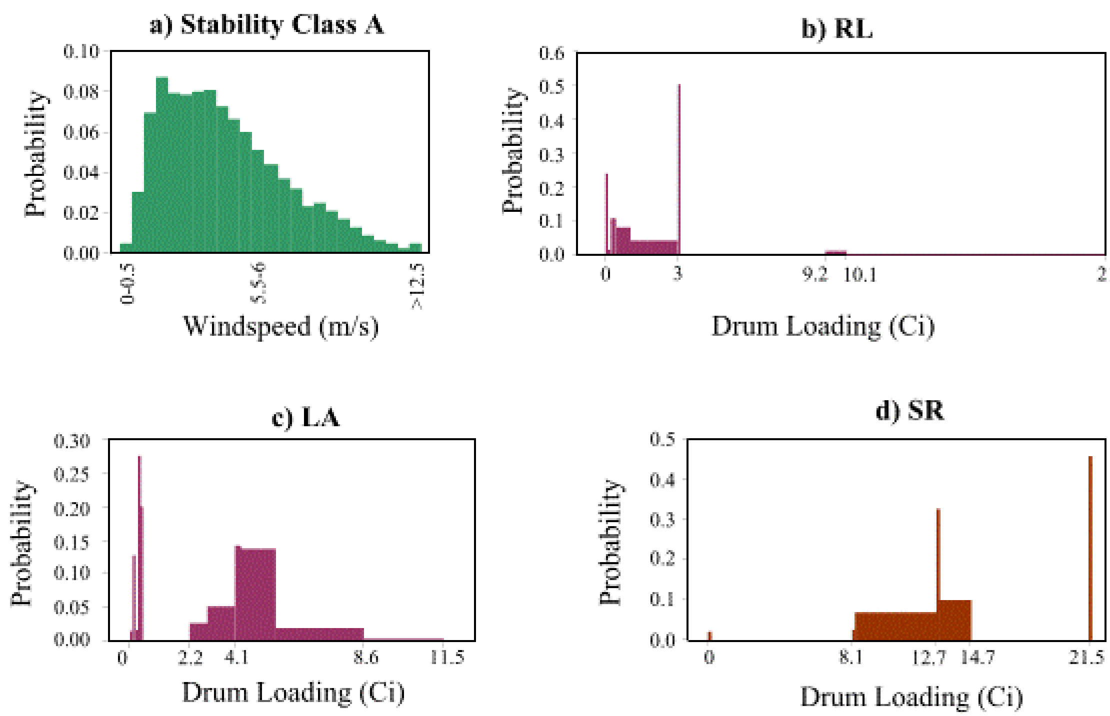

Fig. 2. PDFs used in the assumptions for formulating the probabilistic dose calculations

The source term from each generator site was multiplied by a weighting factor, which normalized the value to the expected number of Curies from each site. Table V shows the weighted fraction used in formulating the source term.

Table V. Weighted fraction used in formulating the source term.

Site	Curies At Each Site	Fraction of Total Curies
IN	195980	0.161
LA	104275	0.0857
LL	292	0.000240
MD	1419	0.00117
NT	3190	0.00262
OR	7805	0.00641
RF	382761	0.315
RL	109161	0.0898
SR	411191	0.3381
TOTAL	1216074	1.00

Lastly, the number of drums expected to be damaged in each scenario was consistent with the SAR.

DISCUSSION

Once all of the proper information was entered into the spreadsheet, including the site-specific meteorological data and the source term data, the Monte Carlo simulation was run by randomly sampling 10,000 iterations from each PDF. The spreadsheet was divided by the 6 stability classes and each stability class was discretized into the 50-m distances, starting at 100 m and ending at 500 m (9 total grid points). Within each distance column, the nine generator sites were sampled for drum loading and the source term was calculated accordingly. A total of 540 PDFs were sampled 10,000 times and the statistical information was retained from the sampling. The large number was chosen to more accurately represent each distribution.

The final result was a matrix of dose forecasts, showing the doses resulting from all scenarios, versus distance. A frequency histogram and a confidence interval further characterized each dose in the matrix. The histogram was compiled by keeping track of all calculated dose values and dividing them into discrete intervals. The intervals show the total count of dose calculation within that interval. The probability of dose for a specific interval can be calculated by normalizing the frequency by the total number of observations, which in this case is 10,000.

