Probabilistic Consequence Study of Residual Radiological Effects from a Hypothetical Ten-Ton Inadvertent Nuclear Yield*

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1. Introduction

In this paper we study the potential radiological consequences of a strategic bomber accident, in which one of the assumed on-board nuclear weapons explodes with an arbitrarily chosen 10-ton nuclear yield. The frequency of such an occurrence is infinitesimal. The safety design features in today's nuclear weapons' systems essentially forbid its occurrence. Although the gist of this study and methodology is generic, as demonstration of it, we have chosen a military base (See Fig. 1) which has the feature of being a representative combination of urban and rural populations.

The assumed "crash site" is near the northwest corner of the military base, close to civilian housing located just across the street from the base. A worst case wind would be from the ESE (east south east). This would cause fission debris to be dispersed toward the largest population centers and, thus, would lead to the largest Pu "collective" doses (i.e., a dose integrated over time and summed over individuals). Also, if an ESE wind were blowing at accident time, some people in nearby housing could receive lethal gamma-ray doses from fallout before evacuation could occur.

It is assumed only one weapon undergoes nuclear yield; the other on-board weapons would HE detonate and the Pu would be aerosolized and lofted. We assume an activity-size distribution and lofting similar to those used to predict fallout measured at NTS.

The main thrust of our study is to provide estimates of probabilistic radiological risks to the population local to a strategic bomber crash site. The studied radiological consequences are: cloud-passage doses from Pu inhalation; doses from groundshine due to gamma-producing radionuclides; and areal contamination from Pu and the long-lived fission products Cs-137 and Sr-90.

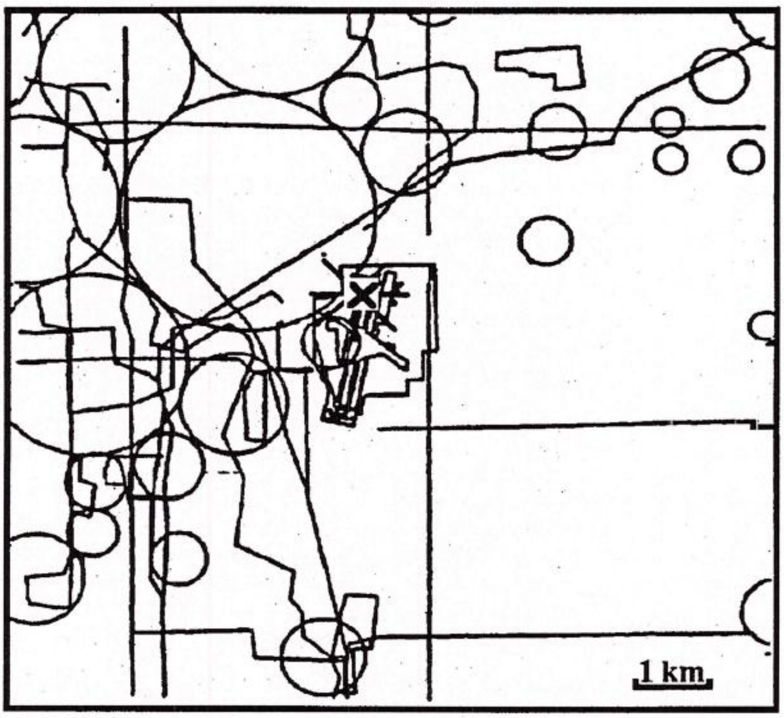


Figure 1. Computer generated overlays of population and geography. The population is represented by a set of circles each with population, location, and radius. The **x** shows the location of the hypothetical accident.

2. Models and Methods

One of the primary reasons for doing a probabilistic study is because doses can be large enough in extreme scenarios to produce alarmist conclusions. However, such scenarios are normally only remotely possible. Depending on uncertainties in wind direction, atmospheric stability, and source term strength, the potential collective doses (given a specific weapon accident in a populated area) usually range over several orders of magnitude. There is a low probability that any given dose will be realized. Extreme scenarios need to be put into proper perspective. A balanced assessment scheme should not only look at the magnitude of consequence, but also frequency of occurrence. Thus, this work assigns probabilities to consequence estimates, given that a 10-ton nuclear explosion occurs at a designated crash site.

The most common definition of operational risk is a product of frequency times a deleterious effect caused by an operation. Thus, two equally risky operations, for example, would be (1) an operational approach leading to a benefit that is expected to cause ten casualties every 1000 years; or (2) another approach leading to the same benefit which is expected to cause one casualty every 100 years. A useful definition of risk for Pu operations, e.g., is

$$\textbf{Risk} \equiv \left(\begin{matrix}\textbf{Frequency}\\ \textbf{of Accident}\end{matrix}\right) \textbf{X} \left(\begin{matrix}\textbf{Amount of Pu}\\ \textbf{Given Accident}\end{matrix}\right) \textbf{X} \left(\begin{matrix}\textbf{Consequence}\\ \textbf{Per Amount}\end{matrix}\right)$$

Then the "total risk" would be the sum of the risks from all the different possible potential accidents as well as risks from normal operations. This assumes no correlations between accidents. Each operational option can then be measured against every other option, for example, by comparing expected annual casualties. From the risk equation it is obvious that there are three ways to reduce risk from nuclear weapons operations:

- reduce the frequency of accidents;
- reduce the amount released given an accident; and,
- mitigate the consequences of an accident, if one occurs.

In this study we concentrate on the consequence term. In predicting the consequences of a potential accident, lessons can be learned on possible mitigating actions that might work, and those that might not.

2.1 Probabilistic Consequence Model

PCAS1 is a model for doing probabilistic consequence assessments. It is being used for a series of assessments, of which, this is the second. PCAS1 is designed to calculate consequences from nuclear device accidents, including devices undergoing assembly, operations, or transportation. In the model there are some important "probabilistic protocols" that provide model and database interfaces fitting probabilistic parameters and models together. The main PCAS1 results are: frequency distribution of individual doses; the areal deposition of device debris; and, the cumulative probability distribution of potential latent cancer fatalities.

PCAS1 can map the U.S. population onto a given deposition grid and use windrose probabilities to generate cumulative collective doses. Uncertainties in respirable fraction, aerosolized fraction, and number of devices involved are possible as stochastic variables. So far, we have been mainly interested in Pu inhalation dose and areal deposition, but in this paper, we broaden the study to look at fresh fission debris as well. Future studies should consider a larger spectrum of effects. PCAS1 roughly can be described as consisting of five numerical models: source term, meteorology, atmospheric transport, population, and health effects. We briefly describe each below.

