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# DNAF-1

## An Analytical Fallout Prediction Model and Code

Atmospheric Science Associates
P.O. Box 307
363 Great Road
Bedford, Massachusetts 01730

31 October 1981

Final Report for Period 12 March 1980—31 October 1981

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DNAF-1 has been developed to rapidly predict fallout γ-ray activity from surface burst nuclear explosions. It is suitable for use in large-scale damage assessment studies. Explosion energy yield range is $10^{-3}$ to $10^{5}$ KT. Minimum input data requirements of the code are: total and fission yields, speed and direction angle of a single effective wind vector, and a wind shear parameter. Wind data in terms of a vertical profile of wind vectors may be supplied by

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20. ABSTRACT (continued)

the user, in which case the code will process the data such as to compute the effective wind vector and shear parameter.

The code will automatically compute and print a fallout map in terms of H + 1 hour exposure rate ordinates for a spatially undistorted array of points on the ground. Alternatively, the user may specify his own map boundaries and grid increments. He also may specify any number of ground points at which the code will compute H + 1 hour exposure rate and maximum effective biological dose. Both model and code are fully documented, and user instructions for the code are presented.

Results of a validation study are presented. Predicted fallout patterns are compared with observed patterns for five test shots that cover a wide range of energy yields. Predictions by the DELFIC and WSEG-10 models also are included. Visual comparisons of contour maps and various statistical comparison methods are used. DNAF-1 predictions are found to be substantially better than those of WSEG-10 and almost as good as DELFIC predictions.

# PREFACE

The author gratefully acknowledges the support and cooperation of Dr. David L. Auton of the Defense Nuclear Agency, and Mr. Ralph B. Mason of the Command and Control Technical Center (CCTC) who made exhaustive runs of the code on the CCTC computer, analyzed the results, uncovered numerous problems, and thus substantially assisted in the development of the model.

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TABLE OF CONTENTS


| Section | | Page |
|---|---|---|
| | PREFACE | 1 |
| 1. | INTRODUCTION AND BACKGROUND | 7 |
| 2. | DATA BASE | 9 |
| | 2.1 ACTIVITY DEPOSITION RATE | 9 |
| | 2.2 FALLOUT ONSET TIME | 9 |
| | 2.3 FIREBALL AND STABILIZED CLOUD DATA | 19 |
| | 2.4 NOMINAL PARTICLE | 20 |
| | 2.5 OBSERVED FALLOUT DATA | 22 |
| 3. | MATHEMATICAL DESCRIPTION | 23 |
| | 3.1 ACTIVITY DEPOSITION RATE FUNCTION | 23 |
| | 3.2 DEPOSITION AS A FUNCTION OF DISTANCE FROM GROUND ZERO | 25 |
| | 3.3 FARFIELD CORRECTION | 30 |
| | 3.4 UPWIND CORRECTION | 34 |
| | 3.5 FALLOUT TIME OF ARRIVAL | 35 |
| | 3.6 HORIZONTAL SPREAD OF THE NUCLEAR CLOUD | 35 |
| | 3.7 TURBULENT DISPERSION OF FALLOUT | 40 |
| | 3.8 WIND SHEAR DISPERSION AND CROSSWIND SPREAD OF THE FALLOUT PATTERN | 41 |
| | 3.9 GAMMA RAY EXPOSURE RATE AND MAXIMUM EFFECTIVE BIOLOGICAL DOSE | 44 |
| 4. | USE OF WIND DATA | 47 |
| | 4.1 GENERAL CONSIDERATIONS | 47 |
| | 4.2 EFFECTIVE FALLOUT WIND | 47 |
| | 4.3 SHEAR PARAMETER | 50 |
| 5. | VALIDATION | 52 |
| | 5.1 DISCUSSION OF RESULTS | 52 |
| | 5.2 DISCUSSION OF THE TEST SHOT DATA AND PREDICTIONS | 55 |

TABLE OF CONTENTS (Continued)


| Section | | Page |
|---|---|---|
| | 5.3 OBSERVED AND PREDICTED FALLOUT PATTERNS | 57 |
| 6. | COMPUTER CODE | 81 |
| | 6.1 GENERAL DISCUSSION | 81 |
| | 6.2 FALLOUT MAPS | 83 |
| | 6.3 INPUT OF WIND PROFILE DATA | 85 |
| | 6.4 STORAGE AND COMPUTATION TIME REQUIREMENTS | 90 |
| | 6.5 DESCRIPTION OF CARD INPUTS FOR THE DNAF-1 CODE | 91 |
| | 6.6 EXAMPLE PROBLEM AND PRINTOUT DESCRIPTION | 93 |
| REFERENCES | | 97 |
| APPENDIX A | GLOSSARY OF SYMBOLS AND FORTRAN MNEMONICS | 99 |
| APPENDIX B | GROUND ROUGHNESS AND INSTRUMENT RESPONSE CORRECTION FACTORS | 103 |
| APPENDIX C | FALLOUT PATTERN COMPARISON BY THE FIGURE-OF-MERIT METHOD | 105 |
| APPENDIX D | FORTRAN CODE FOR THE DNAF-1 FALLOUT MODEL | 107 |

LIST OF ILLUSTRATIONS


| Figure | | Page |
|---|---|---|
| 1 | Computer plots of activity fraction deposition rate vs. time as computed by DELFIC. - - - - - - - - - - - | 10 |
| 2 | Activity fraction deposition rate function, g(t), (eq. (6)), without farfield correction, vs. time for W = 1 KT. A sampling of DELFIC results are included for comparison. - - - - - - - - - - - - - - - - | 24 |
| 3 | Distribution of activity of depositing fallout in the hotline axis direction. - - - - - - - - - - - - - - | 27 |
| 4 | Comparison of Gaussian function with the function used in DNAF-1 to approximate the spatial distribution of cloud activity along the hotline axis. - - - | 28 |
| 5 | Activity deposition rate, $g(t)_f$, including farfield correction, vs. time. A sampling of DELFIC results are included for comparison. - - - - - - - - - - - - - | 32 |
| 6 | Basis of the time-of-arrival calculation. - - - - - - | 36 |
| 7 | Fallout time of arrival vs. distance from ground zero for several yields as computed by DNAF-1 and WSEG-10. | 37 |
| 8 | Crosswind-integrated activity fraction, $D(X)_f$ and $D(X)_u$, vs. distance from ground zero along the hotline. - - - - - - - - - - - - - - - - - - - - - - - - | 42 |
| 9 | Wind data card input for the example data listed in Table 7. - - - - - - - - - - - - - - - - - - - - - - - - | 89 |
| 10 | Test problem card input. - - - - - - - - - - - - - - - | 94 |

LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1 | SETTLING SPEEDS FOR THE NOMINAL PARTICLE, $\delta_{nom}$ = 229 μm | 21 |
| 2 | TEST SHOT DATA | 52 |
| 3 | COMPARISON OF OBSERVED AND PREDICTED FALLOUT PATTERN STATISTICS | 54 |
| 4 | OVERALL MEAN ABSOLUTE PERCENT ERRORS | 55 |
| 5 | EFFECTIVE FALLOUT WINDS AND SHEAR PARAMETERS COMPUTED FROM H HOUR WIND PROFILES FOR USE BY DNAF-1 | 57 |
| 6 | DESCRIPTION OF DNAF-1 CODE SUBROUTINES AND FUNCTIONS | 82 |
| 7 | EXAMPLE WIND DATA LISTING | 88 |

# 1. INTRODUCTION AND BACKGROUND

To quickly and efficiently estimate fallout radioactivity from large numbers of nuclear surface explosions, for example, for military damage assessment studies, a simple, very fast fallout prediction code is needed. While codes based on numerical models[1,2,3] provide flexibility of usage and relatively high prediction accuracy, they are cumbersome, use too much computer storage, require more input data than desired, and use too much computer time per prediction. A model which uses analytical equations rather than a numerical approach is appropriate for this purpose.

The model that has best satisfied these requirements in the past, the WSEG-10 model, has been used for more than twenty years for damage assessment studies[4,5]. WSEG-10 has recently been analyzed[6] and its prediction capabilities compared with those of several other models[7]. It was found that, while in several respects WSEG-10 is satisfactory in terms of its mathematical structure, its data base is obsolete, and this deficiency alone was seen to substantially compromise its prediction capability[7].

To upgrade prediction capability the easiest course would be to upgrade the WSEG-10 data base, but retain its mathematical structure. However owing to several deficiencies of the model itself, this course has turned out to be undesirable. The most important of these deficiencies are as follows. WSEG-10 mathematics are based on a curve fit of an exponential function to radioactivity deposition rate data that were calculated by an early fallout model. The particular model used was developed to predict fallout from surface bursts of large yield (i.e., megaton range) nuclear weapons. For these large yield cases the exponential function fits the deposition rate data reasonably well at intermediate and late times. Unfortunately, this is not the case for low yield explosions. Also, in no case does the exponential function go to zero at detonation time as a physically realistic function should do. Thus, to fit the low yield deposition rate data as well as the high yield data, and to force the fitted function to go to zero at zero time, a new mathematical base is needed.



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Another serious problem with WSEG-10 is that it assumes that a Gaussian function describes the vertical distribution of activity in the nuclear cloud. For shots with yields less than about 50 KT, this is a very poor assumption since much of the activity which will fall out locally is in the cloud stem, whereas the WSEG-10 Gaussian peaks near the cloud cap center height. In effect this procedure ignores the stem, even for low yield cases, and this also seriously compromises prediction capability.

To substantially improve prediction capability, and to extend the range of applicability to lower yields, an entirely new model is required. The DNAF-1 model has been developed to fill this need.

DNAF-1 also is based on a curve fit to calculated activity deposition rate data, though a new set of data is used, and a more appropriate function is used to fit the data. An entirely new approach is used to account for vertical structure of the stabilized cloud, which does account for fallout from the cloud stem. Indeed, revised data and updated modeling concepts are used throughout the development of the new model. Also, the yield range has been extended downward from 1 KT, the lower limit for WSEG-10, to $10^{-3}$ KT. The upper yield limit is $10^{5}$ KT.

The model computes gamma radiation from dry ground-deposited particulate fallout from the nuclear cloud cap and stem. This radiation issues from weapon debris fission products and from induced activity in the fallout. Contributions from throwout and induced activity in the crater or elsewhere are not included. Alpha and beta radiation are not treated.

In the next section, section 2, we discuss the more critical aspects of the data base used for the new model. In section 3 we detail the mathematical structure of the model, and in section 4 we discuss how wind data are used. Section 5 contains results of a validation study: predicted fallout patterns are compared with observed patterns for five test shots, and predictions by the WSEG-10 and DELFIC models are included as well as those by the DNAF-1 model. Finally, the computer code is described in section 6.

Throughout the presentation, we make comparisons between DNAF-1 and WSEG-10 modeling approaches and results wherever such is appropriate.

## 2. DATA BASE

### 2.1 ACTIVITY DEPOSITION RATE

As mentioned above, the DNAF-1 model is based on a mathematical function that is fitted to activity deposition rate data. These data represent rate of deposition of total fallout activity as a function of time and yield. Of course, it would be best to use observed data, but there are none, so instead we have used results generated by a special version of the DELFIC code[1,2].

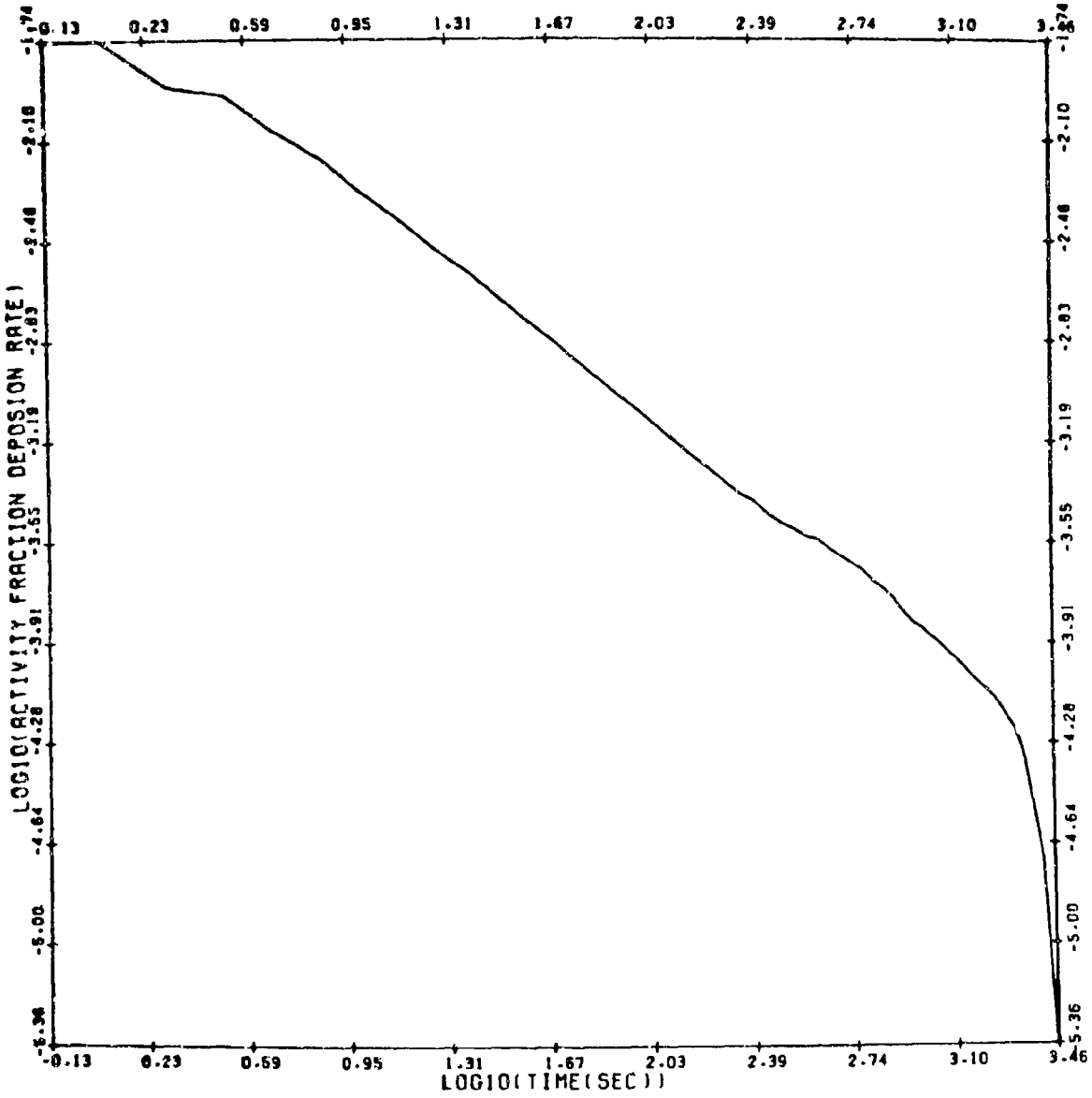
Nuclear cloud rise was calculated through the 1976 U.S. Standard Atmosphere[8] for every decade of yield from $10^{-3}$ KT to $10^{5}$ KT. Explosion was taken to be at sea level. Fission yield was taken to equal energy yield. Twenty thousand fallout parcels (100 particle size classes and 200 cloud subdivisions) were followed for each calculation. Cumulative activity tabulated as a function of time was differentiated to give deposition rate by the method of cubic splines[9]. Results are given in Figure 1. The uneven appearance of the curves at early times was caused by poor deposition statistics for the sparse, though highly radioactive, early fallout. Some numerical experimentation showed that increased resolution of the calculations produced curves of essentially the same shape; therefore, to save computer time the curves shown were accepted as an adequate compromise.

