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# SIMULATED ATMOSPHERIC DISPERSION OF RADIOACTIVE MATERIAL RELEASED IN AN URBAN AREA*

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ABSTRACT

A combination of Gaussian plume and particle-in-cell techniques are used to simulate the atmospheric transport and dispersion of a puff release of radioactive material. The release is caused by an accident that is assumed to occur during the shipment of the radioactive material through central New York City. The simulation provides estimates of volumetric and surface concentrations of the dispersed material that are used to predict radiation doses incurred by the City's population in the event of an accidental release. In the simulation, the release point is arbitrary and the material is assumed to be either a gas or fine particles.

The Gaussian plume model follows cloud concentrations from the release time until times when transport over distances up to 500 m has been achieved. The released cloud may stabilize at street level or above the mean buildings height; at a street intersection or in the middle of the block. The possibility of the formation of multiple clouds, owing to circumstances of wind flow direction and street geometry, is allowed.

Simulation of dispersion and transport of the material over distances in excess of 500 m is continued by the particle-in-cell (PIC) model, which uses the Gaussian plume concentrations as initial conditions, and which follows the subsequent motion of the material until it passes arbitrarily defined urban boundaries (~ 10 km from release point). The particle-in-cell model uses meteorological data and surface roughness (building height) data to estimate wind velocity profiles and eddy diffusion coefficients.

THIS PAPER DESCRIBES TWO MODELS OF THE ATMOSpheric transport and diffusion of material produced in a puff release in an urban setting. The release of material is assumed to occur during a transportation accident along an urban shipping route. The released material is radioactive, and could be a gas or a cloud of fine particles. The atmospheric transport models provide estimates of the normalized concentration (concentration per unit of material released) for use in a radiological health consequence model that is being used in a study of the risks attending the transportation of radioactive materials through a large city - (1).**

The present approach to the problem of matching the small-scale source formed just after release to the needs of a regional atmospheric transport model appears to be identical with the approach taken by Sheih - (2).

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** Numbers in parentheses designate references at the end of the paper.

## DESCRIPTION OF THE MODELS

THE MICROMETEOROLOGICAL MODEL - has been formulated to estimate the concentrations of airborne radioactivite material that may be present near an urban shipping route shortly after a postulated accidental release to the atmosphere. This model - called MICMET - was developed to treat some of the features of air flows that are likely to be encountered in urban street canyons and street intersections. The model is used both to estimate impacts shortly after the release, and to provide initial conditions for an urban-regional transport model that follows normalized concentrations of radioactivity over longer spatial and temporal scales.

The MICMET model uses data concerning the mean horizontal wind velocity at some reference height, the mean building height and the fraction of land occupied by buildings to generate a surface roughness length and a vertical profile of mean wind velocity according to formulae suggested by Lettau - (3) and Nicholson - (4). The turbulence intensities in the alongwind, crosswind and vertical directions are estimated as a function of the time-of-day of the release. These turbulence intensities are converted to standard deviations of cloud size as a function of distance travelled according to a relationship provided by Pasquil - (5).

A layered Gaussian, or plume element, technique was selected to describe the atmospheric transport - (6). The plume element model divides the initial cloud of material into a number of horizontal layers and treats each layer as though it had originated at a point source. The wind speed and turbulence intensity for each layer may be specified separately. As the layer elements are transported with time, the location of the centroid of the combined cloud and the standard deviations of the combined cloud are computed by integrating over the concentration fields of all source element layers. The model allows for variable, stabilized cloud height and number of layers (plume elements).

Depending upon the context of the release within the city, a number of different release conditions are permitted in the model. Two release locations within a street canyon are allowed: a release at a street intersection and a release at the mid-block position between two street intersections.