2.2 Source Term

The source term is defined as fission debris and Pu aerosol that is released and carried upward in a hot buoyant toroid. The fission debris cloud stabilizes above the crash site at an altitude determined by the total energy released by the nuclear explosion. Generally the stabilization altitude is a function of the atmospheric stability. In this study, we assume a slightly unstable atmosphere.

Aerosolization

The amount of gamma radiation is determined by two factors: the amount of fission energy released; and the amount of neutron induced radioactivity in the weapon's and surrounding materials. There are three factors that determine the total amount of Pu aerosolized: the amount of Pu in each on-board weapon; the number of weapons aerosolized by the nuclear explosion; and the fraction of Pu in each weapon aerosolized. The mass of Pu in a weapon and its specific activity versus time are accurately known. The alpha specific activity for 15 year old, weapons-grade Pu is 0.088 Ci/g. The mass of Pu in a weapon is classified and is not given in this report. The on-board weapons are assumed generic, but vulnerable to inadvertent nuclear detonation in some extremely unlikely circumstances.

Based on data from the Roller Coaster Pu dispersal experiments[1] and fallout from nuclear tests, we assume that the majority of fission debris and Pu is on particles that have significant gravitational settling velocity, thus, must be considered fallout particles. These are non-respirable. The particles that are assumed respirable have aerodynamic diameters less than 10 μm.

Activity-Size Distribution

We need activity of the released aerosol and its settling velocity; or equivalently, we need the distribution of activity versus size, where size is defined as the size of a 2.5 gm/cm^3 sphere having the same settling velocity as the physical particle. Such a distribution is referred to as an activity-size distribution (ASD). It is cast into the form of a frequency distribution, i.e., percent activity versus diameter. AMD is the "activity median diameter" of the distribution. Amount aerosolized depends on the dynamics of the 10-ton nuclear explosion. The largest effective aerosol size is directly related to fireball updraft velocity and drag forces. Large updraft velocities would occur. This suggests large aerosol particles would be lofted. For fallout particles, we have assumed a maximum diameter of 1000 μm and a minimum diameter of 10 μm. For the respirable sized particles, we assume an activity median aerodynamic diameter (AMAD) of 1.0 μm.

The chosen ASD for fallout particles is a truncated, renormalized, bimodal lognormal distribution with AMDs of 14 and 150 μm and geometric standard deviations (GSDs) of 4.0 and 2.7, respectively, following the GSDs obtained from the Small Boy nuclear test (See Fig. 2). The weighting factor between the small and large modes is 0.8 and 0.2, respectively. The GSD is a sensitive parameter when calculating areal deposition from fallout-sized particles.

Stabilized Cloud Characteristics

Pu and fission products and induced radioactivity lofting depends on the energy release (assumed to be 10-tons), energy partitioning, and meteorological conditions. The meteorological parameter of most importance for cloud rise is the lapse rate. The ASD and distribution of activity with respect to altitude for the fission debris are given by the KDFOC3 fallout code. They are distributed as shown in Fig. 3, both in the main cloud and the stem cloud. The respirable particle sizes below 10 μm radius are assumed Gaussian distributed in the main cloud.

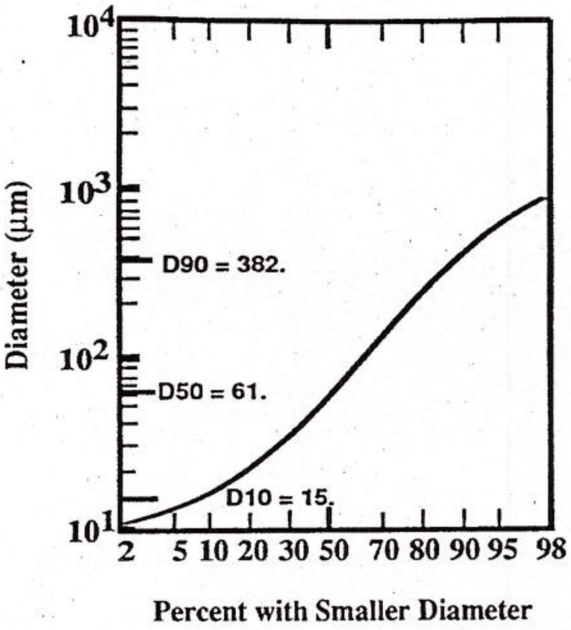


Figure 2. Activity size distribution for 2.5 g/cm^3 density spheres used for the fallout calculation. D90, D50, and D10 are the 90th, 50th, and 10th percentile diameter in micrometers, respectively.

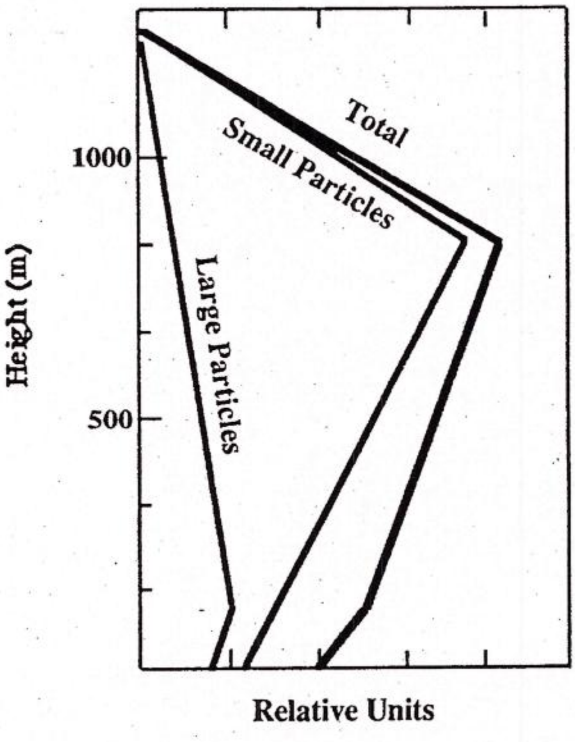


Figure 3. Activity-height distribution for the fission products and induced radionuclides. The abscissa is in relative units.

The initial cloud size for the detonation was based on the 10-ton fission yield. The combined amount of high explosive in all devices involved (i.e., simultaneous detonation is likely) is ignored as an energy source, although individual device HE detonation insures the aerosolization of all the Pu and its lofting into the fallout cloud.

Unlike modeled fire distributions where most of the material remains relatively close to the surface, the nuclear cloud respirable Pu distributions are modeled with most of the particulate lofted relatively high above the surface. The respirable particles Pu cloud resulting from the assumed detonation had a cloud center at 975 meters, cloud top at 1300 meters, horizontal cutoffs at 2.5 standard deviations (with the standard deviation equal to 49 meters). The vertical standard deviation was 130 meters.

