62

This is an informal report intended primarily for internal or limited external distribution. (The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.) This report is not to be given additional external distribution or cited in external documents without the consent of the author or LLL Technical Information Department.

UCID - 16537

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

**NUMERICAL SIMULATION OF THE TRANSPORT AND
DIFFUSION OF NUCLEAR CLOUDS IN 3-DIMENSIONS**

R. Lange

J. B. Knox

July 9, 1974

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NUMERICAL SIMULATION OF THE TRANSPORT AND DIFFUSION OF NUCLEAR CLOUDS IN 3-DIMENSIONS

In this chapter, we describe an emerging validated capability for calculating a 3-dimensional distribution of a nuclear aerosol after its down range transport and diffusion to the site of a scavenging scenario or event. If, however, the scavenging interaction takes place over a reasonable length of time, such as a half hour or more, the processes of transport and diffusion during that finite time of scavenging also needs to and can, in fact, be simulated by the capability we now describe. The numerical simulation model which serves this general purpose has been developed under funding by the AEC's Division of Biomedical and Environmental Research (DBER). The application of this capability is an illustration of synergism between projects funded in our Atmospheric and Geophysical Sciences Division. The model to be described is known by the acronym - ADPIC - which stands for Atmospheric Diffusion by Particle In-Cell.

Estimates of the potential hazard from the rainout of nuclear aerosols to date have been accomplished without the explicit inclusion of the effects of wind shear deforming the cloud in space and time and without the specific inclusion of non-instantaneous deposition. We have deferred estimating the effects of these two factors on collateral damage in the research efforts at LLL until suitable tools were available. It should be remarked that we really don't know if, in fact, we have calculated the worst rainout case until a tool such as ADPIC is actually utilized in a

parametric study of the sensitivity of collateral damage to these effects and others. It could very well be that the worst rainout situation has not, to date, been calculated. By way of introduction and summary, it can be said that during the period the nuclear cloud has an "over-kill" capability, that is, while it has the capability to deliver doses far in excess of 150 rem, any process that spreads the cloud over a larger area may, in fact, lead to cases which are potentially of greater collateral damage than those that we have calculated. There are at least five parameters that must be considered and varied over reasonable ranges in order to examine their effect on rainout deposition patterns. These parameters include vertical wind shear, the time of on-set of rain, the intensity of the rain, the duration of the rain, and the rate of removal of the scavenging mechanism selected. The values of the removal rate selected for the problems in this paper are 10^{-3} per sec and 10^{-4} per sec. As more is learned about precipitation interaction scenarios and about the spatial distribution of removal rates within natural cloud systems, including their seasonal variations, it is quite possible it will be appropriate to examine other removal rates. It appears that the inclusion of a finite rain period when compared to the VI method, especially at early times, results in a substantial increase of the area of the 150 rad contour. For example, the 150 rad contour area is increased by a factor of two for the 1 kt debris cloud with a 30 minute rain period initiated at cloud stabilization.

Our study of the wet deposition surface patterns for a 1 kt FAB all fission nuclear debris cloud is divided into the following elements: (a) a brief description of the formulation of the ADPIC code; (b) a discussion of the verification of ADPIC solutions against closed-form

analytical solutions; (c) the validation of the ADPIC simulation against regional tracer studies at Idaho Falls, NRTS; (d) the formulation of wet deposition in ADPIC; and (e) the wet deposition patterns as a function of removal rate and directional and speed wind shear.

(a): DESCRIPTION OF ADPIC

ADPIC is a hybrid Lagrangian Eulerian 3-dimensional particle-in-cell code for calculating the transport and the anisotropic diffusion of a pollutant from its source to its temporal and regional distribution at arbitrary times. ADPIC represents a convenient mathematical framework in which to include the following effects on a regional basis: speed and directional wind shear; occurrence of calms; space variable surface roughness; wet and dry deposition; radioactive decay; gravitational settling; space and time dependent eddy diffusion parameters; and single or multiple sources of continuous or instantaneous nature. ADPIC solves the 3-dimensional advection diffusion equation in flux conservative form using a pseudo-velocity technique for a given regional mass consistent advection field in 3-dimensions and in time. In this method the Lagrangian particles represent the activity distribution and concentration associated with the nuclear aerosol within the structure of an Eulerian grid (the governing equations are shown in Figure 1). The chief advantages of this ADPIC approach are a) the artificial diffusion inherent in purely Eulerian finite difference codes is practically eliminated and b) the Lagrangian coordinates representing mass or activity can be tagged so that the age of each particle is known at all times. Two versions of ADPIC have been

