ATMOSPHERIC TRANSPORT, DIFFUSION, AND DEPOSITION OF RADIOACTIVITY*

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ABSTRACT

From a meteorological standpoint there are two types of initial sources for atmospheric diffusion from Plowshare applications. One is the continuous point-source plume - a slow, small leak from an underground engineering application. The other is the large cloud produced almost instantaneously from a cratering application. For the purposes of this paper the effluent from neither type has significant fall speed. Both are carried by the prevailing wind, but the statistics of diffusion for each type are different.

The use of constant altitude, isobaric and isentropic techniques for predicting the mean path of the effluent is briefly discussed. Limited data are used to assess the accuracy of current trajectory forecast techniques.

Diffusion of continuous point-source plumes has been widely studied; only a brief review is given of the techniques used and the variability of their results with wind speed and atmospheric stability.

A numerical model is presented for computing the diffusion of the "instantaneously-produced" large clouds. This model accounts for vertical and diurnal changes in atmospheric turbulence, wet and dry deposition, and radioactivity decay. Airborne concentrations, cloud size, and deposition on the ground are calculated. Pre- and post-shot calculations of cloud center, ground level concentration of gross radioactivity, and dry and wet deposition of iodine-131 are compared with measurements on Cabriolet and Buggy.

INTRODUCTION

When a Plowshare device is detonated, a variety of radionuclides is produced in the underground environment. Depending on the

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particular Plowshare application some of these radionuclides, particularly the more volatile ones, may be released to the atmosphere. In the case of cratering applications, the majority of the vented radionuclides are attached to particulate matter and rapidly settle to earth. However, some of the material is either in the form of gases or in the form of particles which are too small to have any significant fall speed.

The purpose of this paper is to discuss methods of predicting the atmospheric transport, diffusion, and turbulent deposition of the material which does not have any significant fall speed. An assessment of the relative accuracies of current prediction techniques will also be made.

Trajectory prediction techniques are common to the effluent which might be released from an underground engineering application and from a cratering application. Thus, these will be discussed first. The diffusion and deposition of effluent from each application will then be discussed separately because the diffusion approach is different for each application.

TRAJECTORIES

The most common method of constructing a trajectory is the central tendency method. This method assumes that the wind field is invariant between times for which no data are available. The best available wind field analysis for the height of interest is used. This could be a streamline analysis or a contour analysis on constant pressure charts. Isotachs aid the analysis. To construct the trajectory, a point is moved along with the available wind field for a time period equivalent to the time between observation periods. This period of movement of the parcel is centered on the time of the analysis.

This central tendency method is one of many possible kinematic methods of constructing trajectories. However, this is about the easiest method to use, and various studies[1,2] have shown that there is little difference in trajectory accuracy among the various kinematic methods, when the accuracies are averaged over a variety of synoptic situations. In any one particular case, one kinematic method may be somewhat better than another.

There are also dynamic methods of constructing trajectories which compute the acceleration of the air parcel. However, these are not widely used because they are more laborious to construct, and they require a high accuracy in the wind and pressure fields. This latter is true because the calculated acceleration is a small difference between two fairly large terms. Consequently, dynamic methods are seldom used in routine trajectory forecasting.

If the trajectory being constructed is a "hind cast," wind maps prepared from observations are used; or if it is a "forecast," then prognostic charts of the wind field are used.

What methods can be used to check the accuracy of trajectory forecasting techniques? As it is the path of parcels of air containing pollutants that are of interest, the best measurement of the trajectory would be a continuous tracking of the air parcel. However, this is difficult to accomplish as it takes almost continuous aircraft tracking of a "tagged" parcel for several days. The tracked air parcels which can be compared to trajectory forecasts are almost nonexistent.

The next best method would be to track a constant level balloon or a constant density balloon. Constant level balloons have been flown at heights of 200-300 millibars and set so that they stay on a constant pressure surface. Constant density balloons, which are also known as tetroons, have been flown in the lower atmosphere, say from 12,000 feet down to a few hundred feet above the ground, and are designed to float on a constant density surface.

Another method which has been used to study trajectories has been to construct a trajectory from observed wind data and compare it to a constructed trajectory based on forecast data. Ironically though, when constant level balloon data have been available, the error in "hind cast" trajectories has been determined to be about the same as in forecast trajectories.[1,2]

Using trajectories from 11 balloon flights at 200 millibars during the period of August 1949 to March 1950, Machta, in an unpublished paper,[1,2] found an average error of 32% of the total trajectory length for an average trajectory length of 855 nautical miles (average flight duration 15½ hours). An Air Weather Service trajectory study at 300 millibars, for 76 cases, compared forecast trajectories to balloon data. This gave an average cross trajectory error of 19.5% and an average along trajectory error of 25.9%. This resulted in a net error of about 32.5%.[1] Moore[3] had an average forecast trajectory error of 23% of the total trajectory path for balloons designed to fly at 300 millibars. "Hind cast" trajectories prepared for 20 balloon flights, selected for good behavior, right altitude, etc., gave an average trajectory forecast error of 20% of the trajectory path length of about 1000 miles.

Trajectory computations can be easily done by computer. By linking a trajectory forecasting technique directly to one of the numerical weather prediction models run by the Environmental Scientific Services Administration (ESSA) at Suitland, Maryland, one has the advantage of using small time steps in the central tendency method. This is because the numerical weather prediction models step forward in time steps of 10 minutes to an hour, whereas, prognostic charts or observational data are usually only available in 12-hour increments. Hurbert et al[4] ran 11 comparisons, with constant level balloons floating at 300 millibars and 72-hour trajectory forecasts prepared by the equivalent barotropic model. The equivalent barotropic model does calculations at the 500-millibar surface, and then it is necessary to extrapolate upwind to 300 millibar in order to compare calculations to the path of the constant level balloons. The average error in these comparisons for flights of 72 hour duration was about 25% of the flight path length.