2.3 Meteorology

Atmospheric pollutant/particulate dispersal patterns are heavily dependent upon the meteorological scenario. Key atmospheric variables needed by the models are surface and upper air wind speed and direction, atmospheric stability, and mixing layer depth. The MATHEW[2]/ADPIC[3] calculational models have extensive capability to treat complex meteorological conditions. The fallout model, KDFOC3,[4] assumes a stable atmospheric condition associated with small yield surface bursts at NTS. Values for the assessment were chosen to simulate conditions using a measured wind in the area of the military base during summertime morning hours. The wind speeds and directions versus altitude are shown in Table 1.

Table 1. Wind vector vs. altitude, at accident location.

altitude (m)	10.	500.	1000.	5000.
speed (m/s)	4.	5.	5.	5.
direction (°)	112.	132.	132.	132

Anisotropy in the population distribution makes wind direction a most sensitive parameter. Directional probabilities are determined by 7 years of hourly wind measurements[5,6] taken over all stability classes and wind speeds at the military base. The windrose provides the frequency for each wind direction as shown in Fig. 4. KDFOC3 and ADPIC inhalation dose isopleths are rotated and overlaid upon the population distribution for each point of the windrose. There are sixteen points. The windrose (showing the probabilities in the direction *from which the wind blows*) is given in Table 2.

Table 2. Sixteen-point windrose

Direction	N	NNE	NE	ENE
Frequency (%)	12.38	5.69	3.89	3.55
	E	ESE	SE	SSE
	5.65	3.76	6.27	13.97
	S	SSW	SW	WSW
	21.08	5.86	2.42	1.78
	W	WNW	NW	NNW
	2.56	1.68	3.41	6.08

To calculate the largest credible case given a 10-ton nuclear yield, we used a wind blowing directly toward the nearest off-base housing development.

The atmosphere is assumed to be slightly unstable (Pasquill-Gifford type C) below a thermal inversion layer at 1500 m. This provides a relatively low ceiling, effectively putting a cap on how high the fission debris and Pu can diffuse. The Pu under our assumed "fumigation" conditions is trapped nearer the ground than would be the case for unstable conditions. This causes higher ground-level doses. We assume a low wind shear, which, for a given wind speed, leads to especially long dose patterns, putting a larger, more-distant population at risk. We assume no rain is falling. For calculating Pu inhalation dose, these are all conservative meteorological assumptions.

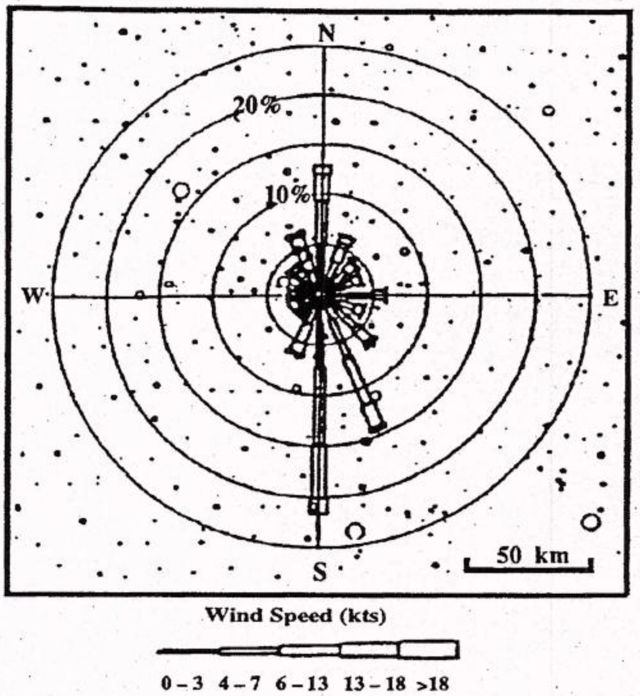


Figure 4. Windrose for the military base region overlaid with the population model. The center of the windrose is at the crash site on the base. Each annulus represents 5% probability. Thus, the most likely wind is from the south and occurs about 21% of the time.

2.4 Atmospheric Transport

ARAC's regional transport and diffusion codes, MATHEW[2] and ADPIC,[3] were used to estimate the ground contamination and dose to individuals from the diffusion dominated respirable particles. The fallout dominated deposition, on non-respirable particles, was estimated using the KDFOC3 model. Results of the two calculations were added to give a complete analysis for all Pu particle sizes. The KDFOC3 model is used to estimate the groundshine gamma doses from the deposited fission debris.

The KDFOC3 Fallout Model

KDFOC3[4] develops nuclear debris parcels that follow trajectories defined by the winds, turbulent diffusion, and gravitational settling. When the parcels hit the ground, their activity is summed to yield overall fallout patterns. KDFOC3 is a so-called "disk-tosser" designed to handle a measured wind sounding. Other attributes are that it: conserves radioactivity; has an empirical stem cloud; uses SMALL BOY activity-particle sizes for surface bursts; and, has a continuous, adjustable activity-height distribution from the top of the main cloud to the ground.

KDFOC3 has been developed at LLNL as an "in-house" tool to assess single-burst scenarios for real and hypothetical nuclear devices. The model is continuous in all physical parameters, both as a function of depth of burial and of variations in specified winds. KDFOC3 uses a unique approach to cloud-rise simulation. It provides enough detail to produce salient features of observed fallout patterns. The empirical establishment of initial conditions is a time-reversal process in which the fallout particles are projected from their actual landing points backward in time to H-hour. This produces a tapered, effective stem cloud over ground zero. To this cloud, an appropriate distribution of debris is assigned with respect to altitude. This helps account for high radiation levels developed during the cloud-rise phase. The success of such a procedure was tested by the model's overall fit to NTS data where it achieved an agreement to measured patterns to a standard deviation of about 40%.[7] Its results have been compared with small yield nuclear shots, especially Little Feller II. The results agreed better than those of other models, and in all but one case, the areas and downwind distances were within a factor of two of those observed.

For this work, we developed a nested version of the KDFOC3 code to overlay the deposition from diffusion of the respirable particles advected and diffused by ADPIC with those advected, diffused, and settled by KDFOC3. The required input to KDFOC3 was kept to a minimum. The only input was the wind and 10-tons of fission yield. The standard output consisted of graphical hard copy of fallout patterns at requested dose levels. The display also lists downwind distance and areal coverage of each contour.

The MATHEW/ADPIC (M/A) Model

M/A predicts airborne concentrations and surface deposition levels of a wide variety of pollutants as well as the resultant health effects. It can handle source terms for fires, explosions, and non-buoyant scenarios.