ADVECTION - DIFFUSION EQUATION:

$$\frac{\partial \chi}{\partial t} + U_A \cdot \nabla \chi = \nabla \cdot K_{ij} \nabla \chi$$

ASSUME:

$$\nabla \cdot U_A = 0 \quad (\text{INCOMPRESSIBILITY})$$

DEFINE:

$$U_D = - K_{ij} \frac{\nabla \chi}{\chi} \quad (\text{DIFFUSIVITY VEL.})$$

PSEUDO-VELOCITY FORM OF
DIFFUSION - ADVECTION EQUATION:

$$\frac{\partial \chi}{\partial t} + \nabla \cdot (U_p \chi) = 0$$

WHERE $U_p = U_A + U_D$

- and
- U_p is the pseudo velocity vector
 - U_A is the advection velocity vector
 - U_D is the diffusivity velocity vector
 - K_{ij} is the diffusivity tensor
 - χ is the concentration

FIG. 1

developed: one version uses a fixed regional Eulerian grid so that complex surface boundary conditions may be incorporated in the solution; the second version uses an expanding grid that travels with the center of the pollutant cloud over flat terrain and automatically expands with the expanding cloud. The latter version is applicable to sensitivity studies in which a large number of parameters are varied. The grid spacing and the eddy diffusivity velocity algorithm used in ADPIC for the 2-dimensional case is shown in Figure 2.

Each ADPIC time cycle (Δt) consists of an Eulerian and a Lagrangian part. As shown in Figure 3, in the Eulerian part, the diffusivity velocity vector, $\vec{U}_d$ and the pseudo velocity vector $\vec{U}_p$ are calculated as functions of the concentration field χ , the eddy diffusivity tensor K_{ij} and the mass consistent regional flow field $\vec{U}_a$. In the Lagrangian part, the new position vector, $\vec{R}$, for each Lagrangian particle is calculated from its old position vector plus the displacement of the particle in the pseudo-velocity vector field $\vec{U}_p$. It should be mentioned that the advective vector field $\vec{U}_a$ could be furnished externally by a regional mass consistent objective analysis code, a regional predictive meteorological code, an urban heat island simulation code, or a hydrodynamic model of a convective system. We have, of course, not achieved all of these objectives at this time, and will report the results when utilization of this code includes the $\vec{U}_a$ input derived from regional objective analysis codes as a higher level of sophistication.

It is perhaps pertinent to explain briefly in a simple 1-dimensional example the way in which the ADPIC formulation eliminates the fictitious diffusion plaguing the purely Eulerian finite difference approach.

GRID MESH:

2-DIMENSIONAL VIEW:

DIFFUSIVITY VELOCITY ALGORITHM:

$$U_{x_D} = - \frac{K_{xx}}{\bar{\chi}} \frac{\Delta \chi_x}{\Delta x}$$

$$U_{x_D} = -2 \frac{K_{xx} (\chi_2 + \chi_3 - \chi_1 - \chi_4)}{\Delta x (\chi_1 + \chi_2 + \chi_3 + \chi_4)}$$

$$0 \leq |U_{x_D}| \leq 2 \left| \frac{K_{xx}}{\Delta x} \right|$$

2-DIMENSIONAL CASE.

FIG. 2

ADPIC TIME CYCLE:

EULERIAN PARTICLES:

$$U_D = - K_i \frac{\nabla \chi}{\chi_i}$$

$$U_P = U_A + U_D$$

LAGRANGIAN PARTICLE

$$R_{NEW} = R_{OLD} + U_P \cdot \Delta T$$

FIG. 3

In the upper portion of Figure 4, we show the fate of a pollutant in a 3 cell simulation of diffusive transport where all of the pollutant is in the first cell initially ($T=0$). At the end of a small time step ($T=1$) a portion of the pollutant in the first box has been distributed to the second cell and, in like manner, at the end of the second time step ($T=2$), a portion of the pollutant has been transported to the third cell. During successive time steps pollutant originating in the first cell is transmitted through the grid "too fast" because the pollutant in any cell with an adjacent empty cell is instantaneously shared. In contrast to this, the particle-in-cell treatment of diffusion moves each particle with the vector velocity $\vec{U}_p$ which incorporates the diffusive transport. The particles are seen in the lower part of Figure 4 to move in a more physically consistent manner.