Coming down in altitude to the lower levels (10,000-12,000 feet), there is the trajectory study done by Allen, et al.[5] This study was done utilizing trajectories originating at the Nevada Test Site (NTS). For the period of about a year four different kinds of trajectories were prepared (or available) at NTS. They were:

(1) A 30-hour 700-millibar forecast which was linked to the output of the three-level baroclinic prediction model being run by ESSA at Suitland, Maryland.

(2) The duty forecaster at NTS routinely forecast 30-hour trajectories from NTS. During the first part of the test period, these were at 10,000 feet and during the second part of the test period they were at 12,000 feet. Although these forecasters did not have access to the numerically prepared trajectories, they did have access to the prognostic charts prepared at Suitland, Maryland.

(3) The duty forecasters at NTS routinely reconstructed 30-hour trajectories using observed wind data.

(4) Small clusters of tetroons were launched almost daily and tracked by radar as long as possible. The maximum tracking time was about 50 hours. In order to minimize the grounding of these balloons and to optimize their radar tractability in the rough terrain of northern Nevada, these balloons were flown at 12,000 feet.

Over a forecast time period of 6 to 24 hours, the standard vector deviation from the tetroon trajectory end point and the NTS forecaster-prepared trajectory end point was 55-60% of the total tetroon trajectory length. The same accuracy was obtained by the numerical forecast trajectories from Suitland. The reconstructed trajectories done by NTS meteorologists had a standard vector deviation from the observed tetroon trajectory of 36 to 57% of the tetroon trajectory path length.

Examination of the data also indicates that there is a 50% chance that the vector standard error will be less than 47% of the total path length for the forecast prepared by NTS forecasters.[5] For "hind casts" prepared by the NTS forecasters, there was a 50% chance that the vector error will be less than 26% of the total trajectory path. Generally, the "hind cast" trajectories were shorter in total path length than the observed tetroon trajectories. There is some rationale for believing that the tetroons, because they are restricted to constant density surfaces, will tend to move faster than air parcels which could move up and down more (see discussion at end of Reference 5).

It is a little surprising in all of these studies to see that the "hind cast" trajectories are not much better than the forecast. The sparseness of upper wind data would contribute to this. In particular, the terrain in northern Nevada and the Rocky Mountain states would have a significant effect on the path of the tetroons studied by Allen, et al.[5] The meteorologists at NTS attempted to allow for terrain effects on their forecasts for the first few hours of the trajectory. However, at late times they relied on ESSA prognostic charts from Suitland, Maryland. In these numerical models the terrain is grossly smoothed. This lack of terrain effect was also very evident in the numerically prepared trajectory forecast from Suitland. Terrain may also help explain why the average error between forecast and tetroon trajectories is like 50-60% for the Nevada studies, whereas for the constant level balloons at higher altitudes the error was 20-30%.

It is also true that long trajectories and smooth "flow" tend to have less percentage error. The smooth flow makes the lack of spacial resolution in the data less critical. Long trajectories also tend toward a more climatically averaged transport speed.

A low-level trajectory study done by Peterson[6] compared tetroon trajectories at 500-1000 feet above the ground, with reconstructed trajectories using an adjusted surface wind, a surface geostrophic wind, a second standard level wind, and a 5000-foot wind. The trajectory construction technique in all cases was the central tendency method. The basic tetroon data was a card mailed back from wherever the tetroon was found. Thus the landing point was known, but not necessarily the path between launching and landing.

Out of these data it was possible to show that the reconstructed trajectory using the adjusted surface wind, adjusted for speed change with height and for veering with height, gave the best fit to the observed landing position of the tetroon.

All of these systems of reconstructing trajectories were unsuccessful in cases of rough terrain and in cases of interaction with frontal surfaces.

In reality it is necessary to deal with air parcels which follow isentropic surfaces. Isentropic surfaces may or may not coincide with isobaric or constant height surfaces.

In particular, isentropic surfaces are nearly parallel to frontal surfaces and thus air parcels rise over fronts. Routine isentropic forecasts were not and are not available to compare with observations of "tagged" air parcels. Isentropic "hind casts" have been used a great deal as a diagnostic tool; this is particularly true for stratospheric trajectories. The framework for isentropic trajectory forecasts is available,[7,8] but it needs to be put to routine use.

Lastly, in closing this discussion of trajectory forecasting it should be mentioned that ESSA currently runs a trajectory forecast program at the numerical weather prediction unit at Suitland, Maryland. The trajectory forecast uses a central tendency method and linear interpolation between the grid points used in six-layer primitive equation model.[9] At each hour during the computation of the 48-hour forecast, wind direction and speed is tabulated at each grid point and for a variety of heights. Trajectories are then prepared utilizing one-hour time steps and these forecast winds. Trajectories can be run at several different heights and with several different starting points. Unfortunately, a comparison of these computer trajectories with tetroon data or even reconstructed trajectories has not been done yet.