Release at Street Intersection - If the stabilized cloud height is greater than the average building height, then the cloud is allowed to travel freely in the mean wind direction. If the stabilized cloud height is less than the average building height, then the cloud is allowed to bifurcate (under certain conditions relating to wind direction and the street directions). The cloud (or clouds) are then constrained to travel along the street (or perpendicular streets) for one block length from the intersection and the cross-wind spread is limited by the width of the street. After the cloud (or clouds) have travelled one block length, the restriction on the cross-wind spread is arbitrarily removed.

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Release at Mid-block Position - If the stabilized cloud height is greater than the average building height, the cloud is allowed to travel freely in the mean wind direction. However, if the initial cloud height is less than the average building height, then two situations are possible: either the mean wind direction is within 30° of the street direction, or it is not. In the former situation, the cloud is constrained to travel along the street for one block, and its width is constrained to a maximum of one street width. In the latter situation, there is evidence from full-scale measurements that indicates development of a vortex flow in the street canyons - (7). The model treats the presence of such a vortex flow by computing a flushing time based on the work of Nicholson - (4). A cloud the width of the street canyon, one block long, is released to the free flow region above the buildings after one flushing time has elapsed.

THE URBAN-REGIONAL MODEL - The urban-regional atmospheric transport model, called PICMET, starts with small-scale estimates of normalized concentration provided by the micrometeorological model and follows the subsequent transport and atmospheric diffusion of the released material over larger spatial and temporal scales, out to the arbitrarily defined boundaries of the urban region under study. The transport and atmospheric diffusion are accomplished by approximately solving the atmospheric diffusion equation (see reference (8)), using the particle-in-cell (PIC) technique first employed for this purpose by Sklarew. The mathematical basis of the PIC technique is summarized by Sklarew, et al. (9) and (10); and only certain special features of the PICMET model will be described here.

The atmospheric diffusion equation is solved on a three-dimensional array of cells covering the urban region of interest. A mean wind velocity field and the three components of the eddy diffusivity must be prescribed at the centers of these cells. In the PICMET model, the mean wind field is constructed from the available measurements of the horizontal mean wind field (usually taken at a fixed reference height above ground level), the mean building heights and the fraction of land occupied by structures in the lowermost cells. These data are used first to construct vertical profiles of horizontal mean wind velocity through the surface layer overlying each base cell. The formulae used to define the vertical profiles are the same as those used in the MICMET model. The stratified horizontal winds so obtained are next forced to be divergence-free at cell centers by the addition of an appropriate, usually small, vertical component of wind. Finally, depending upon the size of particles that constitute the released material, an appropriate free-fall speed is added to the vertical component of wind in all the cells.

The measured horizontal mean wind at reference height, the average building height and the fraction of occupied land are also used to determine the vertical profile of the vertical component of eddy diffusivity, $K_z$, by formulae given in Ragland and Peirce - (11). A neutrally stable atmospheric surface layer is assumed in the calculation of $K_z$. The horizontal eddy diffusivities $K_x$ and $K_y$, are assumed to be proportional to $K_z$.

Boundary conditions in the PICMET model are of two kinds. The vertical sides and top surface of the array of cells are assumed to be transmitting boundaries; that is, material is allowed to freely flow across the boundary and is subsequently lost from the region. The bottom boundary of the array of cells (ground level) can be anything between a reflecting boundary and an absorbing boundary, depending upon a coefficient of surface absorption $\alpha$, $0 \leq \alpha \leq 1$, that is assigned to each ground level cell.

Within the boundaries, the PICMET model follows the motion of a large number, N, of Lagrangian particles each of which is assumed to carry a fraction, 1/N, of the released material. Initially, the Lagrangian particles are positioned in the array of cells with a density proportional to the normalized concentration of released material provided by the MICMET model. These particles are subsequently moved in short time steps along trajectories appropriate to the combined mean wind and turbulent flux velocity fields. A particle weight, P, initially = 1/N, is assigned to each of the Lagrangian particles. The particle weight never changes unless the particle is dropped from the set after crossing a transmitting or perfectly absorbing ($\alpha = 1$) boundary; or the particle crosses a partially absorbing boundary ($0 < \alpha < 1$). In the latter case, the particle is not dropped, but is physically reflected as though the boundary were perfectly reflecting ($\alpha = 0$). However, the reflected particle's weight is multiplied by $(1 - \alpha)$ and it is assumed that a fraction, $\alpha P$, of the released material has been deposited on horizontal surfaces during the time step and within the cell where the particle crossed the boundary. The particle weights P are used to calculate the normalized, volumetric concentrations of the still-airborne material in a mass-conserving way.