The MATHEW code develops a mass-consistent, three-dimensional wind field from multiple surface and upper air measurements of wind speed and direction. MATHEW generates, by variational methods, a mass-consistent, three-dimensional gridded mean wind field, including terrain from available interpolated meteorological data and topography. The input for the model consists of a digitized topographical surface, spatially interpolated surface winds, vertical wind profiles, and a stability parameter.

ADPIC is a three-dimensional, numerical diffusion and transport model capable of simulating the time and space varying dispersal of atmospheric pollutants in complex terrain. It is a particle-in-cell model in which Lagrangian "mass" particles are transported inside a fixed Eulerian grid. The model solves the three-dimensional advection-diffusion equation in flux conservative form using a "pseudo velocity" technique which uses the sum of the mean wind and a diffusive velocity in the x, y, and z directions. The mean wind is supplied by the MATHEW model.

ADPIC computes a horizontal and a vertical diffusivity based on a semi-empirical expression. For the atmospheric surface layer the vertical diffusion is based on similarity theory. In the outer atmospheric boundary layer it is determined using the Von Karman constant, the friction velocity, the height above terrain, and the atmospheric stability function based on the Monin-Obukhov scale length, the geostrophic wind, and the height of the mixing layer.

The M/A model has been extensively evaluated with a number of experimental data sets with a wide variety of terrain types, tracer release scenarios, and meteorological conditions including data from INEL, SRP, TMI, EPRI, and Chernobyl.

2.5 Population

Our population model is based on the 1980 Census.[8] The model consists of P-95 circles. Each has a latitude, longitude, population, radius, and town name (See Figs. 1 and 4). Although all tallied people do not live inside the designated circles, the model was developed so that at least 95% of them do. The total numbers of people in the data base are included in the P-95 circles.

It is assumed that the individuals living near the base are evacuated within approximately one hour after the accident. This does not have a significant effect on the cloud-extent passage inhalation doses, but does affect the groundshine gamma doses. All individuals are assumed to be at home when the accident occurs. For cloud-passage dose, it would significantly bias inhalation doses if sheltering were not accounted for. Thus, we also have included a sheltering model. Most people are indoors most of the time. For inhalation doses, this should provide them with an "unwarned" sheltering factor of about 3 to 4, on average. We know some people will be outside during the event and others will be well sheltered. For inhalation doses, we can safely say that in a population, individuals will have shelter factors that range over orders of magnitude. Considering that the protection factor can be substantially increased by relatively simple measures, any warning should reduce population dose substantially. We choose to consider "warning" as a random variable. Either there will be effective warning or there will not be. Because of the orders-of-magnitude range for protection factors that occur in a population, we have chosen a truncated lognormal distribution to represent its frequency (See Fig. 5). Good and bad weather, time of day, and warning are all significant quantities in establishing sheltered population distributions. Our estimates of sheltering to inhalation dose afforded by various structures and circumstances are based on papers by R. Englemann[9] and B. Cohen.[10] We limit our distribution of shelter factors to between 1 and 200. For a warned population, the average shelter factor is about 7. For an unwarned population, its value would be about half of that.

Groundshine Sheltering from Gammas

For gamma radiation, there is very little sheltering that occurs in residential houses for unprepared populations. In a single-family, one-story residence without a basement, a factor averaging about two is as large as one could expect. This is an average factor which includes the reduction of gamma radiation penetrating a residence

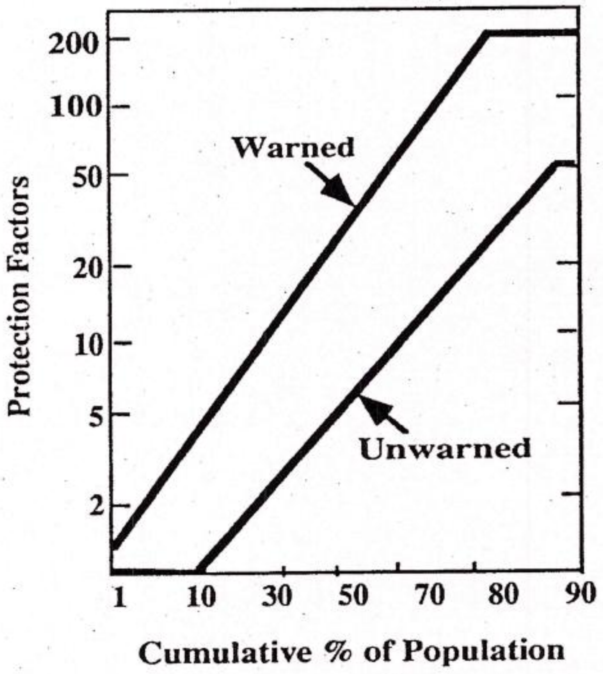


Figure 5. Distribution of Pu-inhalation protection factors versus percent of population with protection factor less than that shown.

or car. The dose integration was done for 24-hours. However, because of the rapid falloff in dose rate during the first few hours, it would be very difficult for emergency personnel to enter the fallout field without receiving enough dose to cause acute radiation symptoms to themselves, for example, vomiting.

2.6 Health Effects

Additional assumptions are made concerning the percentages of plutonium aerosolized due to nuclear detonation. For high explosive detonations, all of the plutonium is assumed to be aerosolized, a fraction of which is within the particle size range retainable by the lungs, the respirable particles. Since we assume that all the weapons except one undergo sympathetic HE detonations, the fractional split of fission debris to respirable particles seems appropriate for the ratio of particles above and below 10 μm, respectively.

The dose conversion factor used to calculate the 50-year committed effective dose equivalent is $3.2x10^8$ rem/Ci. A worker breathing rate of $3.3x10^{-4}$ m^3/sec was assumed. (General public breathing rate is ~$1.9x10^{-4}$ m^3/sec.) Inhalation dose contours are based on Pu concentrations 1.5 meters above the surface.

The alpha specific activity for 15 year old weapons-grade Pu is about 88 Ci/kg. The beta activity is about 300 Ci/kg. Because the biological effect of the low-energy transfer of the betas is substantially less that the alpha particles, we ignore the beta contribution. About two-thirds of the total inhalation hazard is from ^{239}Pu. A representative dose conversion factor for the Pu isotopes is that for ^{239}Pu. Table 3 gives the mixture of the significant isotopes for 15 year old weapons-grade Pu. Thus, to calculate the individual doses we assume the ^{239}Pu dose conversion factor for all alpha activity. We also assume an AMAD of 1.0 μm, a conservative assumption.

Population dosages are estimated from dosage contours and population P-95 circles. These estimates, in person-rem, are converted to latent cancer fatalities (LCF) using the conversion factor of 2000 person-rem/LCF. This number is obtained from BEIR-V[11] and ICRP publication 60.[12]

3. Results

The consequences we have calculated are individual doses, population doses, and areal deposition. We discuss each of these briefly below.