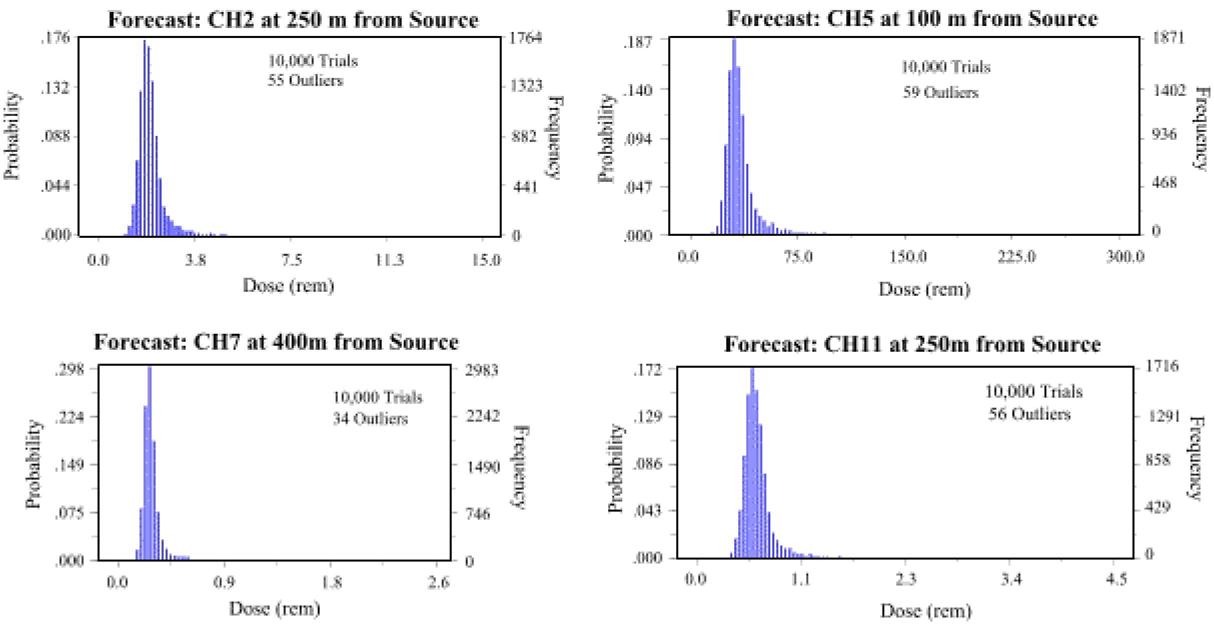

Fig. 3. Frequency distribution of dose calculations for four example scenarios at WIPP

Fig. 3 shows four examples of frequency distributions with their associated probabilities. The four plots show -from upper left to lower right- doses expected from scenario CH2 if the receptor is 250 m from the source doses expected from scenario CH5 at 100 m from the source, doses expected during scenario CH7 at 400 m from the source, and doses expected from scenario CH11 at 250 m from the source. The source in this example is the above ground exhaust shaft outlet or the outside ventilation of the WHB. The example plots of Fig 3 were not chosen for any special reason. They were randomly selected to give a representation of many scenarios. Table VI lists additional statistics for the four frequency distributions.

Table VI. Statistics of Dose Calculations

Statistics	CH2 at 250m	CH5 at 100m	CH7 at 400m	CH11 at 250m
Trials	10000	10000	10000	10000
Mean	2.4	42.5	0.3	0.8
Median	2.0	33.4	0.3	0.6
Standard Deviation	4.3	92.2	1.0	1.4
Variance	18.8	8496.4	1.1	1.9
Skewness	43.74	27.51	38.41	43.74
Kurtosis	2,651.26	1,091.06	1,711.01	2,651.26
Coeff. of Variability	1.81	2.17	3.16	1.81
Range Minimum	0.8	13.5	0.1	0.2
Range Maximum	306.2	5034.6	53.8	96.2
Range Width	305.5	5021.1	53.7	96.0

The main feature to note about the frequency distributions is that it is a lognormal distribution. Every distribution from the probabilistic dose assessment has this shape. The Central Limit Theorem proves this observation mathematically and states that the mean of a set of *n* variables, where n is large, drawn independently from the same distribution will be normally distributed (10). The product of a large number of independent positive variables drawn from different distributions will be approximately lognormally distributed.