(b) VERIFICATION OF ADPIC AGAINST ANALYTICAL SOLUTIONS

The verification studies of the solution of ADPIC against the closed form analytical solutions are summarized in Table 1. These studies indicate that the standard deviation of the pollutant distribution was reproduced by the ADPIC solution within a maximum error of 5% and a mean error of 2% of the standard deviation for the analytical solution. The importance of this result is that the ADPIC code represents a reasonably accurate calculational framework for attacking regional transport diffusion problems in multi-dimensional space for transient regional flow fields. In addition, the accuracy of the method appears to be sufficiently high and the residual errors are normally small in comparison to our knowledge of the source

PURELY EULERIAN DIFFUSION CODE:

SHADED AREA, REPRESENTS CELL CONCENTRATION

PARTICLE - IN - CELL CODE:

1-DIMENSIONAL EXAMPLE

FIG. 4

TABLE 1.

ADPIC VERIFICATION AGAINST CLOSED GAUSSIAN SOLUTIONS

For initially Gaussian, instantaneous, and continuous sources ADPIC has been found to agree with analytic solutions to the diffusion-advection equation to within 5% of the standard deviation for the following cases:

1. Instantaneous Source; Constant K Diffusion
2. Instantaneous Source; Scale Dependent $K(t)$ Diffusion.
3. Instantaneous Source; Constant K Diffusion in simple Vertical Speed Shear $U=U(z)$, $V=W=0$.
4. Continuous Source; Constant K Diffusion.
5. Continuous Source; Constant K Diffusion; Advection $U=2$ m/sec.
6. Continuous Source; Constant K Diffusion; Advection $U=10$ m/sec.

term for most applications. The quality of the ADPIC solutions, therefore, is governed by our knowledge of the temporal-spatial regional flow fields and the spatial distribution and time dependency of the eddy diffusion processes.

We now proceed to discuss in some detail the validation for Cases 2 and 3 of Table 1 performed by the automatically expanding-grid version of ADPIC. (Cases 1 and 4 through 6 are discussed in Reference 1.) Validation Case 2 is the instantaneous source for scale dependent diffusion in the 2-dimensional mode in which we evoke some 14×14 cells in the x, y plane and depict the distribution of particles by a 3,168 Lagrangian marker particles subject to the scale dependent diffusion formulation provided by Walton.^[2] The upper panel of Figure 5 shows the initial distribution of the pollutant in the y, z plane as depicted by the ADPIC code and by the analytical solution. The lower panel of Figure 5 shows the distribution of pollutant in an unbounded y, z plane with the small rectangle in the center of the panel depicting the calculation grid. The initial distribution of the pollutant in 2-dimensional space is shown inside the calculational grid by Lagrangian marker particles. Figure 6 displays the same information after the passage of 88,720 seconds and compares the ADPIC solution to the analytical solution in the upper panel in the y, z plane. The actual spatial distribution in the y, z plane is shown in 2-dimensions in the lower panel after anisotropic diffusion has converted the cloud into a thin horizontal pancake shaped cloud due to the fact that the scale dependent diffusion coefficient operating the y dimension far exceeds that of the vertical eddy diffusion coefficient.

CASE 2. SCALE DEPENDENT DIFFUSION.

$$K(t) = \epsilon^{1/3} \left(\sigma_0^{2/3} + \frac{2}{3} \epsilon^{1/3} t \right)^2$$

I=ADPIC

=ANALYT. SOLN.

Initial particle distribution, Y-Z plane, along the Y- and Z-axes,

Initial particle distribution Y-Z plane,

FIG. 5

CASE 2. SCALE DEPENDENT DIFFUSION.

Plot of particle distribution,
Y-Z plane, along the Y- and Z-
axes at Cycle 100, $T = 88\,720$ s.

Particle distribution at Cycle 100, $T = 88\,720$ s, Y-Z plane.

Figure 7 shows the cloud center concentration as a function of time for both the analytical solution and the ADPIC solution up to approximately 100,000 seconds. It should be noted from Figure 6 that the tails of the distribution and the magnitude of the peak concentration are correctly calculated and are essentially free of the fictitious diffusion processes that have contaminated previous diffusion calculations done in a purely Eulerian framework.