The fitting of a mathematical function to these data is described in section 3.1.

### 2.2 FALLOUT ONSET TIME

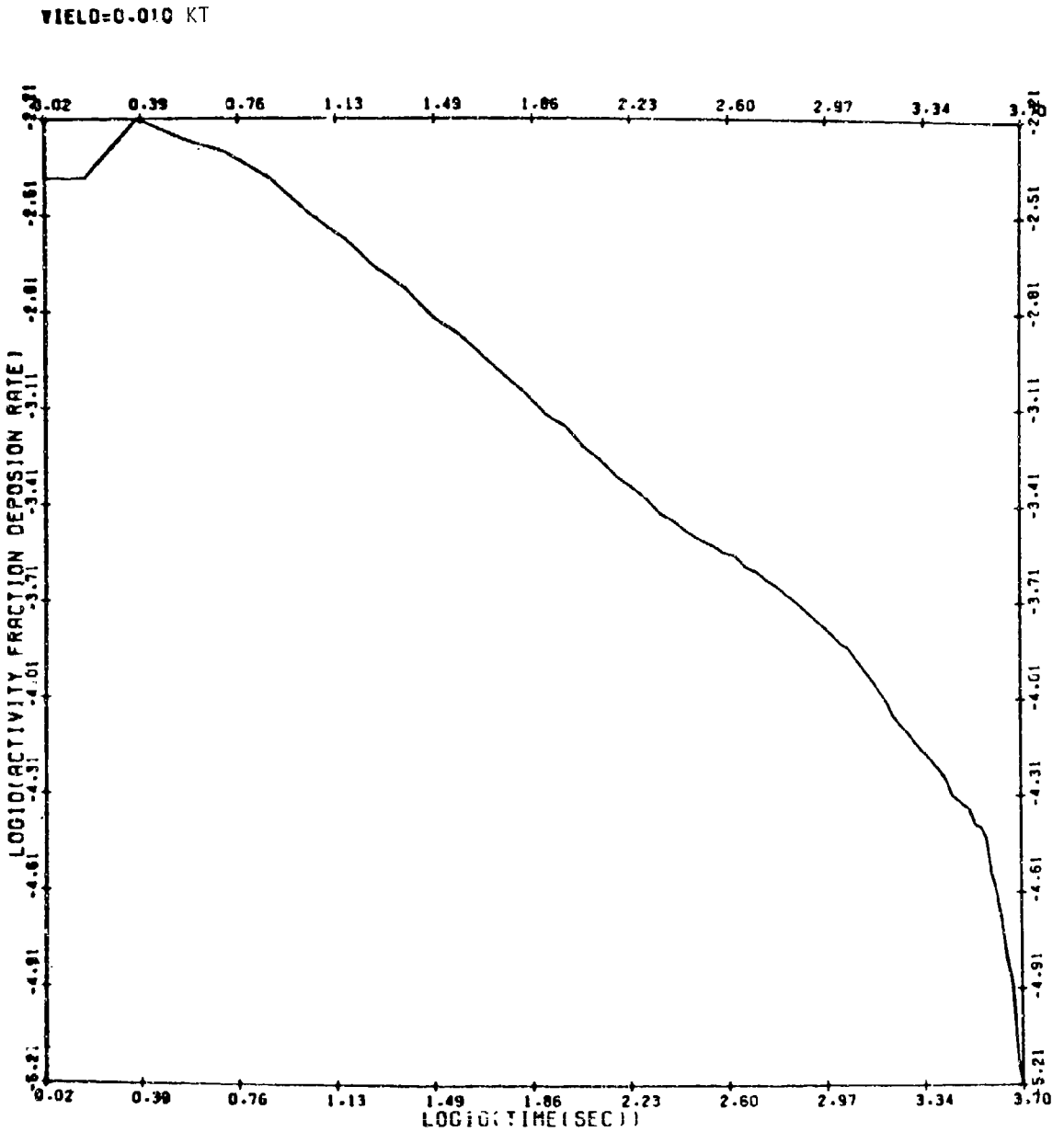
Fallout onset time, $t_0$, is the time of first impact of fallout on the ground. It is needed to calculate fallout time of arrival as a function of distance from ground zero, which in turn, is required for calculation of several critical parameters. Onset times for each decade of yield were tabulated from the DELFIC deposition rate data, and $\ln(t_0)$ was fitted by least squares to a polynomial in $\ln(W)$. The result is

YIELD=0.001 KT




a.

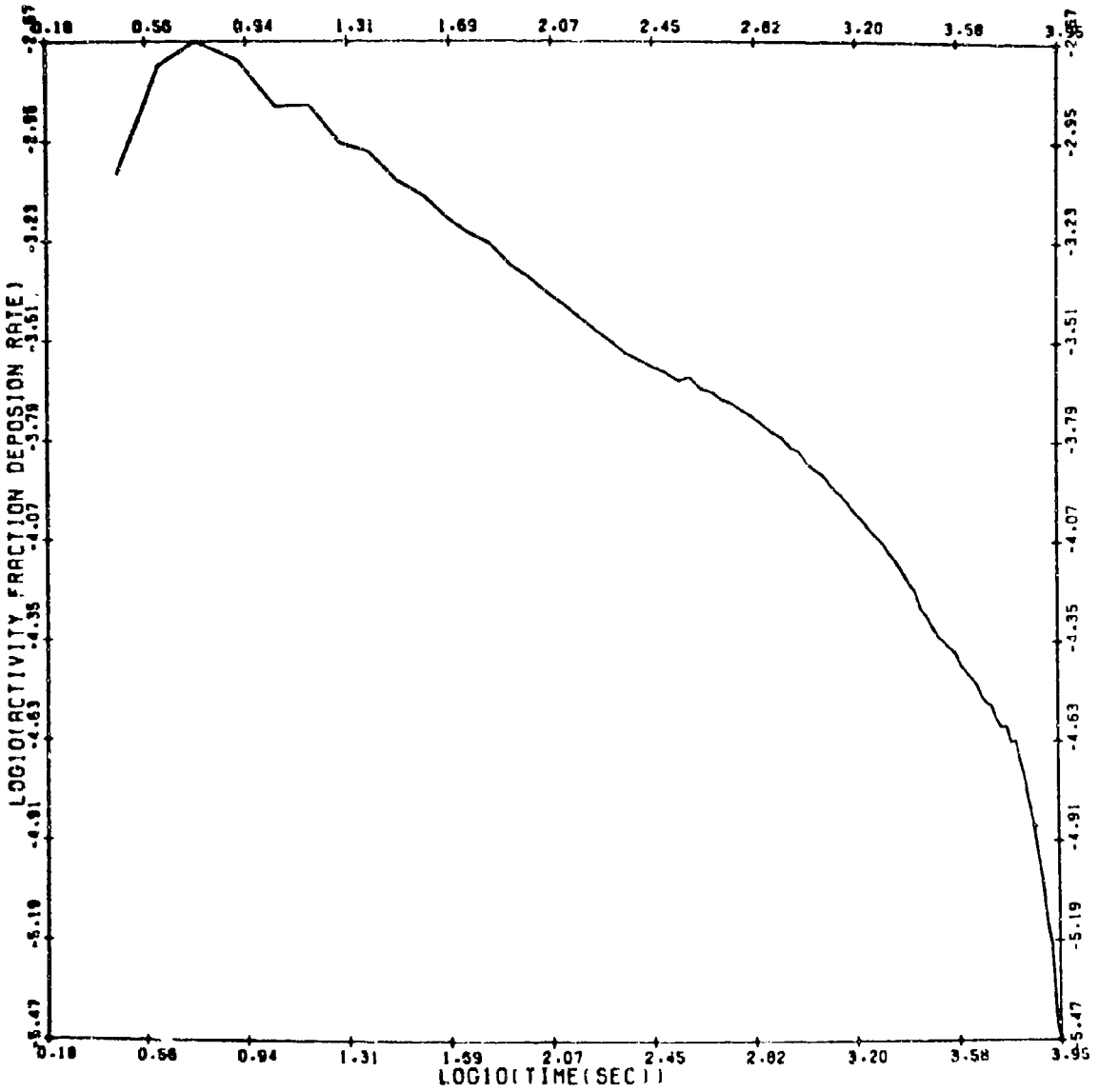
Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC.




b.

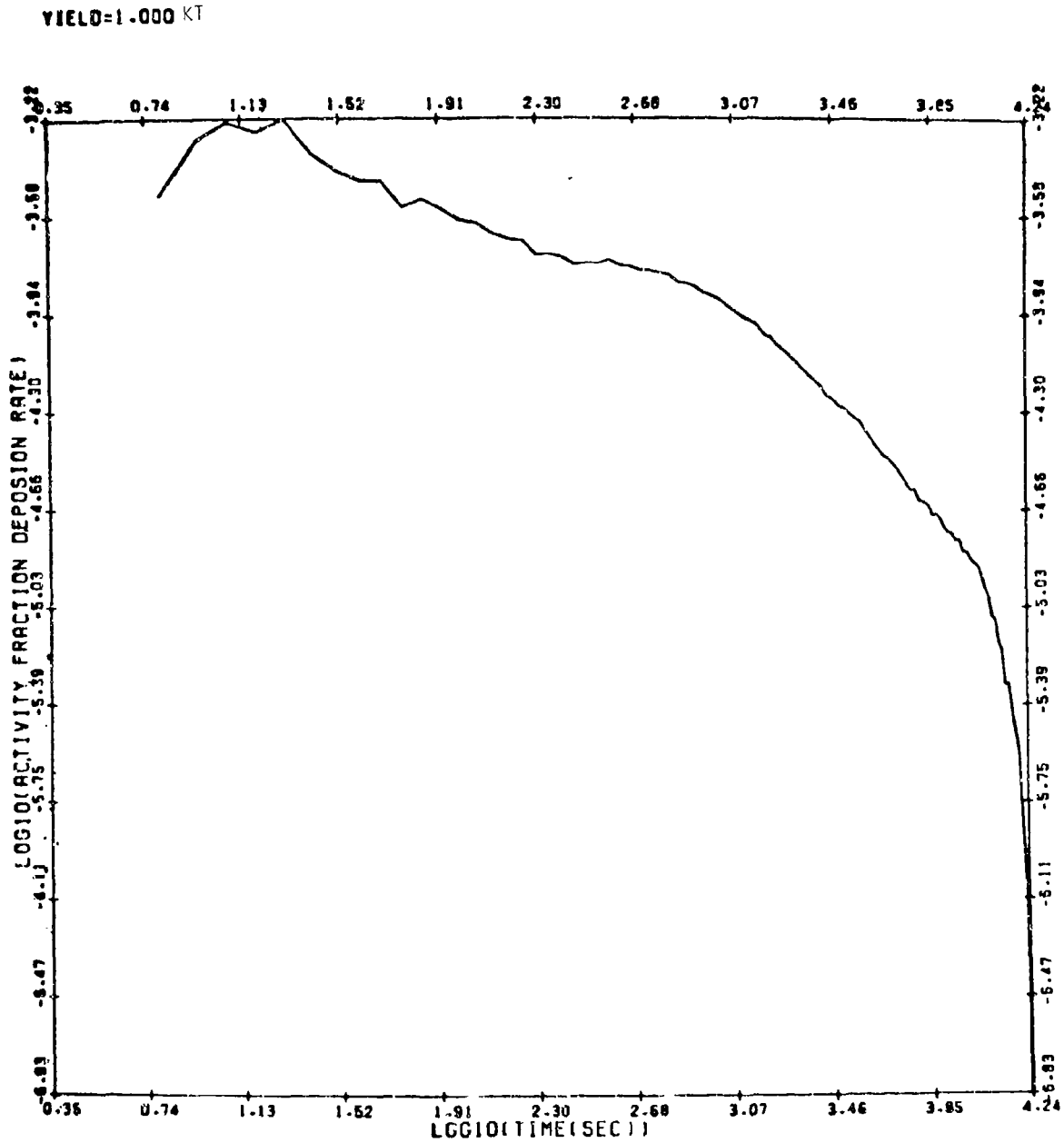
Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC. (continued)