Table 3. The mixture of significant isotopes for 15 year old weapons-grade Pu.

Isotope	Half-life (years)	Initial Weight (%)	15 yr Weight (%)
^{238}Pu	87.7	0.0400	0.0355
^{239}Pu	24100.	93.3	93.3
^{240}Pu	6540.	6.00	5.99
^{241}Pu	14.4	0.580	0.282
^{241}Am	432.	0.000	0.295
^{242}Pu	376000.	0.0400	0.0400

3.1 Individual Dose

Individual doses have been calculated for unsheltered populations. For individual dose cases, we have chosen the worst consequence wind, a wind from the ESE direction blowing directly toward the urban area. Figure 6 depicts doses calculated for inhalation of respirable Pu particles. People are assumed to be taking part in light activity in their yards during cloud-passage.

Thus, for the assumptions we have made, this histogram represents a worst credible event. Note that the maximum Pu inhalation dose received by any individual is less than 1 rem.

The groundshine gamma radiation dose received by unsheltered people in the first 24 hours is shown in Fig. 7. Most of the dose is acquired in the first couple of hours. The radioactivity starts arriving at the nearby houses in the first few minutes after the accident. Dose rates from the fresh fission debris are very high. Some of the population would show signs of radiation sickness and some could even receive doses above lethal levels.

Fig. 8 shows the cumulative distributions of individuals receiving gamma doses greater than the dose shown for each of the sixteen wind directions. The winds with the greatest consequences are winds 6,7,8, and 5 representing winds from the ESE, SE, SSE, and E, respectively. Winds from the west, winds 10-16, generally reduce population doses by orders of magnitude. Unlike the Pu inhalation doses, these doses are not 50-yr committed doses. They are actual whole-body gamma doses received in the first day after the nuclear event.

3.2 Population Dose

An integrated population (collective) dose is the sum of doses to each individual of a population. For each of the sixteen different wind directions we obtain a collective groundshine gamma dose. The spread in the predicted population doses in Figure 9 is caused by the anisotropy of the population distribution about the crash point. Predicted population doses range over roughly four orders of magnitude. The wind direction frequencies are given by the military base windrose shown in Fig. 4. Because of the relative lack of major topographic

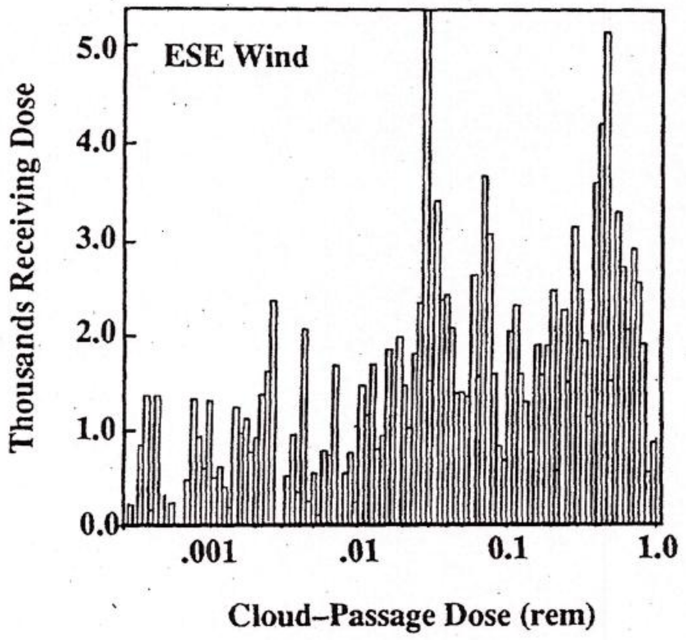


Figure 6. ESE-wind Pu inhalation dose histogram. The ordinate is the number of unsheltered people, all assumed at home, receiving an inhalation dose during cloud passage shown on the abscissa.

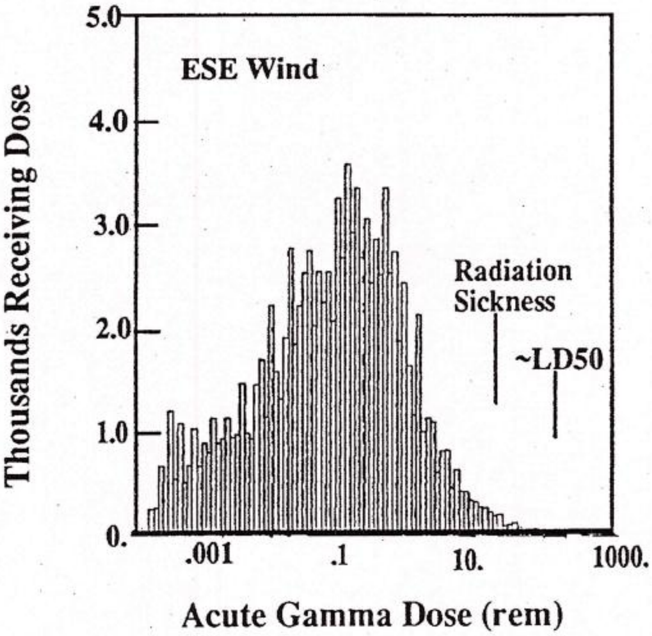
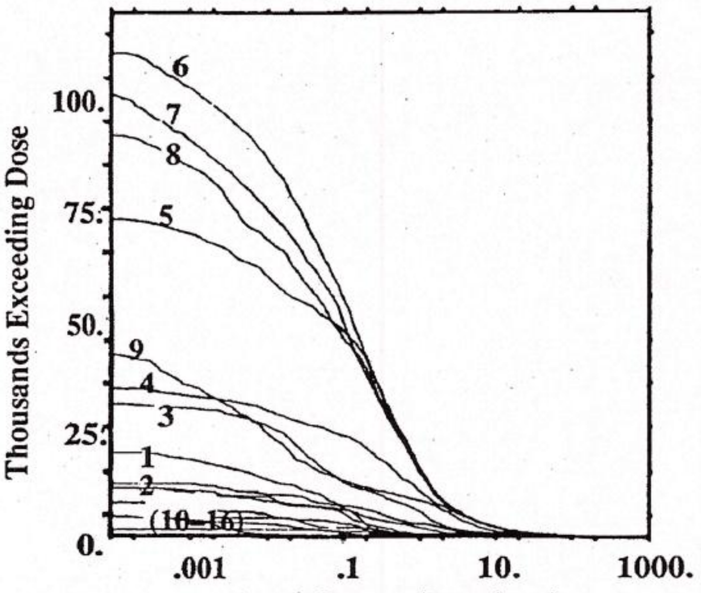


Figure 7. ESE-wind groundshine, whole-body gamma histogram for unsheltered individuals. This is the 24-hr integrated dose. Some receive sufficient radiation to show clinical signs of radiation sickness. Others receive potentially lethal doses.