UNDERGROUND ENGINEERING APPLICATIONS

Most conceivable underground engineering applications would be done with the Plowshare device buried too deep for there to be any significant probability of a dynamic venting. If any venting occurs, it most likely will be in the form of a small continuous leak of volatile radionuclides. This effluent would be carried downwind by the local, near-surface wind pattern. The diffusion of this continuous plume of effluent would be well described by the Gaussian plume diffusion model. This model is represented by Equation (1):

$$\chi = \frac{Q}{2\pi\,\sigma_y\,\sigma_z\,u}\, e^{-1/2\left[\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]} \qquad (1)$$

Where:

χ = the concentration, pCi/m^3

Q = the source, pCi/sec

y = the crosswind distance from plume axis, m

σ_y = the standard deviation of the crosswind Gaussian distribution of concentration, m

z = the vertical distance from the plume axis, m

σ_z = the standard deviation of the vertical Gaussian distribution of concentration, m

u = the mean horizontal wind speed, m/sec

Various forms of Equation (1) have been well studied in the meteorological literature for the last 30 years. The books by Sutton,[10] Pasquill,[11] and the recent (1968) issue of Meteorology and Atomic Energy,[12] give good reviews of plume diffusion. For our purposes here, it is sufficient to say that one needs to know the leak rate, the wind speed, and σ_y and σ_z in order to evaluate Equation (1). If the leak is surface-based and if surface concentrations are desired, then $z = 0$ and Equation (1) is multiplied by two. Much of the discussion of this equation in the meteorological literature has hinged upon different ways of evaluating σ_y and σ_z as functions of atmospheric stability, wind speed, and distance downwind.

The most useful and realistic method of evaluation σ_y and σ_z is to use the many diffusion tests, which have been done over the years, to evaluate σ_y and σ_z as a function of distance under different atmospheric conditions. Thus, these standard deviations are empirically determined from concentration data for different meteorological conditions. Figures 1 and 2 give the variation of these parameters with distance and with atmospheric stability. This presentation of the data was originally done by Pasquill[13] in 1961. Concentration data obtained since then [12] still fits these categories.

Table 1 gives a qualitative description of the stability categories. This description was originally proposed by Pasquill.[13] These stability categories have also now been related to the standard deviation of the wind direction fluctuation when the sampling time for wind directions is about a half hour.[12] This relationship is given in Table 2.

This approach to evaluating the diffusion of continuous point sources has become standard practice. There is enough experience now with these nomographs to indicate that they work reasonably well when the time of effluent emission is long compared to the travel time to the sampler and when the time of plume passage past the arcs of samplers is about an hour or less. The reason for the latter comment is that almost all of the plume diffusion experiments have been done for sampling times of about a half hour to an hour. If longer sampling times were used in the experiments, the values of σ_y and σ_z on Figures 1 and 2 would be larger. In order to evaluate the exposure at some point downwind, the concentration should be calculated for averaging periods of about an hour. Wind direction data can then be used to determine how many hours the plume might be over a particular point downwind if periods of longer than an hour are involved.

CRATERING APPLICATIONS

The majority of the effluent which might be released by a cratering application would be released almost instantaneously and as a large volume source. This large volume source will be diffusing as it travels along its trajectory. Diffusion will be with respect to a coordinate system which moves with the large volume source. Hence the statistics of turbulent diffusion are considerably different for this source than they are for the continuous plume.

In classical diffusion theory, there are analytical solutions for an instantaneous point source. These result in a spherically symmetric Gaussian cloud or puff. However, these solutions are not applicable for the large volume sources that would be generated by a Plowshare cratering application. For instance, as time approaches zero in the instantaneous point source, the concentration goes to infinity. This implies an infinite exposure rate which is unrealistic. Yet, realistic estimates of early time exposure rates are needed.

Let us assume that the fraction of nuclides produced which are vented to the atmosphere is independent of the explosive yield. Then the initial cloud concentration, for those nuclides whose production is directly proportional to the yield, is independent of yield. This is because the initial volume of the volume source is almost directly related to yield.[14] Thus, as the yield increases the nuclide production increases and the initial volume, within which the effluent is distributed, increases in about the same proportion. Total exposure is dependent upon cloud passage time as well as upon concentration. Assuming a constant wind speed during cloud passage, the exposure time is directly related to a cloud dimension. Any one dimension of this initial volume source increases about as the cube root of the yield. Thus, as yield increases, total exposure experienced by an individual in the path of the effluent only increases as the cube root of yield.

For those nuclides whose production is independent of yield, the initial concentration is inversely proportional to the yield. The total exposure to this type of nuclide, from a passing cloud is inversely proportional to the 2/3 power of the yield.

After a day or two, when the effluent size is measured in the hundreds of kilometers, the effluent doesn't know what its original size was. Thus, the initial size associated with the effluent is not important when one is concerned about very late time concentrations.

Another reason that the classical diffusion theory instantaneous point source solutions are not applicable to large volume sources generated by Plowshare cratering applications is that analytical solutions require the assumption that the atmospheric diffusivity is independent of time or space. In fact, the rate of atmospheric diffusion is dependent upon the scale of the process and thus increases with time.

Therefore, at the Lawarence Radiation Laboratory (LRL) a numerical model was developed[15] which incorporates, in a rational way, what is currently known about atmospheric diffusion of large clouds.

The numerical model is two-dimensional; three-dimensional diffusion is obtained by assuming circular symmetry about a vertical axis. The basic differential equation to be numerically integrated is:

$$\frac{\delta \chi}{\delta t} = K_r \left[\frac{\delta^2 \chi}{\delta_r^2} + \frac{1}{r} \frac{\delta \chi}{\delta r} \right] + \frac{\delta}{\delta z} \left[K_z \frac{\delta \chi}{\delta z} \right] \qquad (2)$$

where χ is concentration per unit volume, r is radial distance from the axis of symmetry, z is vertical distance, K_r and K_z are radial (or horizontal) and vertical diffusivity, respectively. Radial diffusivity is assumed to be independent of height, and vertical diffusivity is independent of radial distance from the cloud center. The diffusivities are determined by the turbulent properties of the atmosphere and the scale of the cloud.

The solution of Equation (2) is straightforward. The secret of success lies in the manner in which the horizontal and vertical diffusivities are specified as a function of time and space. In the numerical model being described here, the predictions of similarity theory as applied to atmospheric diffusion[16] are used to predict the horizontal diffusivity as a function of the cloud size and as a function of the turbulent properties (specifically the turbulent dissipation) of the atmosphere.