YIELD=0.100 KT



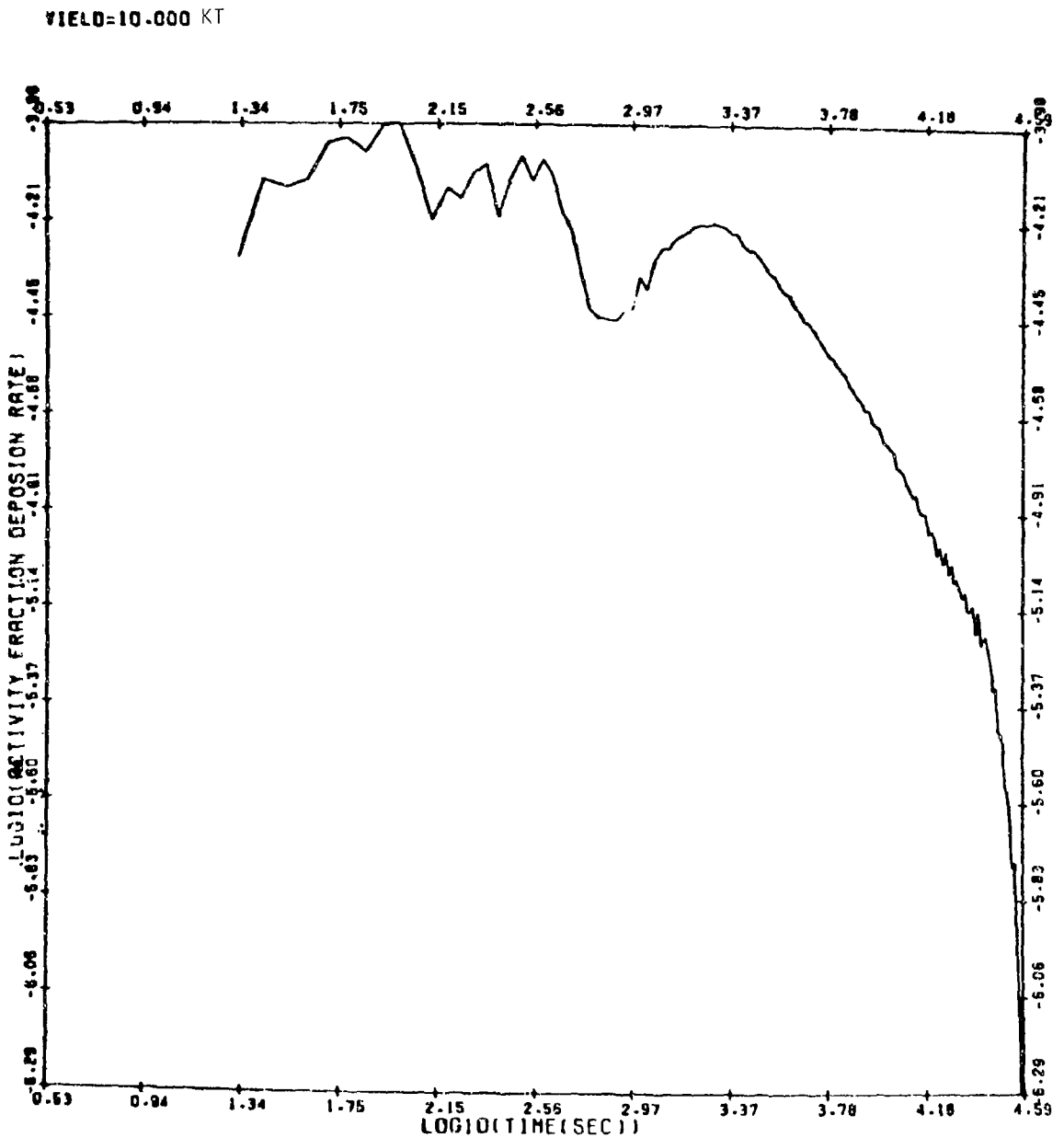

c.

Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC (continued)




d.

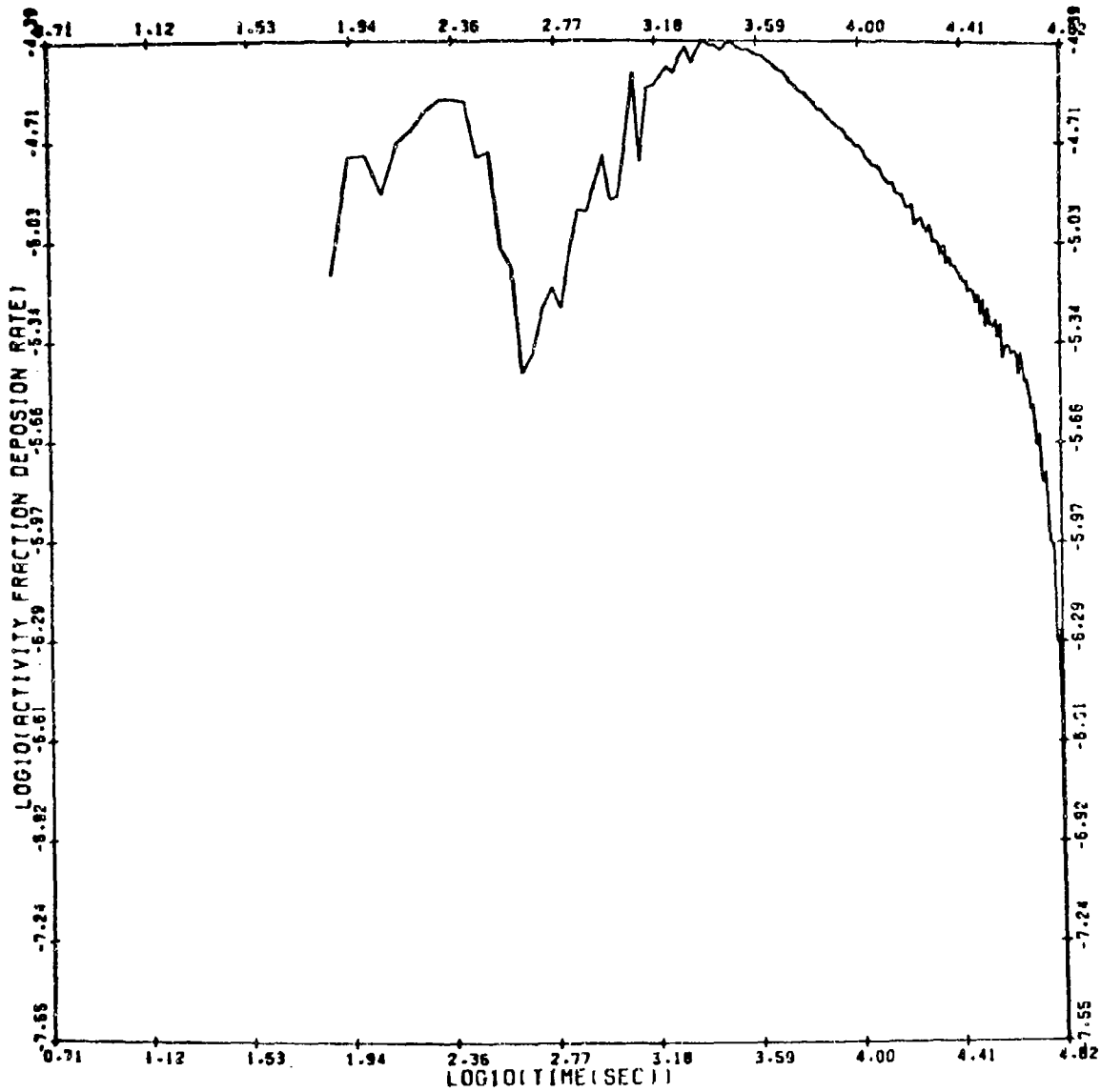
Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DFIFIC. (continued)




e.

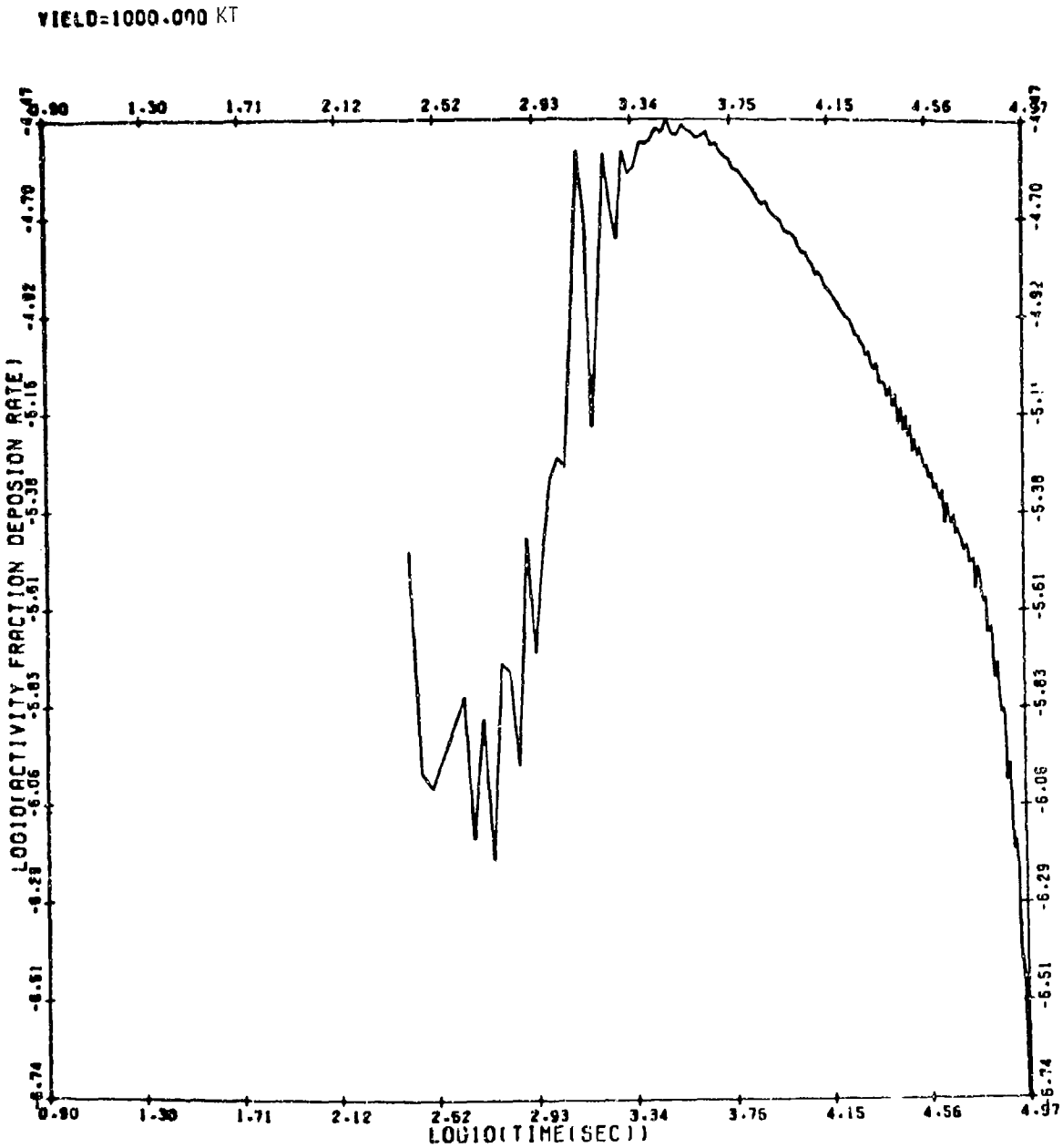
Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC. (continued)

YIELD=100.000 KT



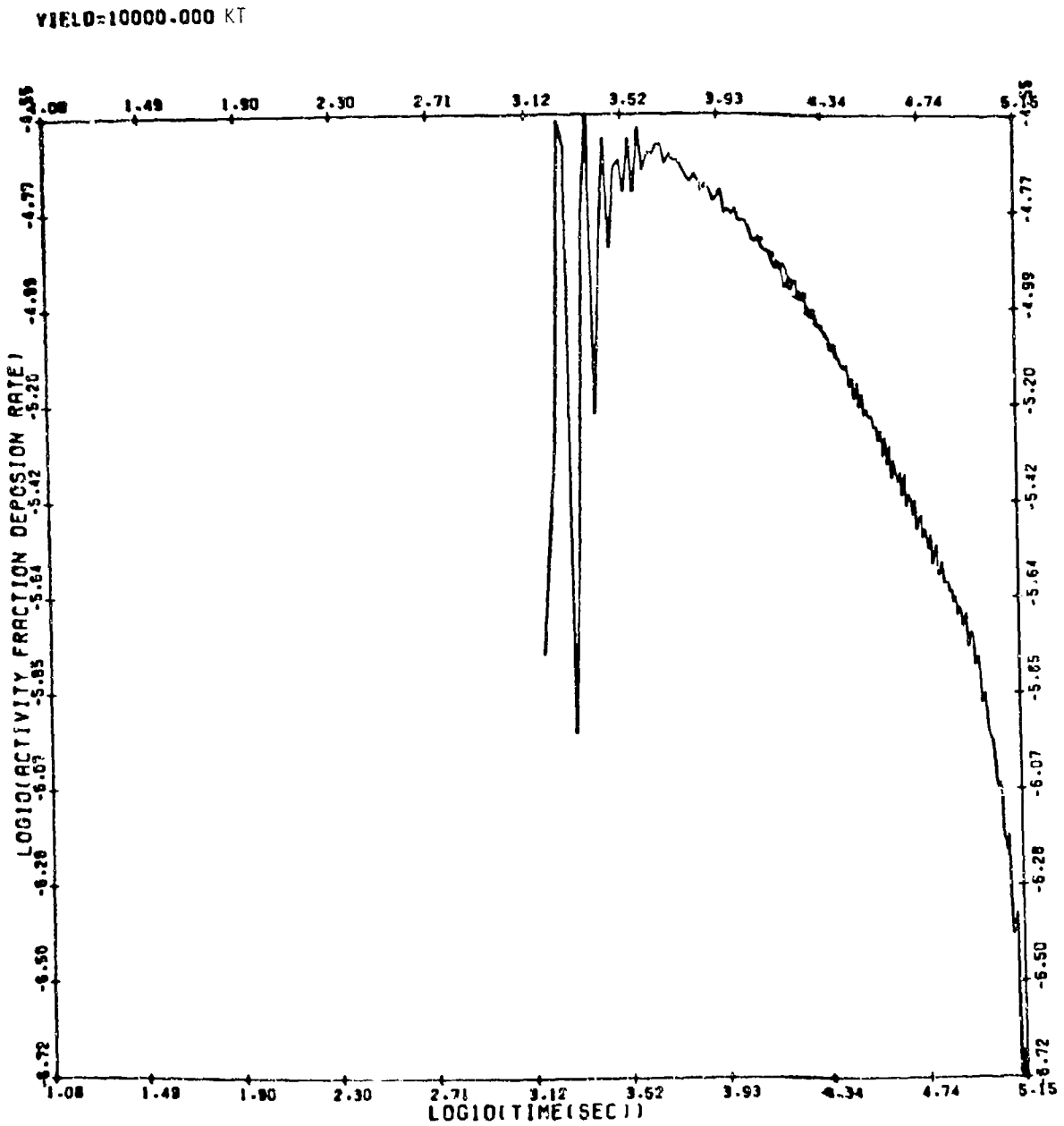

f.

Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC. (continued)




g.