Number	Wind Dir.
1	N
2	NNE
3	NE
4	ENE
5	E
6	ESE
7	SE
8	SSE
9	S
10	SSW
11	SW
12	WSW
13	W
14	WNW
15	NW
16	NNW

Figure 8. Individual-dose, cumulative-distribution sensitivity to wind direction. The ordinate is the number of unsheltered people, located at their homes, that receive the groundshine gamma radiation shown on the abscissa. The integration is for 24 hours. The worst winds are generally from the east. Relatively, the winds from the west do substantially less damage.

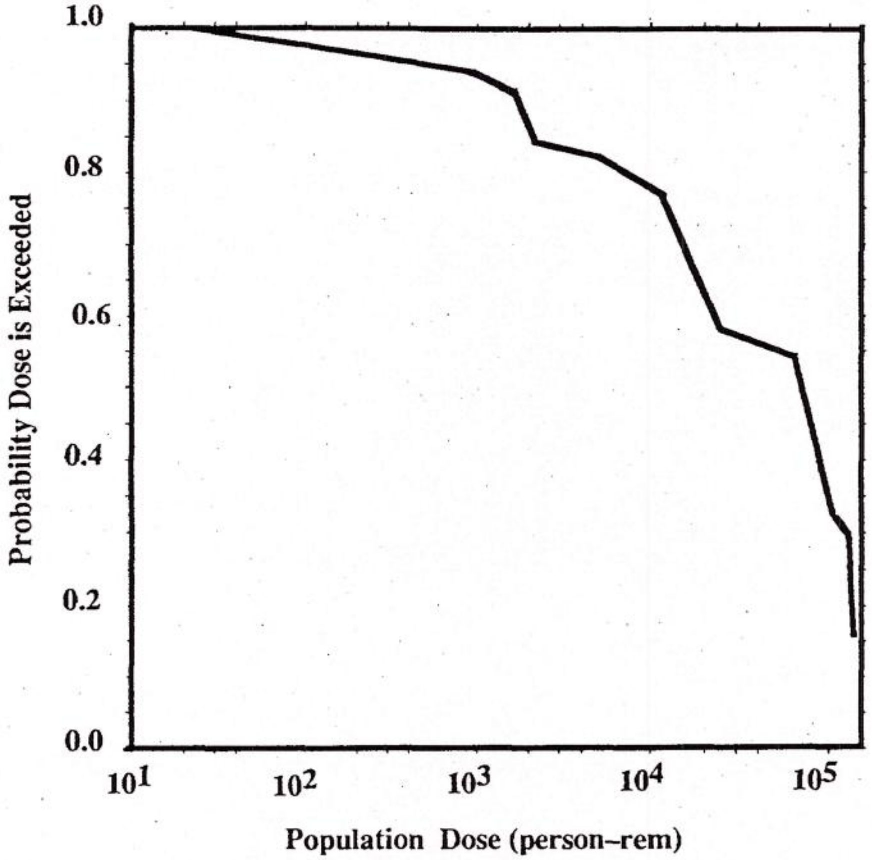


Figure 9. Cumulative distribution of sixteen collective groundshine fallout unsheltered doses. The incorporated probabilities are given by the windrose in Fig. 4.

features around the military base, we expect that any terrain effects on wind direction would be small, and if included in our calculation, would cause little effect on the cumulative population-dose distribution in Fig. 9. For an unsheltered, unevacuated population, the ESE wind leads to over 100,000 person-rem from gamma radiation in the first 24 hours.

Figure 10 shows the so-called "complementary cumulative distribution function" for histograms like that shown in Fig. 6 for the ESE wind. The ordinate gives the probability that the population Pu inhalation dose is exceeded. The probabilities are accumulated from right to left. Because the location of the event is a sensitive parameter for such a low-yield nuclear event, we used the closest location on the base to calculate a largest-consequence population dose. All other parameters were held fixed.

Using a wind blowing directly toward the urban area, we calculated a value of approximately 22,000 person-rem 50-yr committed dose. The expected value considering all the wind directions is 8,000 and the 90% confidence limit is 21,000.

For the inhalation dose, the high-level 0.5 rem contour does not occur until about 10 km from the accident location. Whereas, the groundshine contour is most damaging very close to the accident, the inhalation dose is worse far from the accident because of the lofting of the respirable particles to high altitudes by the nuclear explosion.

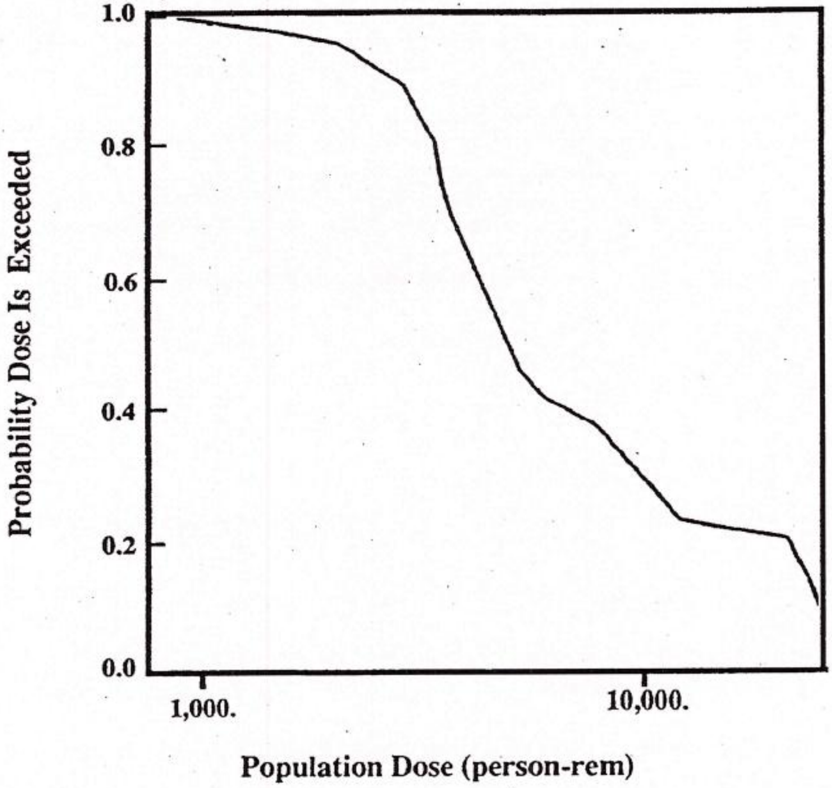


Figure 10. Cumulative distribution of Pu unsheltered, inhalation, population doses in person-rem. For each wind direction, there is a distribution of individual Pu inhalation doses like those shown in Fig. 6. The individual doses are summed to give the collective dose for each wind direction. These doses with their probabilities of occurrence are plotted here. The probabilities are accumulated from the largest to smallest collective dose. The largest dose is associated with the ESE wind as shown in the figure.