## RESULTS AND DISCUSSION

The urban region chosen for the sample calculations shown here is a portion of central New York City, centered roughly on Long Island City (see Figure 3). The region is 10 km long in the north and eastward directions. The PICMET model overlays the region with square cells 1 km on a side with a vertical dimension of 30 meters. There are four layers of cells above ground level. The average building height and fraction of occupied land data required for each ground-level cell were taken from NYC land-use planing maps or in some cases, estimated from aerial stereo photographs. The measured, mean horizontal wind data at a height of 30 m are interpolated from larger scale wind maps presented in an unpublished study of air pollution in New York City - (12).

Some results of calculations with the MICMET and PICMET models are shown in Figures 1-3. The results are for a release of a radioactive gas with a long (>> 1 hour) half-life. The ground surface is treated as a perfect reflector.

Figures 1 and 2 exhibit a sequence of the normalized concentrations that are generated by the combined models, starting with a hypothetical, accidental release in the southeastern corner of Manhattan. The wind pattern used in this example is typical of a day in the late Fall, 0900 EST. The wind is from the southwest (heading 50° east of north). Horizontal wind speeds at the reference level decrease from 4.4 $m \cdot s^{-1}$ in the southern part of the region to about 2.7 $m \cdot s^{-1}$ in the northern part.

A 500 m square area is shown in Figure 1 and is also located on the map of Figure 2-(a). The release is assumed to occur at a street intersection (all streets are assumed to run either parallel to, or perpendicular to the western border). Two clouds are formed; and after about 1.5 minutes, these respective clouds have drifted 281 m along the N-S street to the north of the release point, and 163 m along the E-W street to the east of the release point. These two clouds furnish the initial concentrations for the urban-regional transport model that takes over at R + 1.5$^{m}$* and produces the contours of normalized concentration in the lowermost layer of cells (below 30 m altitude), as shown in Figures 2(a)-2(c).

The particle in cell technique offers some resolution of the cloud structure on a scale smaller than cell dimensions. The dimensions of the particle envelope can be computed and used as standard deviations of a Gaussian cloud, thus providing an estimate of the upper limit on the normalized concentration of material present in the cell at a given time. The other alternative is to use the cell centered concentrations, contoured in Figures 2(a)-(c), as an average concentration in each cell at a given time.

To illustrate these features of the particle-in-cell technique for solving the atmospheric diffusion equation, some projections on the ground of the envelop of Lagrangian particles in a PICMET simulation are shown in Figure 3 at various times after release. The winds in this example apply to a day in late Summer, 0600 EST, when the horizontal wind is blowing from the northeast (heading 250° from North). The horizontal mean wind speeds decrease from 2.2 $m \cdot s^{-1}$ the northeastern corner of the region to about 0.04 $m \cdot s^{-1}$ in the southwestern corner. The hypothetical release occurs above the average building height (8 meters) at a point 1 km east of Long Island City. The elongation of the projected particle envelopes is a consequence of the increase in wind speed with altitude; particles in the upper cells move faster than particles near the ground.

*The notation, " R + A$^{m}$" means A minutes after release.