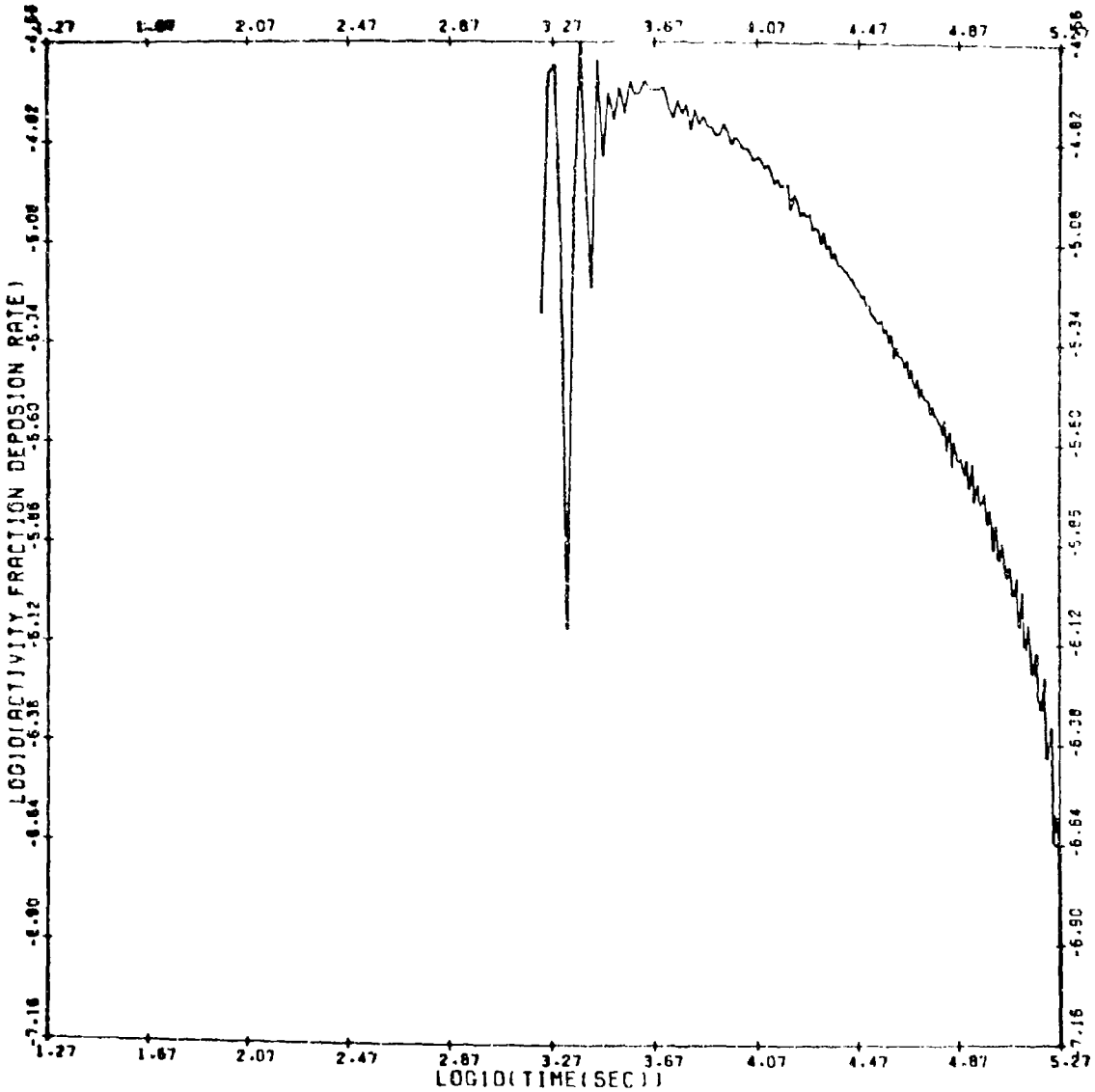
Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DLIFIC. (continued)




h.

Figure 1. Computer plots of activity fraction deposition rate vs. time as computed by DELFIC. (continued)

YIELD=100000.000 KT




i.

Figure 1. Computer plot: activity fraction deposition rate vs. time as computed by DELFIC. (continued)

$$t_s = \exp\left[1.527667 + 0.4089466 \cdot nW + 0.02064322(\cdot nW)^2\right] \; ; \quad W < 10^4 \text{ KT}$$

$$t_s = 1147.54 \qquad ; \quad W > 10^4 \tag{1}$$

where $t_s$ is in units of seconds.

## 2.3 FIREBALL AND STABILIZED CLOUD DATA

The model also requires fireball (i.e., early cloud) radius, as well as radius and top and base heights of the stabilized cloud. The latter are taken to be above mean sea level.

The early cloud radius, $R_i$ (m), is computed from a function used to initialize the SIMPIC cloud rise[9],

$$R_i = 108W^{0.33}; \quad W \text{ in KT}. \tag{2}$$

Stabilized cloud cap base height, $z_B$, and top height, $z_T$, are computed from functions fitted to observed data by Wilsey and Crisco[10],

$$z_B = aW^b \tag{3}$$

$$z_T = cW^d \tag{4}$$

where W is energy yield in kilotons, the heights are in meters, and

$a = 2228$, $b = 0.3463$; $W \leq 4.07$ KT
$a = 2661$, $b = 0.2198$; $W > 4.07$
$c = 3597$, $d = 0.2553$; $W < 2.29$
$c = 3170$, $d = 0.4077$; $2.29 < W < 19$
$c = 6474$, $d = 0.1650$; $W > 19$

Stabilized cloud radius, $R_s$, is computed from a least squares polynomial curve fit to DELFIC results,

$$R_s = \exp\left[6.7553 + 0.32055\ln W + 0.01137478\,(\ln W)^2\right] \qquad (5)$$

where $R_s$ is in meters and W is yield in kilotons.

## 2.4 NOMINAL PARTICLE

The model requires that a single, "effective fallout wind" vector, $\vec{v}$, be calculated from a given vertical profile of wind data. This effective fallout wind vector is an average of the given data, where in the averaging each vector is weighted according to the time required for a "nominal particle" to settle through the wind space stratum represented by that vector.

The nominal particle diameter was calculated from DELFIC results to be the activity-weighted average diameter over all particle sizes. The standard DELFIC lognormal particle size distribution was used,

$$\delta_{50} = 0.407\ \mu m$$

$$s = 4.0$$

where $\delta_{50}$ is the median diameter and s the geometric standard deviation of the distribution of particle number with respect to particle diameter. (See Appendix A of reference 1.)

Calculations were performed for the full range of yields, at every decade of W starting with $10^{-3}$ KT, using a special version of DELFIC. The low yield results were averaged separately from the high yield results, to give

$$\delta_{nom} = 217.05\ \mu m; \quad W \leq 100\ KT$$

$$\delta_{nom} = 240.95\ \mu m; \quad W > 100$$

The average of these diameters is 229 μm, which is the value used in the model.

Using $\delta_{nom}$ = 229 μm, a table (Table 1) of particle settling speeds as a function of altitude in the 1976 U.S. Standard Atmosphere[8], was computed via the equations given in section 2.2.3 of the DELFIC documentation[1]. This table is used by subroutine EFWIND to calculate effective fallout wind.

TABLE 1

SETTLING SPEEDS FOR THE NOMINAL PARTICLE, $\delta_{nom}$ = 229 μm

| Altitude (km above MSL) | Settling Speed ($m\ s^{-1}$) | Altitude (km above MSL) | Settling Speed ($m\ s^{-1}$) |
|---|---|---|---|
| 0 | 1.6538 | 20 | 3.5222 |
| 1 | 1.7124 | 21 | 3.6322 |
| 2 | 1.7744 | 22 | 3.8122 |
| 3 | 1.8401 | 23 | 3.9243 |
| 4 | 1.9097 | 24 | 3.9994 |
| 5 | 1.9836 | 25 | 4.0806 |
| 6 | 2.0621 | 26 | 4.1746 |
| 7 | 2.1458 | 28 | 4.3565 |
| 8 | 2.2350 | 30 | 4.5328 |
| 9 | 2.3303 | 32 | 4.7083 |
| 10 | 2.4324 | 34 | 4.8517 |
| 11 | 2.5419 | 36 | 5.0023 |
| 12 | 2.6446 | 38 | 5.1767 |
| 13 | 2.7489 | 40 | 5.3910 |
| 14 | 2.8551 | 42 | 5.6632 |
| 15 | 2.9630 | 44 | 6.0155 |
| 16 | 3.0723 | 46 | 6.4727 |
| 17 | 3.1831 | 48 | 7.0778 |
| 18 | 3.2951 | 50 | 7.8819 |
| 19 | 3.0482 | | |

## 2.5 OBSERVED FALLOUT DATA

After development of the model, its capability must be evaluated by comparison against observed data. For this purpose, we have used the best whole-pattern fallout data available. Comparison results are not greatly different from those obtained by use of presumably much more capable models[illegible]. Details are given below in section 5.

## 3. MATHEMATICAL DESCRIPTION

### 3.1 ACTIVITY DEPOSITION RATE FUNCTION

Ideal specifications for the activity deposition rate function, $q(t)$, are as follows:

1. It should be a simple single function, requiring as few yield dependent parameters as practicable, which fits the deposition rate data (Fig. 1) over the entire nine decades of yield range.
2. The product of $q(t)$ with a downwind dispersion factor, $F(X,t)$, should be analytically integrable over time to yield activity as a function of downwind distance. (See the next section.)
3. Both downwind and crosswind dispersion functions, $F(X,t)$ and $G(Y)$, should have Gaussian forms as required by theory and confirmed by experiment for diffusion by homogeneous turbulence[11], in the absence of firm data to support alternative functions. Thus, specification 2 is extended to require that $q(t)$ be such as to allow analytical integration of the product $q(t)F(X,t)$ where $F(X,t)$ is specifically a Gaussian function.
4. $q(t)$ should go to zero at the limits of zero and infinite time.
5. Normalization should be exact such that activity is conserved.

These specifications are so restrictive as to require some compromise. Even so, only requirements 3 and 5 are not met by the function selected.

The function which comes closest to satisfying the specifications was found to be

$$q(t) = \frac{4 \sin[\pi(3-\alpha)/2]}{\pi T(3-\alpha)} \left(\frac{T}{t}\right)^{\alpha} \Big/ \left[1 + \left(\frac{T}{t}\right)^{2}\right]^{2} ; \quad \alpha < 4. \tag{6}$$

Here $q(t)$ is rate of deposition of activity fraction ($s^{-1}$), $t$ is time (s), and $\alpha$ (dimensionless) and $T$ (s) are yield dependent constants.

Figure 2 shows a representative plot of eq. (6), for W = 1 KT, and compares this with a sampling of the DELFIC results. Except for a tendency to overpredict the maximum deposition rate (also see Fig. 5) for some cases, the function is capable of reproducing the DELFIC results reasonably well

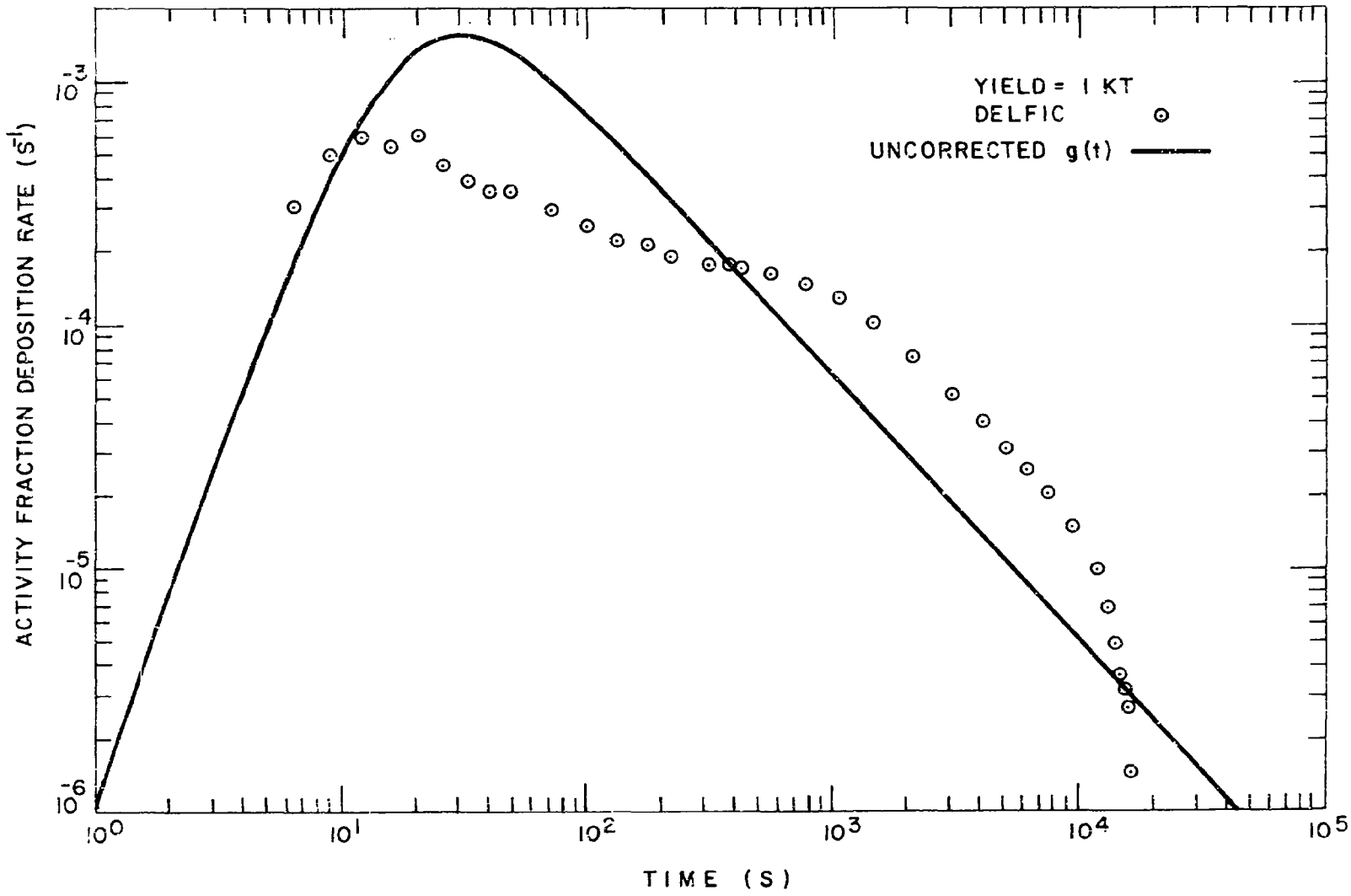



Figure 2. Activity fraction deposition rate function, g(t), (eq. (6)), without farfield correction, vs. time for W = 1 KT. A sampling of DELFIC results are included for comparison.

for early and intermediate times. At late time the eq. (6) function becomes linear (on the log-log plot) whereas the deposition rate data drop off rapidly. This discrepancy requires application of a "far field" correction factor which is discussed in section 3.3.