In the case of K_z, the similarity predictions for kilometer-sized clouds would result in unrealistic values used near the ground surface. Because there are much data on near-ground surface vertical diffusivities and some data on how these vary with height, it was decided to let K_z be an arbitrary function of height and time. This would also allow us to "mock up" the effects of temperature inversions in the free atmosphere on vertical diffusion. However, the computer code currently uses the simplified form of K_z as a function of height, as given in Figure 3. Therefore, K_z is allowed to increase linearly with height in the boundary layer and then is held constant with height until the top of the mixed layer is reached. It is implied that the environmental lapse rate is almost dry adiabatic to the top of the mixed layer. Above this height, vertical diffusivity is allowed to decrease with height until it reaches a prescribed "ambient value" for the free atmosphere. The depth of the boundary layer, the altitude of the top of the mixed layer, the altitude of the stable layer, the value of K_z at one meter above the ground, the value of K_z immediately above the top of the boundary layer, and the value of K_z above the stablizing inversion are all input parameters. In the current version of the numerical model these parameters along with time, altitude above mean sea level of the ground, height of the cloud center, atmospheric dissipation, and rainfall rates are read in as an input table. Thus, all of these parameters can be arbitrary functions of time. The numerical model interpolates linearly between values specified at discrete time intervals. It is obvious that all of these K_z parameters are not well measured for any one particular event. Nevertheless, it should be pointed out that all of the details of K_z which are so important for micrometeorological calculations are not as important for predictions of the gross characteristics of large volumes of effluent. By an examination of upper air temperature and wind data and judicious use of micrometeorological studies in the surface boundary layer, reasonable estimates of these turbulent parameters can be made for any particular event.

The geometry associated with the numerical model is depicted in Figure 4. As is evident from this figure, the numerical model assumes circular symmetry. This is a weakness in this particular model because it is not then possible to explicitly handle accelerated diffusion caused by persistent (in time) changes in horizontal wind speed and/or direction throughout the depth of the effluent.

There are several nondiffusive effluent depletion mechanisms included in the numerical model. Non-falling but near-ground surface effluent tends to deplete some of its material to the ground by impaction of submicron particles on vegetation or by absorption of gas by vegetation. In atmospheric diffusion problems, this form of depletion is usually handled by multiplying an empirically determined deposition velocity times the ground level air concentration. This results in a net flux of material toward the ground. Deposition velocities have been empirically determined for different radionuclides. The numerical model being discussed here uses this approach, with a deposition velocity being specified as an input parameter. As part of the concentration calculations, there results a ground-level concentration value. This is multiplied times the deposition velocity and integrated over time of cloud passage to calculate total deposited amount on the ground. The amount deposited is also depleted from the lower part of the cloud in this calculation.

Another nondiffusive depletion mechanism is precipitation scavenging. There are two forms of precipitation scavenging, one called washout and the other called rainout. Washout refers to the removal of particulate matter by rain drops falling through a cloud of particulates, colliding with the particles, and then carrying them on to the ground. Rainout refers to the condensation of water vapor on particulate matter and then their subsequent scavenging. The washout mechanism is the only one handled so far in this numerical model. Washout is dependent upon the precipitation rate and the particle size of the effluent being washed out. In calculations done with this numerical model, the precipitation rate is input as a function of time. The coefficients which are associated with particle size are put in at the beginning of a calculation. It should also be noted that the top of the precipitation scavenging can be independently specified in this numerical model.

The radioactivity decay of gross fission products as well as specific nuclides can be handled within this numerical model.

A typical calculation starts with the geometry of the stablized (motions which were initially responsible for producing the cloud are no longer important) cylindrical volume source and a Gaussian distribution of activity within this volume. Concentrations and deposition are calculated over the time period of interest, which may be several days, according to the input atmospheric turbulent parameters and nondiffusive depletion mechanisms along the effluent's trajectory. If the calculation is being performed in a diagnostic sense, after the event, then the meteorological parameters are those which are observed along the trajectory. If it is a calculation being done before the event, the along-trajectory meteorology may come either from climatology or from immediately pre-shot forecast meteorology.

Since the development of the numerical model, case studies are being done in order to see how well the model works against data. Before presenting some case study data, it should be noted that it is extremely difficult to obtain airborne concentration measurements with enough time and space resolution to determine the "representativeness" of each sample. In other words, was the sample taken within the majority of the effluent? In order to answer this question, much data are needed. It should be noted on the figures to follow that the concentrations are given in pCi/m^3 with the radioactive decay being included. It should also be remembered that normal atmospheric background has not been subtracted from these data and that this background value is about one pCi/m^3.

The NRX/EST EP-4A nuclear rocket engine test of March 25, 1966, was the first case study done. As such, no climatological or forecast calculations were done ahead of time. Thus, in Figure 5 we see the diagnostic calculation using the along-track observed meteorology and the measurements. All of the available aircraft data are plotted on Figure 5. It is obvious that much of the data was taken on the fringes of the cloud. An examination of the location of each filter sample with respect to the majority of the cloud also would lead one to this conclusion.[17] It should be emphasized that, on Figure 5 and on the figures to follow, an initial amount of radioactivity in the cloud and the along-track meteorology are used in the calculation. There is no attempt to normalize the diffusion calculations to the observed airborne concentrations.

Figure 6 shows calculations and data for the Phoebus IB-EP-4 nuclear rocket event of February 23, 1967.[18] In this case a climatological forecast was prepared ahead of time, using pre-event predictions for the radioactivity in the cloud and along-track climatology for the meteorology. There was no precipitation along this effluent trajectory, and the differences between the climatological and diagnostic prediction curves on Figure 6 are the result of differences in along-track turbulence. Again, all data available from aircraft are plotted on this figure. Thus, much of it is on the fringes of the cloud or just plain background levels. The altitudes of the effluent involved in Figures 5 and 6 were in the 8000- to 12,000-foot MSL range.