Validation Case 3 is that for an instantaneous point source with constant diffusion coefficients and incorporating a strong simple vertical wind speed shear in 3-dimensional space. We utilize 20 cells in each dimension x , y , z and depict the initial distribution of the spherically symmetric Gaussian cloud by some 10,000 Lagrangian marker cells. Figure 8 displays the distribution of Lagrangian marker cells at approximately 5 seconds in the x , y plane in unbounded shear flow for this case.

The upper panel of Figure 9 displays the comparison of the analytical solution and the ADPIC solution in regard to the number of particles per cell as a function of distance in the x , z plane at a time of approximately 6300 seconds. The panel in the lower part of Figure 9 shows the distribution of the pollutant after deformation transport and diffusion in the unbounded shear flow. Figure 10 shows relative cloud center concentration as a function of time for the shear flow case.

The two validation case studies comparing the ADPIC solutions to closed analytical solutions depict in a representative way the calculational capability of this code to treat anisotropic diffusion of pollutants in stratified shear flow.

CASE 2. SCALE DEPENDENT DIFFUSION.

Plot of relative particle concentration per cell at cloud center versus time.

FIG.-7

16
**CASE 3. INSTANTANEOUS SOURCE WITH CONSTANT K DIFFUSION AND
SIMPLE VERTICAL ADVECTION SHEAR $U = U(z)$.**

NUMBER OF CELLS = $20 \times 20 \times 20$ (X-Y-Z PLANES).

NUMBER OF PARTICLES = 10 000.

SHEAR = $dU/dz = .125 \text{ sec}^{-1}$.

INITIALLY SPHERICALLY SYMMETRIC GAUSSIAN PARTICLE
DISTRIBUTION.

Particle distribution at cycle 20, $T = 5.3 \text{ s}$, X-Z plane.

CASE 3.

DIFFUSION IN SHEAR FLOW.

Plot of particle cell concentration
versus distance, cycle 120,
T = 6328 s, X-Z plane, along
the Z-axis,

Particle distribution at cycle 120, T = 6328 s, X-Z plane,

CASE 3. DIFFUSION IN SHEAR FLOW.

Relative cloud center concentrations, puff diffusion in simple shear flow

(c): VALIDATION OF ADPIC AGAINST A REGIONAL TRACER STUDY AT THE IDAHO FALLS NRTS SITE.

The National Oceanic and Atmospheric Administration has maintained a capability for performing regional tracer tests at the Idaho Falls National Reactor Test Station for the past few years. The NRTS staff at that location provided both the meteorological and source term information for one of their methyl iodine releases. That test consisted of a three hour release of methyl iodine injected into a transient regional flow field whose meteorological properties were documented by some 17 meteorological towers as well as upper level wind measurements. In addition, 36 field samplers were arranged in four arcs at various distances downwind from the source.

¶ The regional flow field was calculated by the LLL 3-dimensional mass consistent wind field code known as MATHEW.^[3] Its output for several hours after release provides the description of the regional flow field necessary to do the atmospheric transport diffusion calculations. The ADPIC code was utilized to simulate each sampler on each arc by counting the particles passing through a sampler cell volume as a function of time, thus simulating the time history of the passage of the cloud over each of the samplers, while at the same time calculating the total spatial-temporal distribution of the pollutant. The details of the ADPIC problem set-up and an assembly of the results are indicated in Table 2.

As an aid to interpreting the results, Figure 11 shows the complex topography of the Idaho Falls region and the general outline of the plume as it was transported downwind from its source. It is perhaps pertinent to mention that the same topographic boundary conditions have been utilized in both the regional flow field model and in the solution of regional

- 50 -
Table 2

'ADPIC' VALIDATION AGAINST FIELD TRACER STUDY AT 'NRTS'
IDAHO FALLS.

(Extra space in here)

THE FIXED GRID VERSION OF 'ADPIC' WAS USED TO VALIDATE
the AGAINST AN ^{131}I RELEASE AT 'NRTS'. THE MODELING INCLUDED
COMPLEX TOPOGRAPHY AND A GIVEN MASS-CONSISTENT THREE-
DIMENSIONAL WINDFIELD FROM A CODE DEVELOPED AT LLL (MATHEW).

COMPARISON WAS MADE, IN INTEGRATED ACTIVITY ($\text{mCi} \cdot \text{s} / \text{m}^3$)
FOR 36 FIELD SAMPLERS, ARRANGED IN 4 ARCS AT VARIOUS
DISTANCES FROM THE SOURCE, WITH 'ADPIC' SIMULATED SAMPLERS.