The maximum of the g(t) function occurs at time $t_{max}$ which is given by

$$t_{max} = T\sqrt{\frac{4-\alpha}{\alpha}} \tag{7}$$

The significance of this relation is that only two of these three parameters need to be specified as functions of yield. Approximate best fit values of $\alpha$ and $t_{max}$ were determined somewhat subjectively by trial and error for each decade of yield. These were fitted to simple functions of yield as follows:

$$\begin{aligned} \alpha &= 1.06 && ; \quad 10^{-3} \leq W \leq 10^{-1} \text{ KT} \\ \alpha &= 1.0875 + .0119431 \ln W && ; \quad 10^{-1} < W < 10^{3} \\ \alpha &= 1.17 && ; \quad 10^{3} \leq W \end{aligned} \tag{8}$$

and

$$\begin{aligned} t_{max} &= 30W^{0.41556} && ; \quad 10^{-3} \leq W \leq 1 \text{ KT} \\ t_{max} &= 30W^{0.65407} && ; \quad 1 < W \leq 10^{3} \\ t_{max} &= 893.616W^{0.16273} && ; \quad 10^{3} < W \leq 10^{4} \\ t_{max} &= 2497.18W^{0.05115} && ; \quad 10^{4} < W \leq 10^{5} \end{aligned} \tag{9}$$

where $t_{max}$ is in units of seconds.

## 3.2 DEPOSITION AS A FUNCTION OF DISTANCE FROM GROUND ZERO

The action of effective fallout wind v is to transport the stabilized cloud downwind such that at time t it is centered over downwind distance point X = vt. We assume that fallout deposited from the cloud at this time

has a continuous distribution along the X (i.e. hotline) axis with the distribution centered and peaked at $X = vt$. The situation is illustrated in Figure 3. To determine the total, crosswind integrated fallout deposited at any distance X from ground zero, the contributions of all fallout deposits must be summed over all time, and in this case, this is accomplished by analytical integration from $t = 0$ to $t = \infty$ of the product of q(t) with the downwind distribution function.

As explained in the previous section, a most desirable selection for the downwind distribution function for depositing fallout would be a Gaussian function. It turned out, however, that we could not find a satisfactory function for q(t) that is analytically integrable in combination with a Gaussian distribution in X-vt. Thus, we were forced to use the distribution function

$$F(X,t) = \left\{ \pi\sigma \left[ 1 + \left( \frac{X-vt}{\sigma} \right)^2 \right] \right\}^{-1} , \tag{10}$$

where $\sigma$ is analogous to the Gaussian standard deviation. Figure 4 shows a comparison of the eq. 10) function with the Gaussian function.

Thus, total, crosswind integrated activity fraction, D(X), deposited at distance X along the windward, or hotline, axis is

$$D(X) = \int_0^\infty q(t)F(X,t)dt$$

or

$$D(X) = \frac{4 \sin\left[\frac{\pi}{2}(3-\alpha)\right]}{\pi^2 T\sigma(3-\alpha)} \int_0^\infty \frac{(T/t)^\alpha dt}{\left[1+\left(\frac{T}{t}\right)^2\right]^{\alpha} \left[1+\left(\frac{X-vt}{\sigma}\right)^2\right]} \tag{11}$$

A result is obtained in closed form provided we take $\alpha=1$ inside the integral. This result is

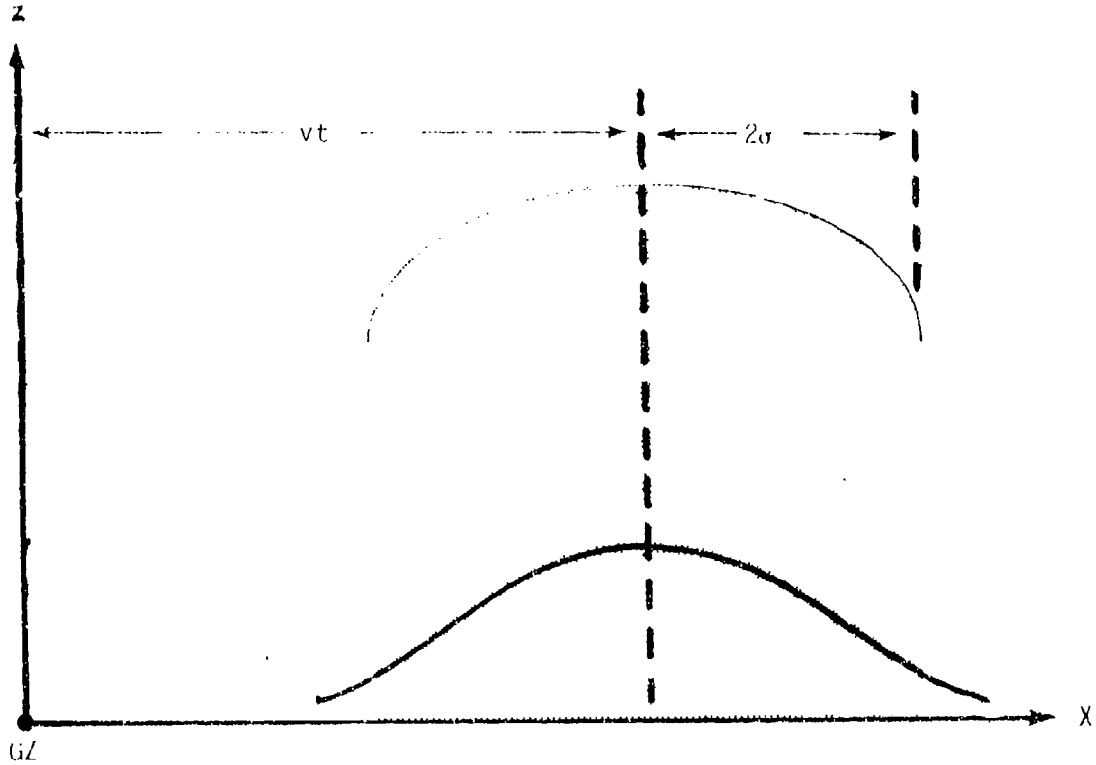



Figure 3. Distribution of activity of depositing fallout in the hotline axis direction.

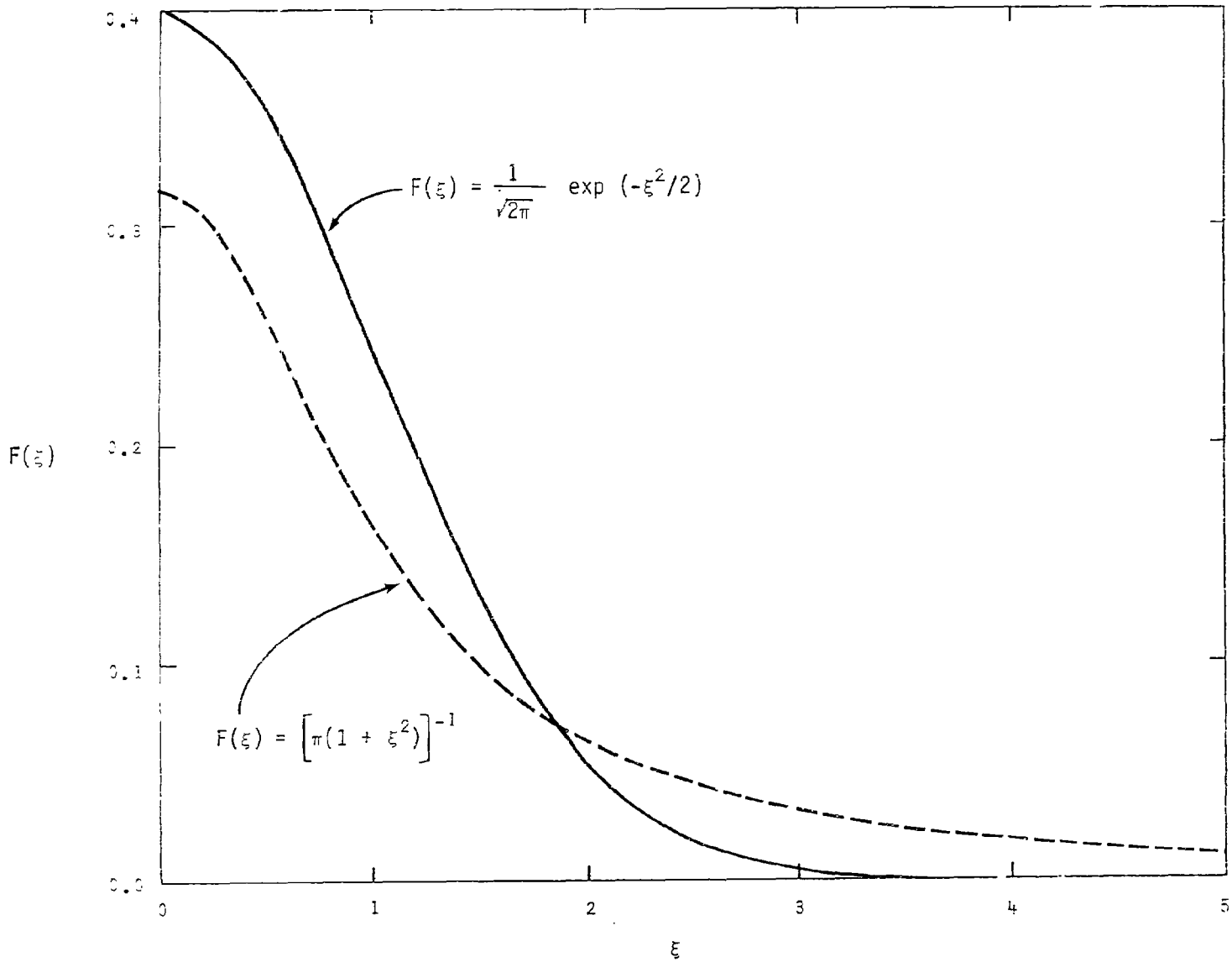



Figure 4. Comparison of Gaussian function with the function used in DNAF-1 to approximate the spatial distribution of cloud activity along the hotline axis.

$$D(X) \sim \frac{2\sigma \sin\left[\pi(3-\alpha)/2\right]}{\pi^2 X_4^8 (3-\alpha)} \Bigg\{ -\pi X X_1 \left[\left(3X_2^2 + X_1^2\right) X_3^2 + 4X^2 X_1^2\right]$$

$$- \left(X_3^4 + 4X^2 X_1^2\right) X_3^2 + \left(X_2^2 X_3^4 - 4X^2 X_1^4\right) \ln\left(\frac{X_2^2}{X_1^2}\right)$$

$$+ \frac{X}{\sigma}\left[\left(X_2^2 + 3X_1^2\right) X_2^2 X_3^2 + 4X^2 X_1^4\right]\left[\pi + 2\tan^{-1}\left(\frac{X}{\sigma}\right)\right]\Bigg\} \qquad (12a)$$

where

$$X_1 = vT$$
$$X_2^2 = X^2 + \sigma^2$$
$$X_3^2 = X_2^2 - X_1^2$$
$$X_4^8 = \left(X_3^4 + 8X^2 X_1^2\right) X_3^4 + 16X^4 X_1^4 \quad ,$$

and D(X) has units $m^{-1}$.

This is the basic equation for the DNAF-1 model. In the computer code (function DNAF1), an alternative form of eq. (12a) is also used, which is required because of limitations of some computers

$$D(X) \sim \frac{2\sigma \sin\left[\pi(3-\alpha)/2\right]}{\pi^2 X_5^4 (3-\alpha)} \Bigg\{ -\pi X X_1 \left[\left(3X_2^2 + X_1^2\right)/X_3^2 + 4X^2 X_1^2/X_3^4\right]$$

$$- X_3^2\left(1 + 4X^2 X_1^2/X_3^4\right) + \left(X_2^2 - 4X^2 X_1^4/X_3^4\right) \ln\left(\frac{X_2^2}{X_1^2}\right) \qquad (12b)$$

$$+ \frac{X}{\sigma}\left[X_2^2\left(X_2^2 + 3X_1^2\right)/X_3^2 + 4X^2 X_1^4/X_3^4\right]\left[\pi + 2\tan^{-1}\left(\frac{X}{\sigma}\right)\right]\Bigg\} \quad ; \; |X_3^2| \geq 1.$$

where

$$X_5^4 = X_3^4 + 8X^2 X_1^2 + 16X^4 X_1^4/X_3^4$$

Thus eq. (12a) is used for small values of $|X_3^2|$ and eq. (12b) for large values.

Negative values of X (i.e., upwind distances) are accomodated as well as positive values in eqs. (12a) and (12b).

For a point cloud, defined by $\sigma = 0$, eq. (12) reduces to

$$D(X)_{\sigma=0} = \frac{4\sin[\pi(3-\alpha)/2]}{\pi(3-\alpha)} \frac{X^3}{(X^2+X_1^2)^2} \; ; \; X \geq 0 \tag{13}$$

which, on substitution of $X = vt$, becomes

$$vD(vt)_{\sigma=0} = \frac{4\sin[\pi(3-\alpha)/2]}{\pi(3-\alpha)} \frac{t^3}{(t^2+T^2)^2} \; . \tag{14}$$

The right hand side of eq. (14) is equivalent to eq. (6) with $(T/t)^\alpha$ replaced by $T/t$.* Thus, provided that $\alpha$ is not much different from unity, eqs. (13) or (14) may be used instead of eq. (6) to represent activity deposition rate as a function of either distance from ground zero or time for a point cloud. These equations are used below for the development of the farfield correction.

### 3.3 FARFIELD CORRECTION

As already noted, the eq. (6) function for deposition rate fits the DELFIC results adequately at early and intermediate times, but at late times (which correspond to farfield deposition) the DELFIC results drop off much more rapidly. Moreover, this discrepency becomes more acute as yield increases. Indeed, as inspection of eq. (14) shows, $g(t) \propto 1/t$; $t \to \infty$, whereas the DELFIC results for large time are proportional to $\exp[-(t/\tau)^n]$, n=1 or 2 and $\tau$ constant.

A correction to the functions for g(t) and D(X) which have general applicability, but are effective only for late times and correspondingly large X are as follows. As shown at the end of the last section,

---

*Recall that $\alpha$ was taken to be unity inside the integral in eq. (11).

$D(X)_{\sigma=0}$, (i.e., downwind deposition for a point cloud) is equivalent to $g(t)/v$. It also turns out that $D(vt)_{\sigma\neq 0} \sim g(t)/v$ for large t. Thus, we can derive a correction factor for the g(t) function for large t, which will also apply to the D(X) function for large X, where X and t are related by $X = vt$.