For the Plowshare cratering experiment, Cabriolet, of January 26, 1968, three different types of predictions were prepared. A climatological forecast using pre-shot estimates of airborne radioactivity was performed several weeks prior to execution. A forecast calculation was prepared using the pre-shot estimates for source term and forecast along-track meteorology as of about four hours prior to execution. Lastly, the diagnostic calculation has been prepared post-shot, using observed along-track meteorology and observed source term data for chemistry. These three types of calculations and the observations are presented in Figure 7. In this event the climatological and forecast calculations were made using the total amount of radioactivity expected; this would be related to exposure rate measurements within the effluent. This total included the gaseous products. The diagnostic calculation on Figure 7 was prepared using only the particulate activity. It is this particulate activity which would be collected on filters. This difference amounts to about a factor of two from H+1 to H+10 hours. At later times, say at H+50 hours, the contribution of the gaseous products to the total activity is negligible. This comment explains some of the difference between the forecast and climatological prediction and the diagnostic on Figure 7 at times of H+1 to H+10 hours.

The hollow symbols on Figure 7 are exposure rate measurements converted to pCi/m^3 with the assumption that the sample was taken in the middle of an infinite volume of effluent. The solid symbols are filter data. Only data which are considered to be reasonably representative of Cabriolet concentrations are presented in Figure 7.

The differences in the three types of predictions, which become apparent around H+10 hours, are the result of there being no precipitation in the climatological forecast, whereas, in the forecast calculation the precipitation was forecasted to start at about H+10 hours. In the diagnostic calculation, precipitation started at about H+8 hours. There is also some difference between the total amount of precipitation forecast and that observed.

Figure 8 gives the measured and calculated airborne concentrations for the Plowshare row-cratering experiment, Buggy, which was executed on March 12, 1968. The format of the data presentation is the same as was on Figure 7 except that all of the measurements are included. The climatological calculation is the only one presented here and it includes both the gaseous as well as particulate material. The forecast calculation is available, but there is little difference between it and the climatological and thus it is not added to the figure. Again, at times later than H+10 hours the contribution due to the gaseous is small compared to that due to the fine particulate matter. Thus, at these times the filter data can be directly compared to the calculation. A complete analysis of the Buggy event is not finished as of the time of the preparation of this paper. Therefore, no diagnostic calculation is presented for Buggy. However, it is not expected to differ by more than a factor of two or three from the climatological calculation presented in Figure 8. There was no significant precipitation along the trajectory of the Buggy effluent.

From these case studies it appears that the calculations made with the numerical model lead to airborne concentrations over time periods of a couple of days, which are within a factor of two of the measurements. This is considered quite good by this author when one considers the difficulty of numerical modeling on this time and space scale, and when one considers the dynamic range of 8-10 orders of magnitude involved in the concentrations.

A variety of other parameters are calculated with the numerical model. However, in the interest of brevity, only one other type of calculation will be presented here. This is a calculation of the deposition of material along the ground under the center of the volume of effluent. It must be stressed that this is not a fallout calculation. Deposition in this numerical model results from a turbulent impaction of submicron particles on vegetation, utilizing the empirical deposition velocity concept, and/or that material deposited by precipitation scavenging throughout the cloud. Figure 9 is such a deposition calculation for iodine-131 for Cabriolet. The data on this figure come from two sources: (1) Public Health Service (PHS) milk samples, and (2) material deposited on large plastic sheets which were located downwind and which are coated with a sticky substance. These data are probably only accurate to within a factor of two. The difference between the climatological and the diagnostic curves of Figure 9 at distances of 10-100 kilometers is one of source term. Pre-shot, seven to eight times more iodine-131 was expected to be vented than was actually observed. The other significant difference is the large peak in the diagnostic calculation about 400 kilometers downwind. This was a result of the interaction with snow shower activity in Cabriolet. The two milk samples above this hump were both collected in a "snow-out area." The remainder of the milk samples was presumably collected in areas for which there was no significant precipitation. The surface deposition data between 600 and 700 kilometers downwind was all snow data. The snow which fell on plastic sheets was bundled up and taken back to the laboratory for analysis. The range in values at this distance is the result of these samples being collected along a line which traversed the path of the effluent cloud. The hump in the climatological calculation at about 1000 kilometers is a result of depletion of effluent near the ground at night. On the next day vertical diffusion rates increase, more effluent diffuses down to near ground levels, and then the dry deposition increases.

Figure 10 is the iodine-131 deposition, calculations and measurements for Buggy. As the diagnostic calculations have not been performed, only the climatological one is presented here. There was no precipitation scavenging in Buggy.

In both Figures 9 and 10, all available data beyond about 100 kilometers are presented. Some locations are obviously closer to the path of the cloud center than are others.

SUMMARY

For the most part, trajectory predicting methods use wind data on isobaric surfaces and/or constant height surfaces and have accuracies of 20-60% of the total trajectory length over time periods of a day or two. Trajectories at low altitudes and particularly over rough terrain are the most difficult to forecast and have the worst accuracies in the above statistics. It is possible, however, to recognize meteorological situations which would result in a higher than average accuracy in trajectory predictions. A significant increase in trajectory forecasting accuracy, particularly at low levels, will probably not occur until observational data becomes available with more spacial resolution than is available now. For instance, the horizontal spacing between wind observation stations in the U.S. is around 300 kilometers.

Air parcels follow isentropic surfaces. As isentropic trajectories do not necessarily coincide with isobaric or constant height surfaces, it would be useful to perfect isentropic trajectory technique for routine use.