'ADPIC' SIMULATES SAMPLERS BY COUNTING PARTICLES PASSING
THROUGH A CELL VOLUME WITH SAMPLER COORDINATES AT ITS CENTER.

THE ^{131}I 'ADPIC' PROBLEM SETUP.

NUMBER OF GRID CELLS: $16 \times 24 \times 24 = 9216$

VERTICAL CELL SIZE = 50 m ; HORIZ. CELL SIZE = 4300 m.

STABILITY CATEGORY PASQUILL C.

SOURCE RELEASE RATE = .379 mCi/s FOR THREE HOURS. AT .25

mCi/PARTICLE, THIS CORRESPONDS TO 14720 PARTICLES TOTAL.

DEPOSITION VELOCITY = 0.1 cm/s.

'ADPIC' RESULTS COMPARED WITH FIELD SAMPLERS IN THE FOLLOWING
WAY:

AGREEMENT WITHIN FACTOR OF:	2	5	10
FRACTION, $\frac{\text{ADPIC SAMPLERS}}{\text{FIELD SAMPLERS}}$	.44	.81	.89

IDAHO FALLS TOPOGRAPHY AND PLUME OUTLINE

FIG. 11

transport-diffusion by ADPIC. These boundary conditions are essentially depicted in this figure. The spatial distribution of the methyl iodine cloud at 1 hr is shown in Figure 12 by means of a projection of each of the Lagrangian particles onto the horizontal plane; sampling arcs a, b, c and d are shown as black dots. The region of calculation by the ADPIC code is also indicated.

Figure 13 shows the horizontal projection of the same Lagrangian marker particles representing the cloud onto the x, y plane at three hours. Embroidery along the left side of the pollutant cloud is introduced by topography. A simulated ADPIC surface air concentration history at sampler A-3 is shown in Figure 14 and is compared in terms of its breadth to the actual plume passage time documented by field measurements.

Figures 15, 16 and 17 show the integrated concentration at the samplers along arcs b, c, and d, as a function of crosswind distance. In Figure 16 the observed integrated concentrations are compared to the results that obtained by solutions with the standard bivariate Gaussian plume equations for the stability categories C and D. It should be noted that although one of the Gaussian solutions matches the peak concentration at what might be construed to be the plume axis, the general breadth of the pattern is badly missed and plume errors of 2 or more orders of magnitude occur on the left and right flanks/^(insert) We interpret this to be a result of the effects of regional directional wind shear and transient regional flow on the distribution of the pollutant. As can be seen from Table 2, ADPIC in fact predicts the breadth of the plume reasonably correctly with 44% of the points being within a factor of 2 of those observed and 80% being within a factor of 5.

(insert) and the second peak cannot be accounted for by the simple Gaussian plume model.

TOTAL X-Y PLOTS CYCLE 30 TIME 3.692E+03 (1 hr)

FIG 12

2-3-33N

FIG-13

FIG. 14

PROBLEM 2-3-33N

FIG. 15

FIG. 16

FIG. 17

Our interpretation of the sources of error in regard to ADPIC matching the observations is as follows: The principle sources of error result from the objective prescription of the regional flow field, the state-of-the-art prescription of eddy diffusion coefficients as a function of bulk meteorological variables and the sensitivity of the surface air concentration to simplifications made in representing topography in the MATHEW and ADPIC formulations. It should be clear that these sources of error far exceed the sources of error discussed in the comparison of the ADPIC code capability to be analytical solutions discussed in section (b).

(d): THE FORMULATION OF WET DEPOSITION MECHANISMS IN ADPIC

Washout is treated in the following way in ADPIC. For a specified rain rate prevailing over a given surface area, a washout coefficient $\Lambda(r)$ is assumed as a function of debris particles of size r . Because of their limited number, each ADPIC particle is much larger than a debris particle. Therefore, an ADPIC mass particle is initially considered to represent an integrated debris particle size distribution over sizes such that

$$M(0) = \int_{r=0}^{\infty} m(r, 0) dr,$$

where $M(0)$ is the initial mass of an ADPIC particle and $m(r,0)$ is the mass per unit radius of a debris particle of radius r at time 0. Constant density is assumed for the debris particles. $M(t)$, the mass of an ADPIC particle remaining after a time t in the rain for a given constant rain rate and raindrop size distribution, can then be written as^[4]

$$\begin{aligned} M(t) &= \int_{r=0}^{\infty} m(r, t) dr \\ &= \int_{r=0}^{\infty} m(r, 0) e^{-\Lambda(r)t} dr. \end{aligned}$$