The atmospheric inversion level plays a large role in the doses that do occur. A less stable atmosphere without a low-lying inversion would lead to lower inhalation doses. Not having a thermal inversion layer at 1500 m, that puts a ceiling on the upward diffusion, would also lead to lower doses. Higher diffusion rates in the mixing layer would lead to larger cumulative doses, because the Pu would get to the ground more quickly.

For the Pu inhalation hazard from a 10-ton nuclear explosion effective emergency response could make a big difference in population dose received because respirable aerosol takes substantial time to diffuse to the ground and because significant sheltering can be achieved from being inside a sealed building.

3.3 Areal Deposition

For Pu, radiological risk would take two forms: a short-term dose from inhalation of respirable PuO_2 during cloud-passage; and a long-term dose caused by deposited Pu entering the biosphere. The main long-term concern would be from resuspension of respirable plutonium. Mitigation procedures could substantially reduce both short-term and long-term doses. The major long-term risk appears to be Pu, not the fission products ^{90}Sr and ^{137}Cs (See Table 4).

Table 4. Comparison of potential cleanup areas contaminated at greater than 0.2 µCi/m^2 for the 15 yr old weapons-grade Pu (WGPu) isotopic mixture, and long-lived fission products ^{137}Cs and ^{90}Sr. The results are for the ESE wind.

	Cleanup Area (km^2)		
Radionuclides	Urban Centers	Rural Centers	Agriculture
WGPu	120	30	500
^{137}Cs	0.6	–	–
^{90}Sr	0.2	–	–

Areal deposition of Pu includes the effects from all particle sizes. The majority of aerosolized mass forms particles too big to be respirable. It is this large-particle fraction that contributes most to the deposition pattern.

The larger fallout particles detrain from puff during cloud rise. Such particles are too big to be a respirable hazard from resuspended particles unless they break up, which is not an unreasonable possibility as the larger PuO$_2$ are found to be crushable in some experiments.[13] Even larger particles are categorized as projectiles and produce a pattern of continuous ejecta around ground zero. They would be scattered in nearly a circular pattern. Their mass would be found close to the accident site, and they should be fairly easy to clean up. Particles larger than about 100 µm radius fallout within about one kilometer from the crash site.

Pu Deposition

EPA draft regulations[14] recommend a screening level (EPA SL) for soil contamination by Pu of 0.2 µCi/m^2 for samples collected at the surface to a depth of 1 cm and for particle sizes under 2 mm. Using that screening level, the cleanup areas for the accident scenario cases are as shown in Table 5. These areas are comparable to other estimates.[15,16]

Table 5. Urban and rural population centers Pu clean-up areas at the EPA SL. The "agricultural" area is the contaminated open land between P-95s, most of which is used for farming.

Clean-up Area	Worst-Case Wind (km^2)	Wind-Averaged (km^2)
Urban Centers	120	20
Rural Centers	30	50
Agricultural	500	580

It is suggested that no mitigating actions should be necessary below the EPA SL. However, Pu is easily detected in the environment. Depth-integrating the Pu deposited from atmospheric testing gives about a hundred times less areal deposition in mid-latitudes than the EPA SL. This is almost all contained in the first ten centimeters of soil, where it is nearly uniformly distributed with depth. If one only integrates the amount of Pu in the first centimeter (as this might be considered the only part important to resuspension), then background from atmospheric testing would be about three orders of magnitude less than EPA SL. Pu contamination from an accident would be detectable to background levels and lower since the isotopic mixtures of the 10-ton event and that from atmospheric testing would be different. At Rocky Flats, the government purchased land with less contamination than 0.2 μCi/m^2 to avoid litigation.[17] At 0.2 μCi/m^2, the contour is 80 km long and covers 650 km^2. Clean-up would be very costly if, for example, an urban area had to be decontaminated. The wind blows toward the urban area about thirty percent of the time. When it blows from the west the population dose is small.

An interesting observation is that if we had considered only respirable particle sizes there would have been essentially no area contaminated above the EPA SL. Contamination levels are very sensitive to activity-size distribution, deposition velocity and rainout. These phenomena are all based on uncertain parameters. Their effect probably should be assessed. For example, choosing a different slope for the size distribution (See Fig. 2) could substantially alter the predictions in Table 5. Area covered at the EPA SL that is designated as urban, suburban, or towns could be as large as 150 km^2. Such areas would be more expensive to clean up or purchase than rural areas. Because the U.S. Government has not been able to provide a definitive cleanup standard and because dispersed Pu will be easily detectable to very low contamination levels, the cost of mitigating actions cannot currently be established. Without a standard, cost of litigation and property condemnation for levels of contamination far below levels of biological concern could be substantially higher than if a standard were to be promulgated.

4. Conclusions

Our summary of collective (population) dose results is shown in Table 6. The number of LCFs for Pu inhalation is low relative to those estimated for groundshine. Table 6 shows population doses for deterministic and probabilistic calculations. For the deterministic calculation, the largest

Table 6. Summary of predicted major radiological health effects from first-day doses from a hypothetical ten-ton nuclear yield at a military base.

Effect	ESE Wind		Wind-Averaged
	Unsheltered	Sheltered	
Pu Inhalation (LCFs)	15	2	1
Early Gamma deaths	10	3	1
Gamma Radiation sickness	200	70	30
Groundshine (LCFs)	70	20	7

consequence value is for an unsheltered population. If we wished to do a "worst-case" assessment, there are worse meteorological parameters that could increase our largest-consequence inhalation estimate by about an order of magnitude.[18] The gamma groundshine estimate is not nearly as sensitive to meteorological conditions, with the one exception being the wind direction. Choosing all other parameters at worst values could increase our results by even more. Thus, a worst-case prediction for committed inhalation dose could be roughly as high as a thousand LCFs. The probability of realizing such a combination of unlucky circumstances, however, is minuscule, i.e., probably less than one in a million. A better approach would be, for example, to take a 90% confidence limit for the assessment. Our results predict that there is a ninety percent probability that there would not be more than a fraction of a Pu inhalation LCF. Conversely, areal deposition of Pu is easily observed. Currently, there is no U.S. regulation on a *de minimus* level of Pu land contamination. The EPA has suggested a screening level (EPA SL) of 0.2 μCi/m^2.[14] This is at least two to three orders of magnitude above background levels. Based on background levels, approximately 0.1 nCi/m^2 could be detected. Given a 10-ton event, very large areas would be above this level. In Table 5, we show areas covered at the EPA SL. There are over 600 km^2 exceeding this level, much of which could be within the urban/suburban area.