The correction factor is derived by means of an exponential interpolation, $1-\exp\left[-X/(avt_c)\right]$, between the functions $\ln\left\{D(X)\right\}$ and $\ln\left\{\frac{k}{v}\exp\left[-\left(\frac{X}{v\tau}\right)^2\right]\right\}$, where a is constant and $t_c$, k and $\tau$ are functions of yield. The farfield corrected D(X), $D(X)_f$ $(m^{-1})$, is

$$D(X)_f = D(X)\exp\left\{-\left[\ln\left(vD(X)/k\right) + \left(\frac{X}{v\tau}\right)^2\right]\left[1-\exp\left\{-X/\left(avt_c\right)\right\}\right]\right\} \; ; \qquad X \geq 0 \tag{15}$$

where D(X) is computed by eq. (12a) or (12b), and

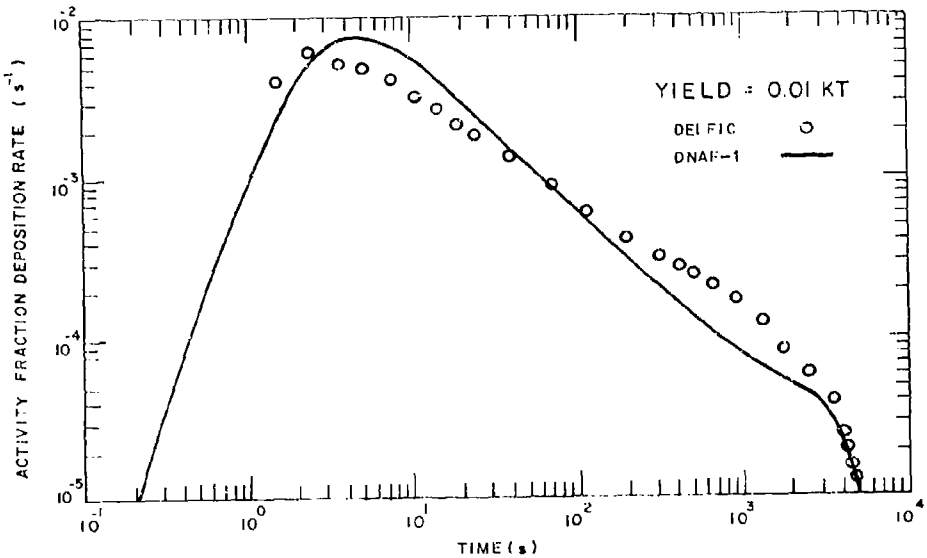
$$\begin{aligned}
a &= 1.443 \\
k &= 9.867\times10^{-5}W^{-0.26045} \quad (s^{-1}) \\
T &= 8160W^{0.2463} \quad (s) \\
t_c &= 14667W^{0.26208} \quad (s); \quad W \leq 98.787 \text{ KT} \\
t_c &= \exp\left[10.124706 + 0.1861768\ln W - 0.008660444(\ln W)^2\right] \quad (s) \; ; \quad W > 98.787 \text{ KT}
\end{aligned} \tag{16}$$

Figure 5 shows the function $g(t)_f$ (actually $vD(vt)_{f,\sigma=0}$, see eq. 14)) for every other decade of yield along with a sampling of the DELFIC results and the corresponding quantity for the WSEG-10 model.

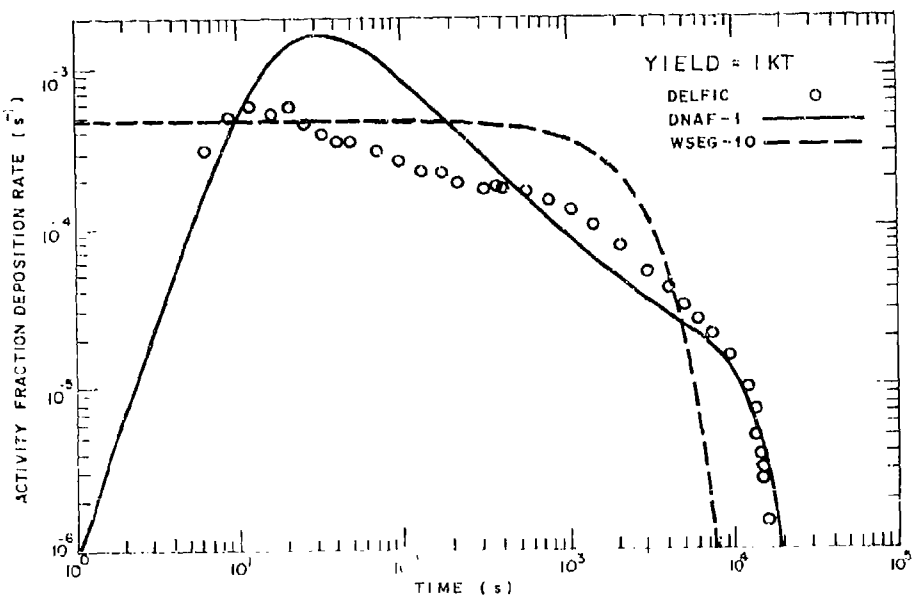
The WSEG-10 model uses the deposition rate function

$$g(t)_{WSEG-10} = \frac{1}{T'\Gamma(1+1/n)} \exp\left[-(t/T')^n\right] \tag{17}$$

where $\Gamma$ is the gamma function, T' is a yield dependent constant and n has a value between 1 and 2. In calculating the results shown in Figure 5, we have used $n = 1.5$. Notice in Figure 5 that the WSEG-10 function

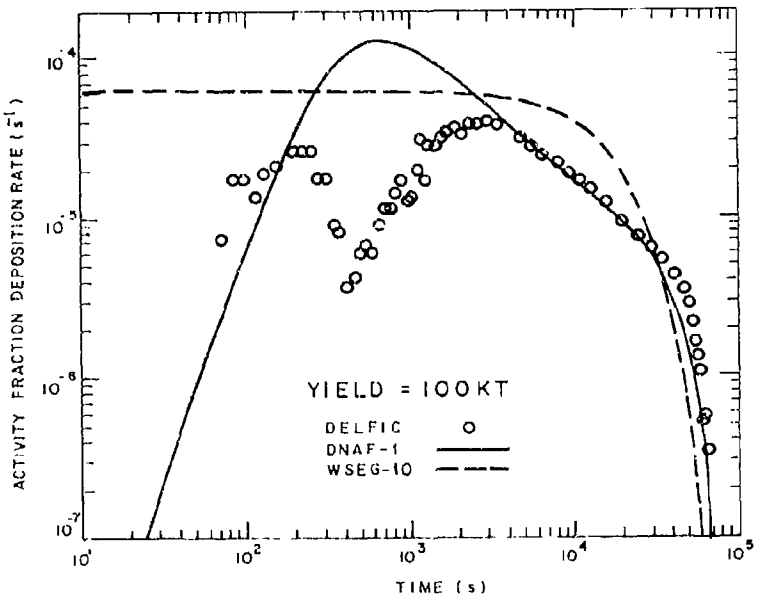



a.




b.

Figure 5. Activity deposition rate, $q(t)_f$, including farfield correction, vs. time. A sampling of DELFIC results are included for comparison.

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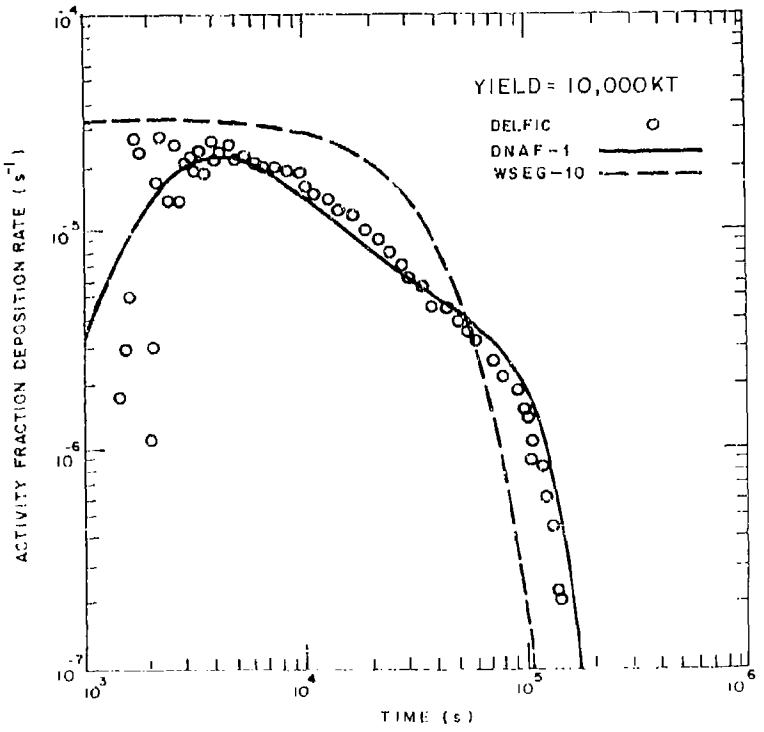



d.

Figure 5. Activity deposition rate, $q(t)_f$, including farfield correction, vs. time. A sampling of DELFIC results are included for comparison. (continued)

matches the DELFIC deposition rate data only in the farfield region, and that instead of going to zero at t = 0, it actually peaks there. Also note that the WSEG-10 curve fit probably is adequate for very high yields, but is very poor for low yields.

### 3.4 UPWIND CORRECTION

In comparing calculated fallout patterns with observed patterns for low yield test shots, it was found that the calculated activities decreased too slowly with upwind distance from ground zero. Analysis of the discrepancies indicated a correction factor that is independent of both yield and wind speed for yields less than 10KT.*

For high yield shots there is little credible upwind fallout data to serve as a guide. However, a correction was developed that is reasonably consistent with data available for shots Koon, Zuni and Bravo, and that provides a continuous transition to the low yield correction at W = 10 KT.

As with the farfield correction, an exponential interpolation in log(D) - log(X) space is used to compute the upwind-corrected activity deposited, $D(X)_u$, which is given by

$$D(X)_u = D(X)\exp\left\{bX\left[1.0-\exp(X/c)\right]\right\} \quad ; \quad X<0 \tag{18}$$

where D(X) is calculated by eqs. (12a) or (12b), and

$$\begin{aligned} b &= 0.0176 \\ c &= 570 \qquad\qquad W \leq 10 \text{ KT} \\ b &= 0.08045W^{-0.66} \\ c &= -8179.82 + 3800\ell nW \qquad W > 10 \text{ KT} \end{aligned} \tag{19}$$

---

*Though one would guess that this correction should be a function of wind speed, there is not enough variation of v among the cases available to allow for a quantitative evaluation of the dependence.

## 3.5 FALLOUT TIME OF ARRIVAL

An estimate of fallout time of arrival as a function of distance from ground zero is required for computation of maximum effective biological dose and turbulent and wind shear dispersion of the nuclear cloud during atmospheric transport. By time of arrival we mean the time of deposition of the first fallout at distance X from ground zero along the hotline.

Time of arrival, $t_a$, is estimated by means of the following simple model. The first fallout to touch ground anywhere does so at onset time $t_o$ (eq. (1)) in the form of a horizontally distributed parcel centered at $X = vt_o$. We take the radius of this parcel to be that of the early cloud, $R_i$ (eq. (2)). Thus, for any point with coordinate $X \leq vt_o + R_i$, we take $t_a = t_o$. For $X > vt_o + R_i$, we take $t_a = t_o + (X-vt_o-R_i)/v$. The geometry is shown in Figure 6a.

Figure 6b shows that the plot of $t_a$ vs X consists of two straight lines that intersect at point $(t_o, vt_o + R_i)$. We desire a smooth transition between the two curves rather than the discontinuous transition shown. This is achieved by replacing the straight lines with a hyperbola that is asymptotic to both lines and has its center at the intersection point of the lines. Thus $t_a$ (s) is calculated from the equation

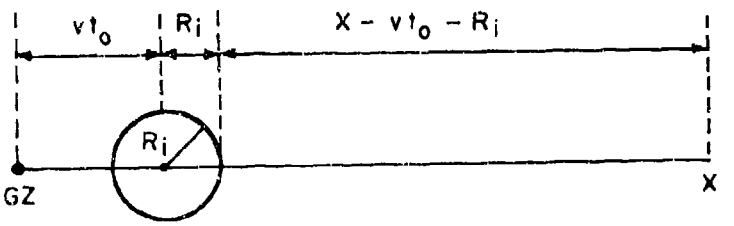
$$t_a = t_o + \frac{1}{2}\left[\frac{X}{v} - t_o - \frac{R_i}{v} + \sqrt{\left(\frac{X}{v} - t_o - \frac{R_i}{v}\right)^2 + \left(t_o + \frac{R_i}{v}\right)/100}\right];$$

$$v \geq 0.01 \text{ m s}^{-1} \qquad (20)$$

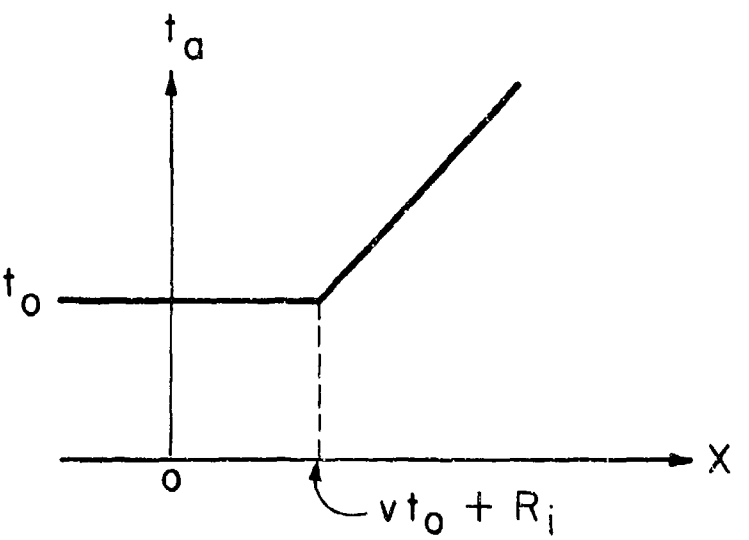
Figure 7 shows plots of $t_a$ vs X for an effective fallout wind speed of 10 m $s^{-1}$ at several different yields. WSEG-10 results also are shown. Since according to WSEG-10 the minimum $t_a$ is 30 minutes, we see that for low yield shots WSEG-10 grossly overestimates $t_a$, and hence correspondingly underestimates maximum effective biological dose (eq. (32)).