To account for the diffusion and transport of pollutant as calculated by ADPIC, this function $M(t)$ is computed (or looked up from a table) at each ADPIC time step Δt . The fraction of mass $F(\Delta t)$ of an ADPIC particle washed

out and deposited on the surface during one ADPIC time cycle then becomes

$$F(\Delta t) = \frac{M(t) - M(t+\Delta t)}{M(t)} = 1 - \frac{\int_{r=0}^{\infty} m(r,0)e^{-\Lambda(r)(t+\Delta t)} dr}{\int_{r=0}^{\infty} m(r,0)e^{-\Lambda(r)t} dr}$$

This fraction of mass loss per cycle for each ADPIC particle is stored cumulatively each cycle in a two-dimensional, surface deposition array.

(e): WET DEPOSITION PATTERNS AS A FUNCTION OF RAIN RATE OR A REMOVAL RATE AND DIRECTIONAL AND SPEED SHEAR FOR 1 KT ALL FISSION DEBRIS CLOUDS

For the study of rainout from stabilized debris clouds following trajectories over long distances and time, the moving, automatically expanding grid version of 'ADPIC' is used. This insures uniform resolution of the cloud by the grid over many orders of magnitude of cloud growth.

In the following survey 'ADPIC' is used to examine the effects of instantaneous vs. non-instantaneous rainout under no shear, speed shear and speed plus directional shear conditions on a 1 kt all fission cloud, at both early and late time. Table 3 describes the problem parameters.

TABLE 3

DESCRIPTION OF THE 1 KT ALL FISSION PROBLEM

Number of ADPIC cells = 20 x 20 x 20

Number of particles = 11000

Initial Cloud Center Height = 3000 m

Initial Cloud Thickness* = 1860 m

Initial Cloud Radius* = 950 m

} at stabilization
time H+600 s

Yield = 1 kt at H+1 hour

Radioactive decay $\propto t^{-1.2}$ (t in hours)

Mean Advection Velocity = 11 m/s

Speed Shear $dU/dz = .0015 \text{ s}^{-1}$

Directional Shear $dV/dz = .001 \text{ s}^{-1}$

Horizontal Scale Dependent Diffusion $K_h = \epsilon^{1/3} (\sigma_0^{2/3} + \frac{2}{3} \epsilon^{1/3} t)^2 \frac{\text{m}^2}{\text{s}}$
with $\epsilon = 10^{-4} \text{ m}^2/\text{s}^3$

Vertical Diffusion $K_z = .1 \text{ m}^2/\text{s}$

Rain rates $\Lambda = \infty$, $.001 \text{ s}^{-1}$ and $.0001 \text{ s}^{-1}$

Rainout over the entire cloud

Rainout Times** 0 - 1800 s and 3600-5400 s

*Corresponds to two st. deviations from cloud center

**T=0 corresponds to stabilization time H-600 s

A summary of the survey problems and results is shown in Table 4. Note that the instantaneous VI was calculated at mean time of arrival defined as the midpoint of the rain period.

TABLE 4

TABLE OF SURVEY PROBLEMS AND RESULTS FOR 1 KT RAINOUT

PROB. #	SPEED SHEAR $\frac{dU}{dz}$ (sec ⁻¹)	DIR. SHEAR $\frac{dV}{dz}$ (sec ⁻¹)	Λ (sec ⁻¹)	RAIN PERIOD** (sec) START/STOP	PEAK DOSE*** Rad _∞	FRACTION OF† INITIAL ACTIVITY REMAINING AFTER RAINOUT	APPROX. AREA†† INSIDE 150 Rad CONTOUR (Km ²)
A	-	-	∞*	900/900	11,000	0	12
B	-	-	10 ⁻³	0/1800	7,700	.2	20
C	.0015	-	10 ⁻³	0/1800	7,700	.2	21
D	.0015	.001	10 ⁻³	0/1800	7,700	.2	21
E	-	-	∞*	4500/4500	850	0	78
F	-	-	10 ⁻³	3600/5400	480	.01	66
G	.0015	-	10 ⁻³	3600/5400	450	.01	68
H	.0015	.001	10 ⁻³	3600/5400	350	.01	68
I	.0015	.001	10 ⁻⁴	0/1800	830	.7	13
J	.0015	.001	10 ⁻⁴	3600/5400	50	.4	0

* Instantaneous vertical integral

** From stabilization time H=600 sec.

*** Infinite dose from mean time of arrival.

† Initial activity defined as $4.4 \times 10^{+8}$ Ci at H-1 Hrs.