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(12) Readers interested in the data sets from the unpublished study of air pollution in New York City should contact:
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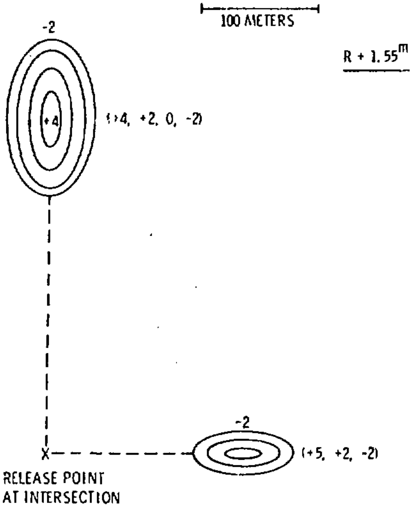



Fig. 1. Early-time contours of normalized concentration (MICMET). Contour values in: $\log_{10}$ [Ci·km$^{-3}$·(Ci released)$^{-1}$]. Release at street intersection southeastern Manhattan.

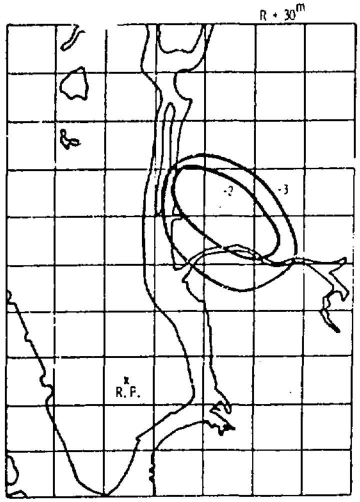
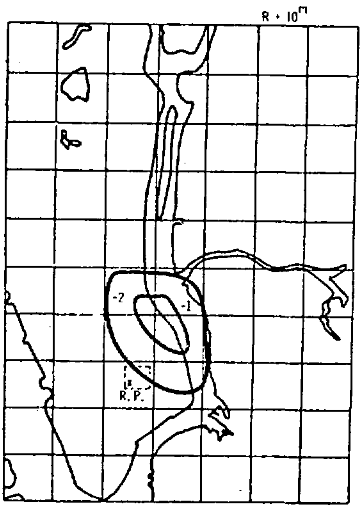



Fig. 2(b).



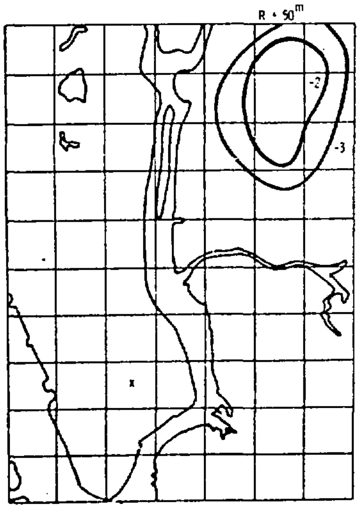




Fig. 2(a)-(c). Late-time contours of cell averaged normalized concentration (PICMET). Contour values in: $\log_{10}$ [Ci·km$^{-3}$·(Ci released)$^{-1}$]. Winds are for late Fall, 0900 EST.

Fig. 2(c).

PICMET - SAMPLE CALCULATION (Winds: 8/7/64, 0600 EST)

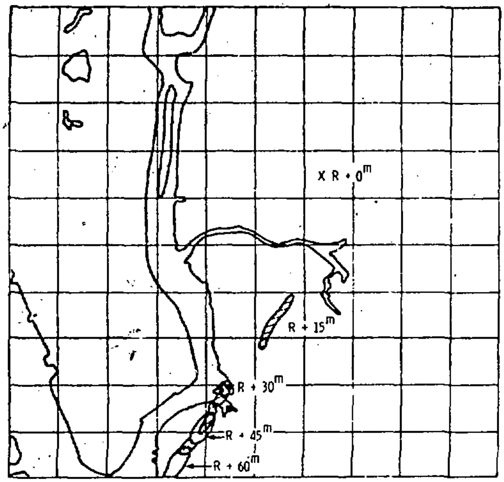



Fig. 3. Trace of particle envelope in PICMET simulation. Winds are for late Summer, 0600 EST.