## 3.6 HORIZONTAL SPREAD OF THE NUCLEAR CLOUD

In this section we consider horizontal spread of the nuclear cloud before we account for dispersing effects of atmospheric turbulence and wind




a. Geometry of the time-of-arrival model.




b. Representative plot of $t_a$ vs X.

Figure 6. Basis of the time-of-arrival calculation.

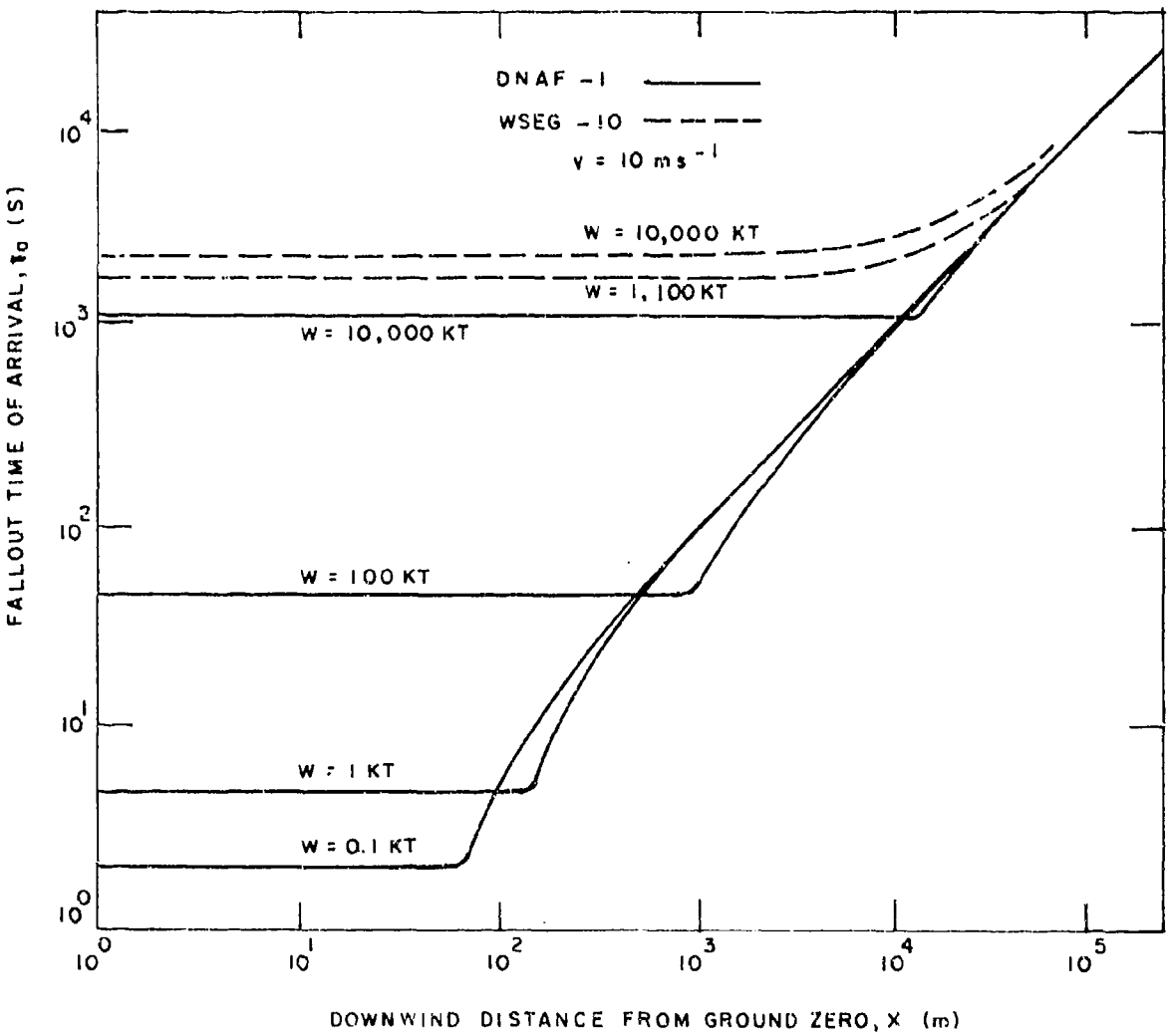



Figure 7. Fallout time of arrival vs. distance from ground zero for several yields as computed by DNAF-1 and WSEG-10.

shear. Vertical cloud structure is included implicitly. We have shown elsewhere[6,7] that close-in fallout patterns from surface bursts of yields less than roughly 50 KT are dominated by fallout from the cloud stem. Thus, for a low yield shot we cannot make the conventional assumption that close-in fallout comes from the cloud cap, nor that it begins its atmospheric transport with a horizontal spread derived from the stabilized cloud radius. Accordingly, in the following analysis we differentiate between stem and cap fallout.

Three critical times are involved here:

$t_o$ fallout onset time (eq. (1))

$t_a$ fallout arrival time (eq. (20))

$t_B$ time of ground impact of a nominal particle which begins its descent at the stabilized cloud base, $z_B$.

Time $t_B$ (s) is approximated by use of a simple relation between settling speed of water drops and altitude[12], which for this purpose is found to apply well enough to fallout particles. The settling speed of a particle at altitude z, f(z), is

$$f(z) = f(o)e^{\zeta z} \tag{21}$$

where $\zeta = 2.90 \times 10^{-5}\ m^{-1}$ and from Table 1, $f(o) = 1.6538\ (m\ s^{-1})$ for our nominal particle. Thus,

$$t_B = -\int_{z_B}^{0} dz/f(z) = \left(1 - e^{-\zeta z_B}\right)\Big/\left(\zeta f(o)\right) \tag{22}$$

where $z_B$ is given by eq. (3).

Horizontal dimension of the cloud prior to atmospheric transport is specified in terms of the standard deviation of its spread, $\sigma_c$ (m). Define a yield dependent parameter, $\sigma_w$, as

$$\sigma_W = R_i \qquad ; W \leq 10 \text{ KT} \tag{23a}$$

$$\sigma_W = R_i + (2.5R_i - R_i)(\log_{10}W - 1)/2$$

$$= R_i(1 + 3\log_{10}W)/4; \; 10 < W < 1000 \text{ KT} \tag{23b}$$

$$\sigma_W = 2.5\, R_i \qquad ; W \geq 1000 \text{ KT}, \tag{23c}$$

where $R_i$ is given by eq. (2). Then upwind and in the region of ground zero we have

$$\sigma_c = \sigma_W \qquad ; X \leq vt_o. \tag{24}$$

For fallout from the stem we have

$$\sigma_c = \sigma_W + \left(\frac{t_a - t_o}{t_B - t_o}\right)\left(\frac{R_s}{2} - \sigma_W\right) ; \; X > vt_o \text{ and } t_a < t_B \tag{25}$$

and for fallout from the cap we have

$$\sigma_c = R_s/2; \quad t_a \geq t_B \tag{26}$$

where $R_s$ is given by eq. (5).

Equations (24) and (23a) express the fact that onset of fallout from low yield shots is early enough that the upwind and ground zero area fallout has essentially the spread of the late fireball. Equations (24) and (23c) account for the fact that the debris from high yield shots is carried aloft rapidly, which causes the earliest fallout to traverse a substantial vertical path and thus experience substantial horizontal dispersion. Equation (23b) is simply a linear interpolation in $\log_{10}(W)$ between eqs. (23a) and (23c).

Equation (26) sets the standard deviation of horizontal spread of fallout in the stabilized cloud cap at one half of the stabilized cloud radius, and eq. (25) provides for stem fallout via a linear interpolation in altitude (in terms of arrival time) between the base and top of the stem.

## 3.7 TURBULENT DISPERSION OF FALLOUT

During transport from its initial location in the stabilized cloud to the ground, fallout is acted upon by the ambient atmospheric turbulence such as to produce additional dispersion. To calculate this effect, we use the scale dependent equations of Walton[13] which require specification of turbulence level in terms of a quantity called turbulent energy density dissipation rate, $\varepsilon$. Of course, $\varepsilon$ will depend on local conditions in the atmosphere, but Wilkins[14] has found that $\varepsilon$ can be approximated, with surprisingly consistent accuracy, by a simple reciprocal function of altitude. Thus, the variance of the horizontal spread of fallout at ground level, $\sigma^2$ ($m^2$), not including crosswind dispersion owing to wind shear, is given by

$$\sigma^2 = \left(\sigma_c^{2/3} + \frac{2}{3}\langle\varepsilon\rangle^{1/3} t_a\right)^3 \qquad ; \sigma^2 \leq 10^9\ m^2 \qquad (27a)^*$$

$$\sigma^2 = 10^6\left(3\sigma_c^{2/3} + 2\langle\varepsilon\rangle^{1/3} t_a - 2000\right) \qquad ; \sigma^2 > 10^9 m^2 \qquad (27b)^*$$

where $t_a$ is given by eq. (20) and $\sigma_c$ is calculated as described in the preceding section.

Wilkins' relation for $\varepsilon$ is $\varepsilon \approx 0.03/z$, and we have taken for our average value, $\langle\varepsilon\rangle = 0.03/z_B$. Using a power function in W relation for $z_B$ which is approximately valid over the entire yield range[15], we obtain

$$\frac{2}{3}\langle\varepsilon\rangle^{1/3} = 0.016522W^{-0.10233}; \quad W \text{ in KT.}$$

The value of $t_a$ at which $\sigma^2 = 10^9 m^2$ is given by

$$\left(t_a\right)_\ell = \left(10^3 - \sigma_c^{2/3}\right)/\left(\frac{2}{3}\langle\varepsilon\rangle^{1/3}\right) \quad .$$

---

*See ref. 1, sec. 3.3 for a more complete presentation of these equations.

Thus if $t_a \leq (t_a)_\ell$, use eq. (27a); otherwise use eq. (27b).

The value of $\sigma$ calculated by one of eqs. (27) is used in one of eqs. (12) to calculate crosswind integrated fraction of activity deposited at hotline distance X from ground zero.

At this point in the presentation we have discussed how to determine all of the quantities needed to calculate D(X) via one of eqs. (12a) or (12b). Figure 8 shows plots of D(X), including upwind and farfield corrections, at every other decade of yield for an effective fallout wind of 10 m $s^{-1}$. WSEG-10 results also are shown for comparison.

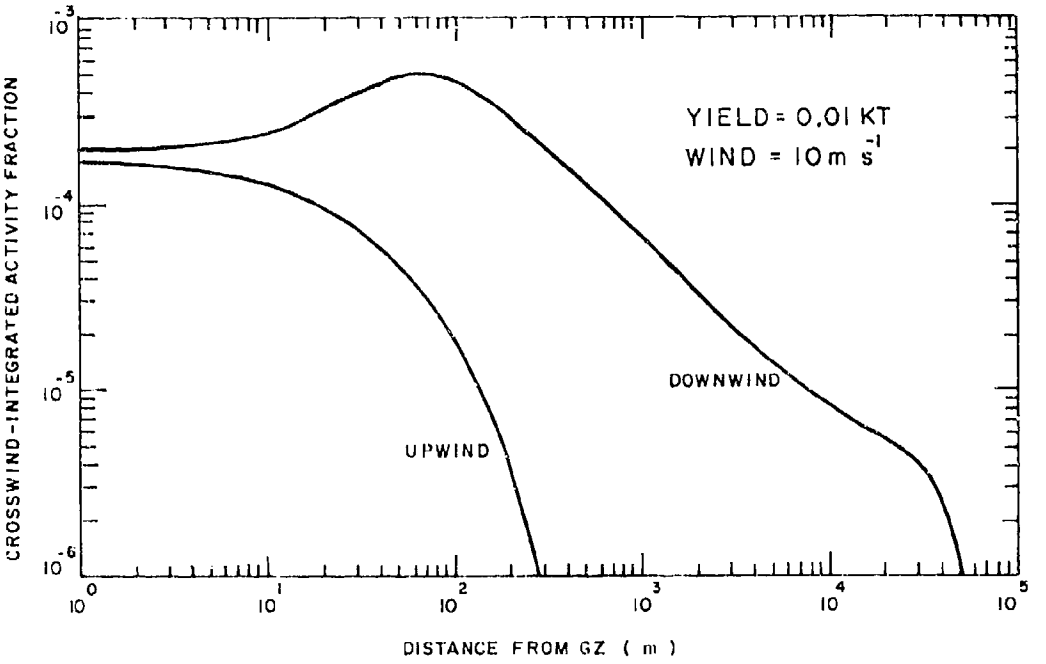
The most obvious difference between the DNAF-1 and WSEG-10 predictions is the much sharper peak downwind of ground zero (GZ) predicted by DNAF-1. For the higher yields this peak falls off more rapidly toward GZ, according to DNAF-1, such that the DNAF-1 GZ activity is substantially less than predicted by WSEG-10. The farfield activity curves have nearly the same shape, as expected, though they are significantly displaced, except for $10^4$ KT for which case they are essentially coincident. Upwind, the curves have similar shapes, though again the displacements are significant. Shapes and displacements at near and intermediate downwind distances are significantly different.