Although the mechanisms of turbulent diffusion are not yet well understood, there has been much experience with the use of Gaussian plume models to describe the diffusion from continuous point sources. Thus, in this paper only a brief review of the subject of diffusion from continuous point sources has been done. The only intent here was to show that such procedures do exist and to show how they are used.

The diffusion of almost instantaneously produced large volume sources of pollutants for time periods of a few days has not been well studied in the past. Thus, a major portion of this paper was devoted to discussing a numerical model, developed at LRL, of the large cloud diffusion processes. This numerical model uses the similarity theories of atmospheric turbulence for horizontal diffusion and permits the use of time- and height-dependent vertical diffusivities. Although not well vindicated for the diffusion of kilometer-size clouds, similarity theory predictions are consistent with the available atmospheric data.

The depletion of the cloud by ground deposition and precipitation has been included in the model, but the diluting effects of vertical shears in the horizontal wind field have not been included. Parameter studies indicate that the effect of any one atmospheric parameter is not too important on the long-term concentration calculations. However, the elimination of many of the real physical parameters in this model would have a significant effect on predictions. With the existence of such a numerical model, it is easy to perform sets of calculations with different possible real physical situations. This could give an expected range in concentration predictions for any particular application. Calculations using this numerical model for four case studies have indicated that accuracies of about plus or minus a factor of two in airborne concentration for time periods of a few days. The same range of accuracy is applicable to the long-range deposition calculations. It is satisfying to this author that these kinds of accuracies can be obtained with the model over such a period and over such a dynamic range in the concentration values.

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Table I. Relation of turbulence types to weather conditions.

A -- Extremely unstable conditions
B -- Moderately unstable conditions
C -- Slightly unstable conditions
D -- Neutral conditions*
E -- Slightly stable conditions
F -- Moderately stable conditions

Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or $\geq$ 4/8 cloudiness†	$\leq$ 3/8 cloudiness
<2	A	A - B	B		
2	A - B	B	C	E	F
4	B	B - C	C	D	E
6	C	C - D	D	D	D
>6	C	D	D	D	D

*Applicable to heavy overcast, day or night

†The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

Table 2. Relationship between Pasquill stability categories and the standard deviation of the wind direction fluctuation over 30 minutes.

Pasquill stability categories	
A, extremely unstable	25.0°
B, moderately unstable	20.0°
C, slightly unstable	15.0°
D, neutral	10.0°
E, slightly stable	5,0°
F, moderately stable	2.5°

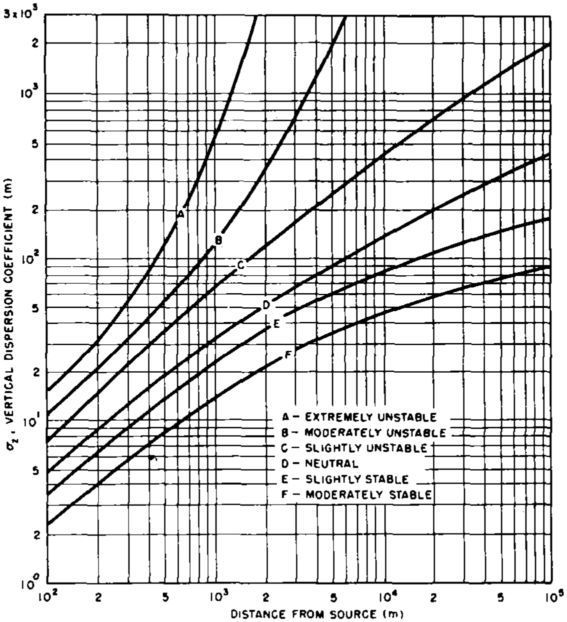

Figure 1. Vertical diffusion σ_z versus downwind distance from source for Pasquill's turbulence types.

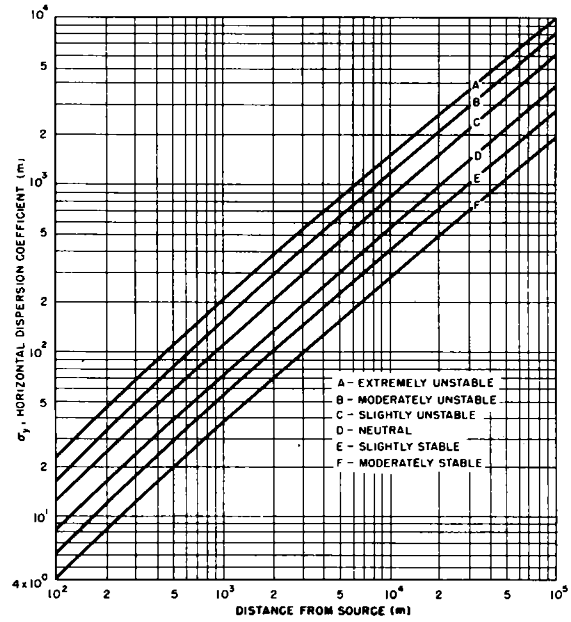

Figure 2. Lateral diffusion σ_y versus downwind distance from source for Pasquill's turbulence types.