Our major conclusions from the study include that the predominant radiological risk is the very short term gamma radiation from the surface deposited fission debris and may cause some early deaths from gamma radiation. Most of the gamma radiation received nearby would be received in the first few hours. Falloff in gamma exposure rate from fission debris is extremely rapid; thus, emergency response is unlikely to provide much relief to those residing nearby. After a week, the Pu hazard would probably dominate the fission debris hazard. Also, if we disregard the early observable effects of the gamma radiation, about one-third of the affected population would die from various kinds of normally-induced cancers. These normally expected cancer cases would number in the thousands. Thus, the number of LCFs caused by the postulated accident, even as high as the worst predicted case, would be well within the expected random noise associated with normally occurring cancers. Therefore, they would never be directly observable.

A major cost could be incurred by the need to clean up areas with detectable Pu surface contamination (i.e., areas that exceed background from atmospheric testing). These areas could cover hundreds to thousands of square kilometers.

Caveats

It is important to note that this has been a calculation to demonstrate a new probabilistic methodology and also to roughly indicate the severity of the short-term residual radiological effects on a nearby urban area. Our main thrust was to study population dose and areal deposition. Our predictions have been calculated for relatively conservative, but non-worst case conditions. Some major concerns are:

* Gamma doses are very sensitive to assumed nuclear yield. The effect is compounded; the higher the yield is, the larger the doses and bigger the fallout contours. Potentially much higher or lower yields are as likely as the one chosen. Also, none of the other weapons have been assumed to have experienced the sequence of events leading to nuclear yield. It cannot be ruled out that if one experienced the sequence that others would not also experience it.

* For the collective doses (both inhalation and whole-body) we are using the "no threshold, linear hypothesis" with 2000 person-rem per LCF. Although this is the convention in doing radiological risk assessments, this is an extremely uncertain and controversial number. For example, if there is a dose threshold for damaging biological effects, for the low individual Pu inhalation doses that we

have predicted here, there could actually be no future LCFs.

- It is important to note that these consequence values: cleanup area, latent cancer fatalities, and costs, are very uncertain. Although the dispersion codes, KDFOC3 and MATHEW/ ADPIC, are well validated, the agreement with tracer measurements in simple terrain is, in general, only good to within about a factor of two. More importantly, only one stochastic meteorological parameter, the wind direction, was varied. Variations in wind speeds and stability conditions could easily cause a variance in contamination levels of a factor of three or more.
- Long-range, long-term consequences are strongly dependent on particle sizes, release fractions, and rainout. Wet deposition removes most small atmospheric aerosols. The long-range and long-term doses could dominate the Pu inhalation risk. We have not included these in the calculation.
- Cloud-rise and activity-size distributions, as part of the source term, contain large uncertainties and are especially sensitive parameters for gamma dose prediction.

Recommendations for Additional Studies

We have not looked at long-range and long-term consequences. Without mitigating actions, it is possible that long-term doses (i.e., after cloud passage) could be as large as the cloud-passage inhalation doses. Resuspension and rainout phenomena would have to be included in such a study.

The location of the accident was fixed. A more complete analysis would include additional crash sites, with probabilities of an accident occurring at each site. This would substantially change the predicted collective gamma doses, but would have little effect on the Pu doses. The analysis would increase from sixteen trials to at least a factor of several more.

We have not considered prompt effects in our population dose calculations. It is realized, however, that prompt gamma and neutron radiation from a nuclear yield, if there is no intervening shielding could cause significant prompt doses at relatively large distances, both on and off the base. Some of these doses could be lethal in the first two months.[19]

Gamma doses are very sensitive to yield. Additional calculations looking at larger yields, including potential sympathetic detonations should be done.

Some Additional Observations

Cleanup/compensation costs are often associated with vague standards. Unnecessary limits for predicting environmental and human health effects may destroy credibility of weapon system assessments, e.g., artificial distance cutoffs and health-effects thresholds. These are not consistent with the conventions used by the Health Physics community for doing other types of risk analyses, e.g., analysis of the Chernobyl accident. Other detrimental pathways, such as those from ingesting contaminated foodstuffs and rainout, for example, should also be considered in a more complete analysis.

Health effects criteria from ICRP/NCRP are conservative. We need to develop best estimates with uncertainties for some of these effects. For example, we have used the breathing rate of a worker undergoing mild activity for our individual immersed in a Pu cloud. This is a higher breathing rate (leading to higher dose predictions) than the average breathing rate of a calm person at home.

Worst-case analyses can lead to alarmist results. Probabilities for some combinations of parameters leading to alarmist scenarios have much smaller occurrence probabilities than, for example, the sun exploding. There should be a legally promulgated *de minimus* level for probability of annual occurrence, below which scenarios should not be seriously considered in risk analyses. This could reduce future assessment costs significantly.

5. References and Notes

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4. T. Harvey, F. Serduke, L. Edwards and L. Peters, "KDFOC3: A Nuclear Fallout Assessment Capability" UCRL-52338, Lawrence Livermore National Laboratory, 1992, DRAFT; KDFOC3 is a widely accepted model and was empirically developed for fallout predictions during the last three decades. It has been validated against many observations spanning a large range of measurements and has seen three major revisions. Of those engaged in modeling fallout, the KDFOC3 code is one of the standards of the industry. It has recently been chosen by the U.S. DOE, DoD, and the British AWE as a principal fallout assessment code tool.

5. The windrose measurements were made 6.0 m above the ground for the years 1973 to 1979, at the military base. The windrose mean speed is 5 m/s. We used 4 m/s as our surface wind speed, a conservative value. Ambient surface temperature was chosen as 288 K.

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17. R. Cuddihy and G. Newton, "Human Radiation Exposures Related to Nuclear Weapons Industries," LMF-112, UC-48, Inhalation Toxicology Research Institute, P.O. Box 5890, Albuquerque, NM 87185, Sept. 1985.

18. Use of an elaborate meteorological model was beyond the scope of this work. Where a more complete work would include stochastic variables for terrain, stability, and wind-speed, with appropriate correlations between them and wind-direction, such an approach would require substantially more effort than we could devote to it. Thus, we limited ourselves to sampling wind directions and a flat-terrain model.

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