The confidence intervals for each set of scenarios were also calculated from the compiled information. The most meaningful representation of confidence is showing the 5%, 50%, and 95% confidence limits, i.e., the expected dose that falls at or below that given confidence limit. Fig. 4 shows all eight scenarios' expected dose including the confidence intervals described above. Each subplot in Fig. 4 shows dose vs. distance, between 100 m and 500 m from the source at 50-m grid points. The dose is in rem and represents the 50-year whole body committed effective dose equivalent (CEDE). From Fig. 4, one can see that the CH5 scenario is the most catastrophic event with a dose of 64 rem at 100 m from the source with a confidence that 95% of the doses fall at or below 64 rem. CH5 is the waste hoist scenario, where the hoist plummets 655 m with 28 drums. The WIPP SAR calculated a dose of 61 rem at 100 m (Table II) and is approximately equal to the probabilistic dose assessment.

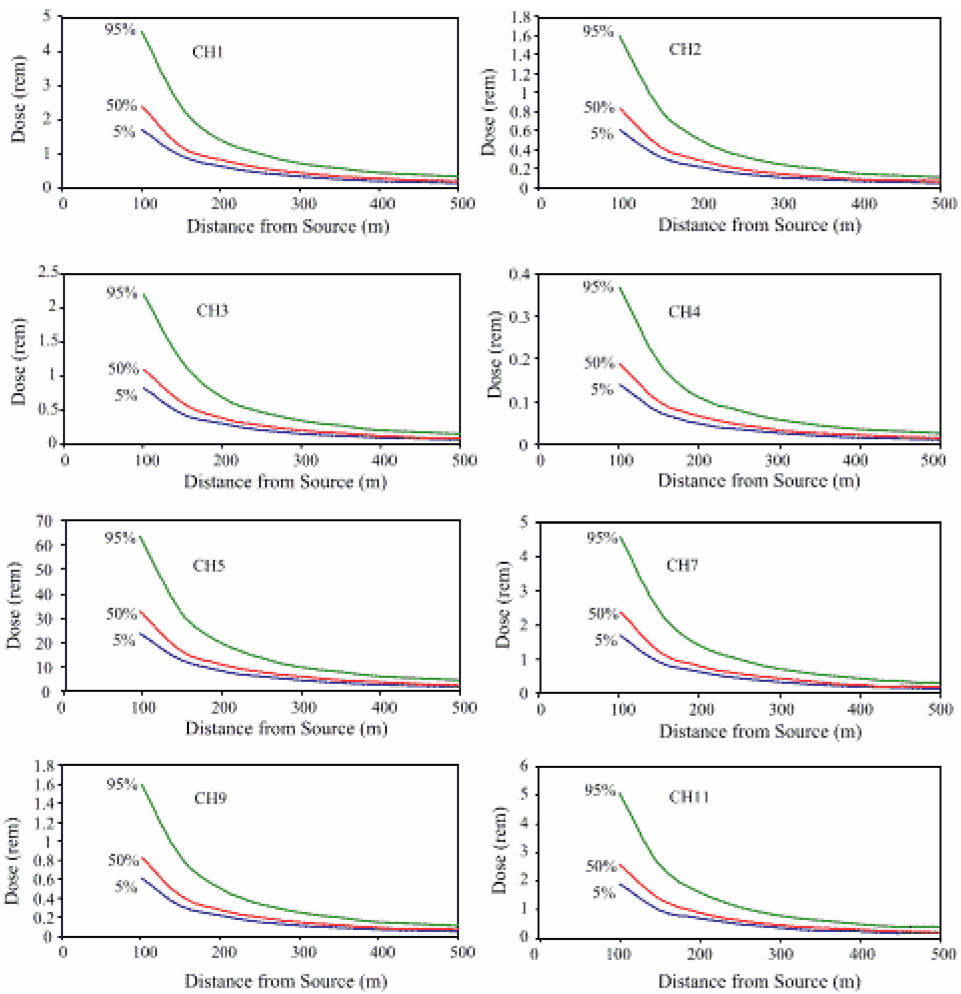

Fig. 4. Expected doses with confidence limits calculated at discrete distances.