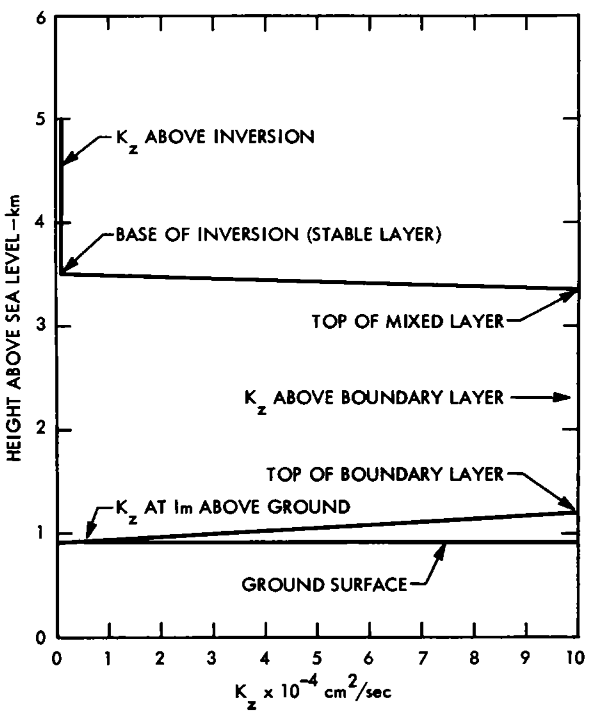

Figure 3. Model for vertical diffusivity as a function of height.

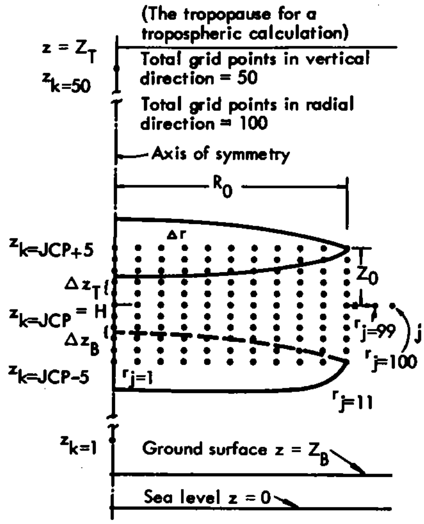

Figure 4. Grid system for the numerical diffusion model.

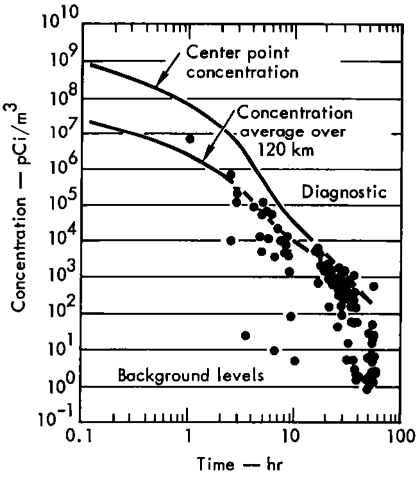

Figure 5. Calculated and measured airborne concentrations as a function of time for the NRX/EST EP-4A event of March 25, 1966.

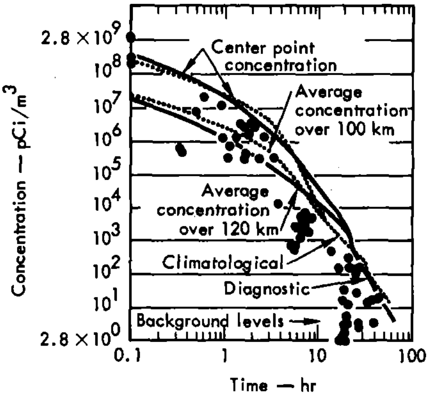

Figure 6. Calculated and measured airborne concentrations as a function of time for the Phoebus IB EP-IV event of February 23, 1967.

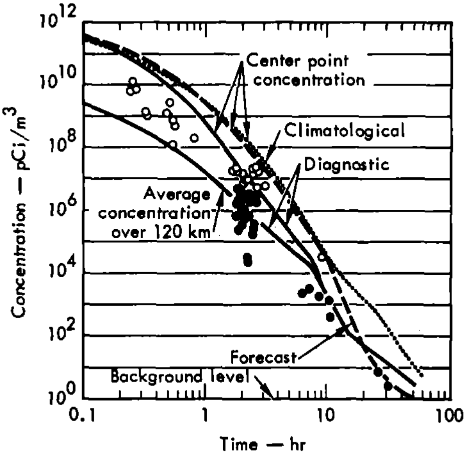

Figure 7. Calculated and measured airborne concentrations as a function of time for the Cabriolet event of January 26, 1967.

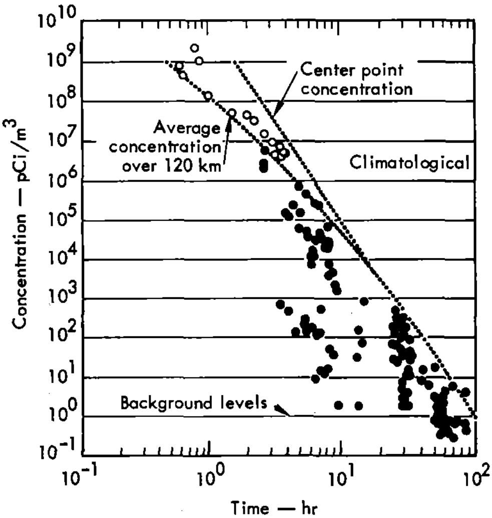

Figure 8. Calculated and measured airborne concentrations as a function of time for the Buggy event of March 12, 1968.

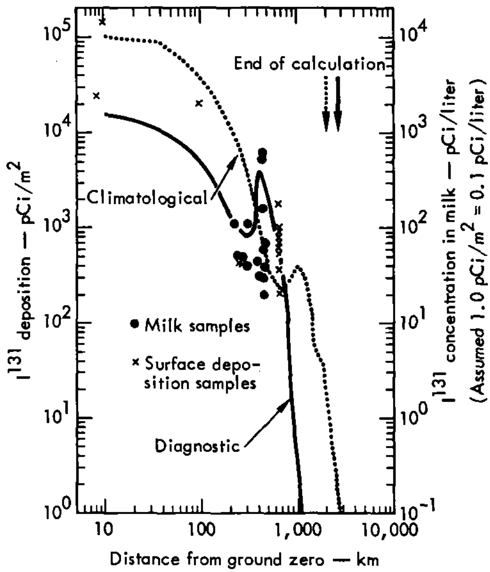

Figure 9. Calculated and measured iodine-131 deposition as a function of distance for the Cabriolet event of January 26, 1968.