†† Estimated from contour plots

Figures 18, 19 and 20 show the ground wet deposition patterns in isopleths for infinite dose from mean time of arrival for various rain rates and shear conditions for an early rain time from $t=0$ to $t=1800$ sec.* Problem A, Fig. 18 is the instantaneous total vertical integral at mean rain time of 900 sec without any shear. Problem B of the same figure shows the effect of noninstantaneous deposition over one half hour with a rain rate of $\Lambda = 10^{-3} \text{ sec}^{-1}$ again with no shear. Problem C and Problem D of Figure 19 show the additional effect of speed shear only and of speed plus direction shear. Problem I, Figure 20 is the same as Problem D but with a rain rate of $\Lambda = 10^{-4} \text{ sec}^{-1}$.

Figures 21, 22 and 23 show deposition patterns for a 30 minute rain period at later time from $t = 3600$ to $t = 5400$ sec. for the same variation of parameters of rain-rate and shear as for the early rain period discussed above. These are problems E, F, G, H and J.

In conclusion, Table 4 shows a summary of results for all the problems run in terms of peak infinite dose, fraction of H+I activity remaining after stop of rain and approximate area inside the 150 Rad_{∞} contour all as a function of rain period and rain rate. In general and within the limitations of this parameter study, one can say it appears that:

- 1) Shear effects are minimal at early times but become significant at later times in terms of lowering peak dose, increasing the overall total area and altering the shape of the entire deposition pattern. For a 1 Kt cloud the increase of the 150 Rad_{∞} contour area is not as critical at periods of 1 hour or later insofar as the peak dose is not much higher any more than the 150 Rad_{∞} level. For a larger yield this area increase would be expected to be critical.

* $t=0$ refers to time of stabilized cloud at H+10 min.

FIG. 18

PROBLEM C

ISOPLETHS

1.500E+03 1.500E+02 1.500E+01 1.500E+00 Rad $_{\infty}$

PROBLEM D

ISOPLETHS

1.500E+03 1.500E+02 1.500E+01 1.500E+00 Rad $_{\infty}$

FIG. 19

FIG. 20

FIG 21

PROBLEM G

ISOPLETHS: 150, 15, 1.5 $\text{Rad} \infty$

PROBLEM H

ISOPLETHS: 150, 15, 1.5 $\text{Rad} \infty$

FIG. 22

FIG. 23

2) Finite rain periods increase the areas of equal dose isopleths over those obtained from instantaneous full vertical integral deposition at a time equal to the mean rain time. This effect is most pronounced at early times, where an increase of about a factor of 2 is found.

3) The shape of dose isopleths is strongly affected by shear and by the time of occurrence of the rain period. Typically early dose ($t=0$ to $t=1800$ sec) isopleths tend to be cigar shaped while later time ($t>3600$) isopleths are more circular.

4) Inclusion of shear effects and finite rainout periods in the rainout calculations as done by ADPIC appears to be essential in determining a "worst case." For example comparing Problem H, Fig. 22 with Problem I, Fig. 20 indicates that a later rain period at a higher rain rate may be much worse than an early rain period at a lower rain rate in terms of the area inside the 150 Rad_∞ isopleths.

REFERENCES

1. Lange, R., "A Three-Dimensional Computer Code for the Study of Pollutant Dispersal and Deposition Under Complex Conditions," Lawrence Livermore Laboratory, Rept. UCRL-51462 (1963).

2. Walton, J. J., "Scale-Dependent Diffusion," J. Appl. Meteorol. 12, 547 (1973).

3. Knox, J. B., et al, "Methods of Calculating Atmospheric Transport and Diffusion," Lawrence Livermore Laboratory (to be published as a UCRL report).

4. Crandall, W. K., C. R. Molenkamp, A. L. Williams, M. M. Fulk, R. Lange, J. B. Knox, "An Investigation of Scavenging of Radioactivity from Nuclear Debris Clouds: Research in Progress," Lawrence Livermore Laboratory, Rept. UCRL-51328, January 17, 1973.

DISTRIBUTION:

Richard G. Semonin, Assistant Head
Atmospheric Sciences Section
Illinois State Water Survey
Box 232
Urbana, Illinois 61601

TID (3)

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."