Other scenarios, such as the CH1 and CH7 show that the SAR is conservative in its estimate of dose. The SAR's version of the CH1 scenario, where a drum spontaneously ignites in the WHB, is represented by a dose of 33 rem at 100 m (Table II). The dose calculated in the present study is 4.6 rem with a 95% confidence limit. Similarly, the dose estimate for CH7 in the SAR is approximately 7 times greater than calculated in Fig. 4.

CONCLUSIONS

The radioactive dose to an individual for various accident scenarios was calculated using a probability model for Eq. 1. Two of the four input parameters of Eq. 1. were assigned ranges of expected values; the remaining two were constant. A probability density function (PDF) was assigned to each data range to appropriately represented the uncertainties of the problem. A Monte Carlo simulation was employed to randomly sample from the range of values as dictated by the PDF. A large number of samples were chosen to more accurately mimic the behavior of each PDF. Hence, a large number of dose calculations were performed and statistical information was derived for the set of calculations. The results, displayed in Fig. 4., show a dose versus distance from the source of release of radioactivity for each plausible scenario in the WIPP SAR (2), given site-specific meteorological conditions and expected radioactive content of each drum involved.

This technique was different than what was presented previously in the WIPP SAR(2). The SAR listed deterministically calculated dose, where single-point parameter values were used in modeling Eq. 1. The values for this type of modeling can be "best-guess" estimates, but the SAR chose to use conservative values in their calculations to bound the expected radioactive uptake and dose to a downwind receptor. The calculations for the SAR are shown in Table II, and the unmitigated dose can be compared to Fig. 4. In addition to the deterministic calculations, the SAR presented a limited sensitivity analysis of the effect of different drum activity loading. For example, Table II shows scenario CH4 with three sets of calculations: 1) the base case with 1 drum loaded at 80 Ci, and 3 drums loaded at 8 Ci, 2) 1 drum loaded at 1100 Ci, and 3) 4 drums loaded at 80 Ci. The source calculation of case 2 in this example has shown that although the drum loading is much higher than the base case, the dose is expected to be much lower. The discrepancy is due to the method in which the standard 55-gallon drums containing more than 80 Ci are stored. Large Curie-containing drums are overpacked into 85-gallon drums for safer handling, and the product of the damage ratio, airborne release fraction, and the respirable fraction shown in Eq. 10 will be orders of magnitude lower.

Comparisons of Table II and Fig. 4 show that many of the dose calculations in the SAR are higher than the probabilistic dose at the 95% confidence level. Lower doses calculated in the probabilistic dose assessment are expected, since many of the input data are sampled from a relatively large range, hence a smearing of high and low values. However, higher doses seen in the probabilistic dose assessment are not expected, and may show where the deterministically determined doses may be underrepresenting the worst case conditions. For example, the probabilistic dose assessment assumes that all drums are loaded equally, and when a relatively large number of drums are involved in an accident, such as scenario CH5 (waste hoist accident – 28 drums involved), a larger dose is expected. The justification for the drums of equal loading is from observations of recent operating procedures at WIPP. A shipment of TRUPACT IIs will typically transport drums from a single waste stream, with the drum loading of each waste stream being similar. Handling of drums between unloading of the TRUPACT IIs to placement underground is typically confined to single shipments. It is recommended that the SAR be revisited and updated based on current operating procedures to ensure that an adequate level of safety has been characterized for a non-mitigated release.

Finally, although the two methods described above are different, they are not meant to be mutually exclusive, but as complementary techniques (1). The ICRP identified both methods for assuring an adequate level of safety has been achieved and that no major contributors to risk has been overlooked (1). With that, it is recommended that the WIPP SAR be updated to include a probabilistic dose assessment. The inclusion would add to the level of safety and give confidence that all possible ranges of expected conditions have been addressed. However, consistency between the results will have to be analyzed and assessed.

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FOOTNOTES

[i] For consistency with the SAR, English units for dose (rem) and activity (Ci) are presented. The SI equivalents are Sieverts (Sv) for dose and Bequerels (Bq) for activity. 100 rem = 1 Sv. 1 Ci = 3.7×10^{10} Bq.

[ii] All quantities of radionuclides in the waste are expressed as Pu-239 equivalent Curies (PE-Ci). The PE-Ci is derived by comparing the 50-year effective whole-body dose commitment due to inhalation of various radionuclides to that of Pu-239.

[iii] The W class is a simple classification for the chemical form of the radionuclide referring to the retention time in the body. W is short for weekly; others include D as in days and Y as in years.