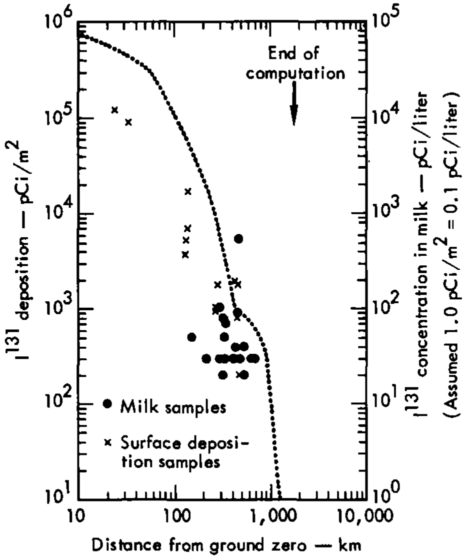

Figure 10. Calculated and measured Iodine-131 deposition as a function of distance for the Buggy event on March 12, 1968.

QUESTIONS FOR TODD CRAWFORD

1. From Alex Grendon:

   Was it a slip of the tongue when you said that dilution was inversely proportional to wind speed and hence earlier arrival at a given point is accompanied by greater dilution?

   ANSWER:

   No, I'm not sure of the use of the term "inversely." If you look at concentrations as a function of distance downwind, it's got wind speed on the bottom of the denominator. So as wind speed goes up, concentration goes down. That's what I meant to say.

2. From Alex Grendon:

   How would you interpret the horizontal line for the surface in the graph of K_z vs. height? It seems to imply that K_z near the ground is indeterminate.

   ANSWER:

   I'm not sure I completely understand the question, but the bottom curve on the graph I showed was a ground surface which was a horizontal line. Then I had a surface K_z coming back to some low value which I think on this particular example was 10^3. No, it is not zero at the ground and the values range at one meter from a few hundred centimeters squared per second at nighttime to a few thousand in daytime.

3. From Frank Baker:

   Can you predict the effects of a heavy rainfall on the deposition of radioactive fallout? I am assuming that you purposely detonated an explosive to coincide with the rain.

   ANSWER:

   Well, the example I showed was a calculation for Cabriolet in a snow storm and this was in a factor of 2 accuracy. I am the first to admit that our understanding of all of the precipitation scavenging mechanisms and the mechanics of a good heavy thunderstorm are not very well known. But, I think we can make a good stab at it and calculate the effect of a detonation in a heavy storm.

4. From T. C. Rozzell:

In the four case studies presented for concentration of radioactivity as a function of time in the cloud, what radioactivity was measured--was it total or of one isotope such as iodine-131 used in the deposition study?

ANSWER:

The curves I showed for the four case studies were total activity.

5. From George Collins:

Are standard values of diffusion parameters such as those of Pasquill always used for predicting short-term micro-meso scale dispersion patterns, or are these parameters determined from on-site measurements where the detonation is to take place?

ANSWER:

There are two sides to that question. The discussion of Pasquill categories is related to the underground engineering, small gaseous leak kind of phenomena. That could be easily determined by a very general categorization of on-site weather and it would be used. The other question perhaps relates to the parameters used in the large cloud diffusion model which is not necessarily Pasquill's category. Those would also be determined from an examination of observed weather or forecast weather depending on the kind of forecast or what kind of calculation you were doing. Yes, on-site and near-cloud data are used.

6. From L. Anspaugh:

Your calculations evidently depend on an initial measurement of cloud concentration. How well can this initial value be predicted for a cratering shot?

ANSWER:

They don't depend so much on an initial value of concentration as they do on an initial estimate of total curies to put in the cloud. And the best way of answering that is to refer to the two Cabriolet and Buggy case studies I showed where the climatology, of course, had a calculation and pre-shot estimate of total curies, and post-shot calculations have actual measurements of total curies.

7. From William King:

Empirical values of σ_y and σ_z were obtained from observing particulate behavior. Do gases diffuse in a similar manner or do you use different values for predicting concentration of gases?

ANSWER:

In the context of my talk, we have been talking about both gases and particulate. If we have been talking about particulate, we have been talking about particles which are too small to act much like a particle--act more gas-like. So the answer to your question is that I used the words particulate and gaseous interchangeably, but with the assumption that the particles are too small to have any significant fall speed.

8. From C. A. Pelletier:

Apart from the health significance, clouds of radioactivity can be a nuisance to other nuclear operations by setting off stack monitors, contaminating low-level experiments, etc. Is it possible to give warning to these facilities in terms of estimated arrival time, and cloud concentrations?

ANSWER:

Yes.

9. From Darryl Randerson:

The presence of a cloud of radioactive debris is associated with an internal boundary condition, namely, a tight gradient of radioactivity. Finite-differencing schemes tend to "smooth-out" this discontinuity at a physically unrealistic rate. In your model, were you able to resolve this difficulty?

ANSWER:

A mutual concentration as a function of distance about the cloud center in my model is a gaussian one, and horizontally it's always gaussian. Numerical errors don't diffuse it faster, but horizontally it is always gassian. It's not gaussian vertically because the diffusion rates are a function of height according to that slide I showed and also your deposition seems to wipe out the bottom of the cloud.

SESSION III - PART B

Chairman: Mr. Ross L. Kinnaman
Nevada Operations Office
U. S. Atomic Energy Commission
Las Vegas