## 3.8 WIND SHEAR DISPERSION AND CROSSWIND SPREAD OF THE FALLOUT PATTERN

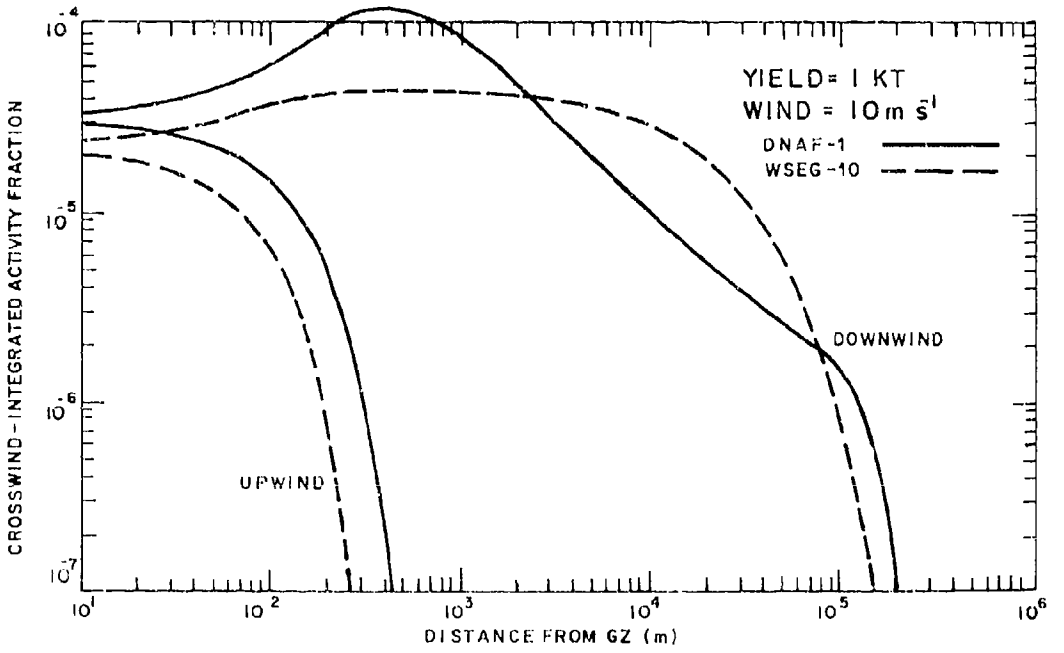
Following in principle, but not in detail, the procedure of Pugh and Galiano[4], we account for the effect of vertical wind shear on crosswind dispersion variance by an added variance increment, $\sigma_s^2$ ($m^2$), given by

$$\sigma_s^2 = \left[S_Y(z_T - z_B)t_a/10\right]^2 \tag{28}$$

Here $S_Y$ is an approximation to the crosswind component of vertical wind shear, determined as described in section 4.3, and the other quantities are as defined by eqs. (3), (4) and (20). In addition to being a very rough approximation, this equation is somewhat arbitrary in that some height difference other than $z_T - z_B$ could have been used. The divisor 10 was

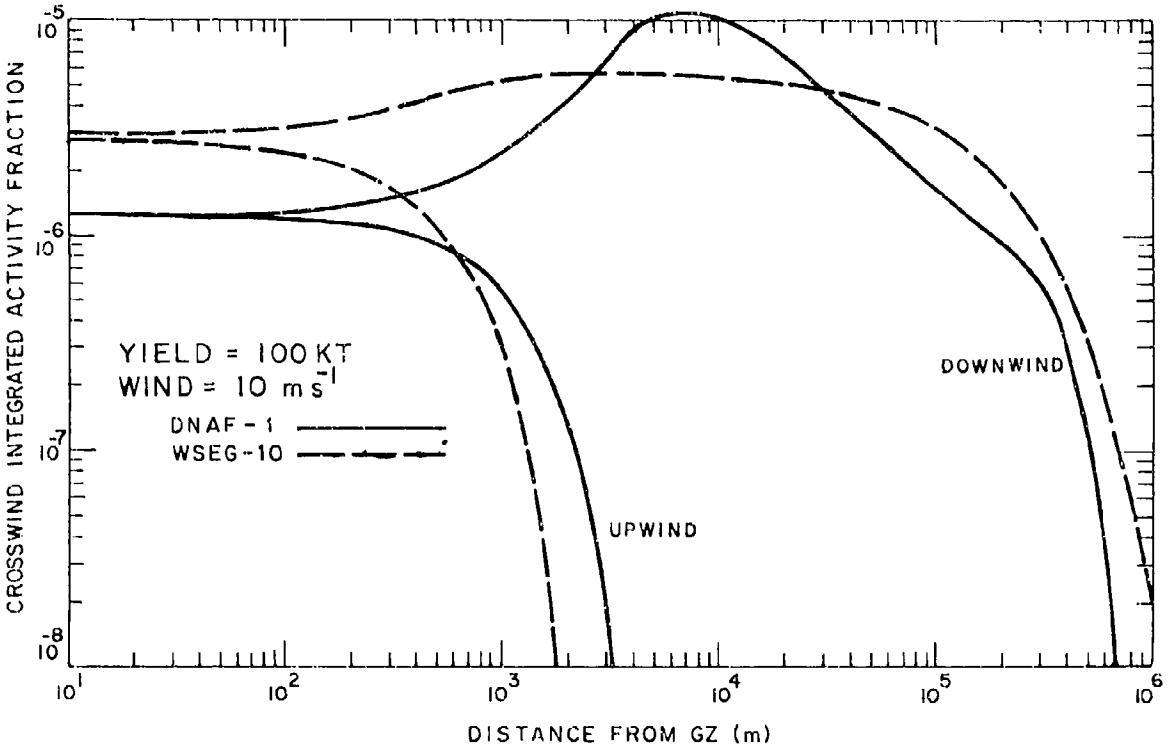



a.




b.

Figure 8. Crosswind-integrated activity fraction, $D(X)_f$ and $D(X)_u$, vs. distance from ground zero along the hotline.

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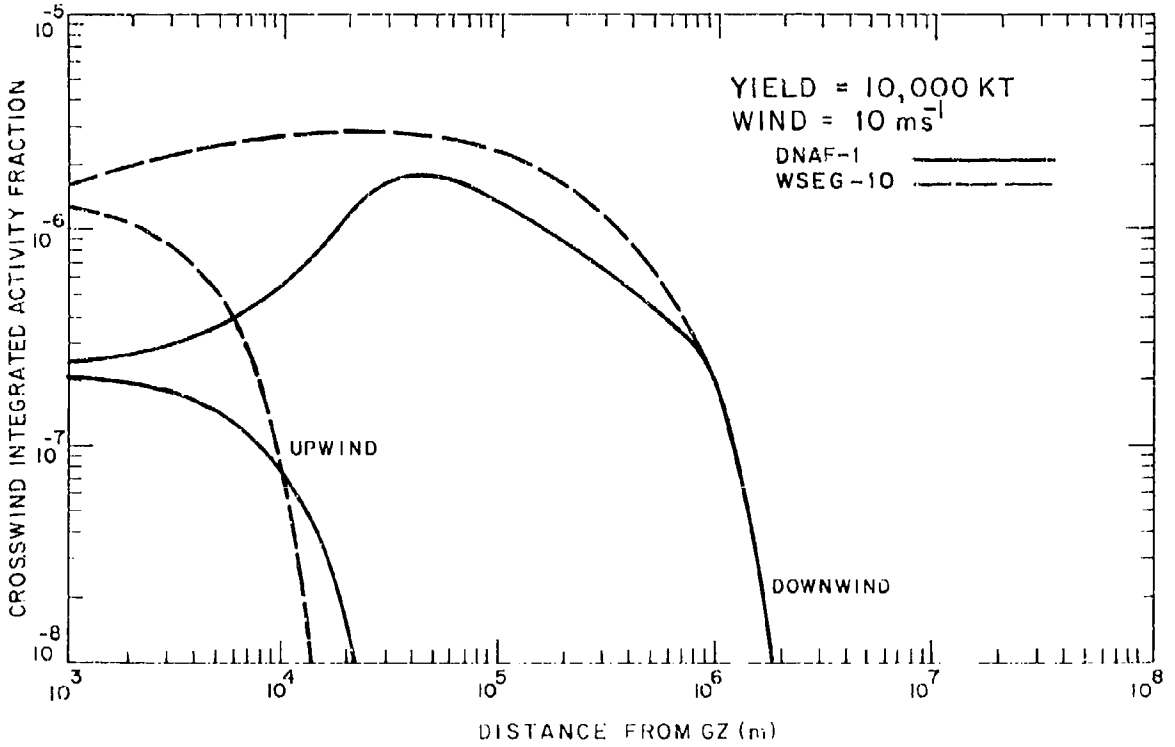



d.

Figure 8. Crosswind-integrated activity fraction, $D(X)_f$ and $D(X)_u$, vs. distance from ground zero along the hotline. (continued)

chosen by numerical experimentation to give good comparisons between observed and calculated test shot fallout patterns.

Crosswind (i.e., Y axis) dispersion of the fallout pattern is provided by multiplication of eqs. (15) and (18) by a Gaussian function

$$G(Y) = \frac{1}{\sqrt{2\pi}\sigma_Y} \exp\left[ - \frac{1}{2}\left(\frac{Y}{\sigma_Y}\right)^2 \right] \tag{29}$$

where

$$\sigma_Y^2 = \sigma^2 + \sigma_s^2 \quad , \tag{30}$$

and $\sigma^2$ and $\sigma_s^2$ are given by eqs. (27) and (28) ($m^2$).

## 3.9 GAMMA RAY EXPOSURE RATE AND MAXIMUM EFFECTIVE BIOLOGICAL DOSE

If we define, as usual, X to be the distance from ground zero along the direction of the effective fallout wind vector, positive in the downwind direction, and Y to be perpendicular distance to the X axis in the ground plane, then the H + 1 hour normalized* gamma ray exposure rate (Roentgens per hour) at a height of one meter above a point X, Y on the ground is

$$A(X,Y) = CKW_F G(Y) D(X)_\eta \tag{31}$$

where C is a scale factor (for example, see Appendix B), $W_F$ is fission yield (KT), $K = 6.9733 \times 10^9$ (Roentgens - $m^2$)/(hr - KT)**, and G(Y) is given by eq. (29). $D(X \geq 0)_{\eta=f}$ is given by eq. (15), while $D(X<0)_{\eta=u}$ is given by eq. (18). Fallout maps are symmetrical across the X axis (i.e., A(X,Y) = A(X,-Y)).

---

*The "normalized" H + 1 hour exposure rate assumes that all fallout is deposited at H + 1 hour, regardless of whether this is actually the case or not.

**In the older, more familiar units, K = 2692.4 (Roentgens - $mi^2$)/(hr - KT)

To estimate radiation damage to people, in terms of short-term survivability for damage assessment/vulnerability analysis studies, a quantity here called "maximum effective biological dose" is conventionally used[5]. This quantity is designed to allow for effects of a continuing exposure of ever decreasing intensity, and to account for some coincident repair of radiation damage by the human body. Following a theory postulated by Blair[16], Davidson[17] assumes that 90 percent of total radiation injury is reparable, while the remaining 10 percent is irreparable. Further, he estimates that for humans the repair rate is about 0.1 percent per hour of the residual reparable injury. Taking fallout gamma radiation exposure rate to vary with time according to the usual $t^{-1.2}$ approximation[18], Davidson derives an equation for the ratio of biological effective dose to H + 1 hour exposure rate that is a function of two variables: time of arrival of fallout (or time of entry into the fallout field), and time of exit from the fallout field. This equation has been evaluated numerically, and when plotted against exit time for specified $t_a$, the curve is found to have a maximum: the late-time falloff in effective biological dose being caused by combined effects of damage repair and decay of exposure rate intensity. The maximum in this curve gives the quantity called maximum effective biological dose, M(X,Y), and if we assume that residence in the fallout field is from $t_a$ to at least the time of the maximum, it is a function only of A(X,Y) and $t_a$, where A(X,Y) is a simple multiplier.

The numerical calculations necessary to define the ratio M(X,Y)/A(X,Y) as a function of $t_a$ have been done by the DoD Command and Control Technical Center and simple functions have been fitted to the results to give the following "quick approximation" equations:[5]

$$M(X,Y) = A(X,Y)(a_0 + a_1\beta + a_2\beta^2) \qquad (32)$$

where

$$\left.\begin{aligned} \beta &= 0.8685833 \ln(t_a) \\ a_0 &= 15.2891 \\ a_1 &= -2.903225 \\ a_2 &= 0.1662315 \end{aligned}\right\} \quad t_a < 1157.9 \text{ s}$$

$$\left.\begin{aligned} \beta &= 2 \ln(t_a) \\ a_0 &= 4.6182 \\ a_1 &= -0.53587 \\ a_2 &= 0.016923 \end{aligned}\right\} \quad t_a \geq 1157.9 \text{ s.}$$

As discussed in sections 3.1 and 3.2, a Gaussian dispersion function for deposited fallout is preferred for both the alongwind and crosswind directions. In this model a Gaussian crosswind function, G(Y), is used, but the alongwind function, F(X,t) (eq. (10)), is non-Gaussian. These functions are compared in Figure 4. A consequence of this inconsistency is that the fallout pattern is always asymmetric, even for zero wind, in which case all activity contours should be circles centered at ground zero. Specifically for $\vec{v} = 0$, eq. (31) becomes, if we omit the upwind and farfield corrections,

$$A(X,Y)_{\vec{v}=0} = KW_F \frac{\exp\left[-\frac{1}{2}\left(\frac{Y}{\sigma}\right)^2\right]}{\sigma^2\sqrt{2\pi^3}\left[1 + \left(\frac{X}{\sigma}\right)^2\right]} ,$$

which obviously cannot give circular contours for A = constant.

In practical terms this defect in the model is of little consequence. This is because a zero effective fallout wind is physically unacceptable. Indeed, it has been found that for other reasons (see sec. 4.2), the minimum acceptable value of v is about 0.5 m $s^{-1}$.

# 4. USE OF WIND DATA

## 4.1 GENERAL CONSIDERATIONS

Wind data are used to determine two essential model parameters: the effective fallout wind vector, $\vec{v}$, and the crosswind shear parameter, $S_Y$. Use of the magnitude of the effective fallout wind vector, v, is described throughout section 3, and use of $S_Y$ is explained in section 3.8.

The code accepts wind data in two forms: either the user can specify $\vec{v}$ and $S_Y$ directly or he can supply a single vertical profile of wind vector data, in which case, the code computes $\vec{v}$ and $S_Y$ from these data. In this chapter we describe these computations.

## 4.2 EFFECTIVE FALLOUT WIND

The code accepts a single vertical profile of wind vectors, each vector representing the wind speed and direction at a specified altitude. As is described in detail in section 6.3, considerable flexibility is allowed in terms of form and format of the input data.

After some preprocessing (subroutine INWIND), the data are stored in tabular form. There are four tables which contain the following data: $z_i$, $U_{E,i}$, $U_{N,i}$ and $z_{b,i}$. Here $z_i$ is the altitude (m above ground) at which wind vector components $U_{E,i}$, $U_{N,i}$ are defined*, i is the table entry (i.e., wind stratum) index (i = 1, 2 - - - I), and $z_{b,i}$ is the base altitude (m above ground) of the $i^{th}$ wind stratum defined as

$$z_{b,i} = \frac{1}{2}(z_{i-1} + z_i) \tag{33}$$

*Note that it is standard practice to measure surface wind at an elevation of 10 meters.

with $z_{b,1}=0$. $U_{E,i}$ is the wind component along the west-east axis, positive toward the east, and $U_{N,i}$ is the wind component along the south-north axis, positive toward the north (m $s^{-1}$).

Strictly speaking, altitude should be relative to mean sea level (MSL). However, in most cases MSL can be replaced by ground level (GL) without substantial error, and in practice this substitution will be implicit in most land surface burst predictions, as it is in the cases of the predictions of the Nevada Test Site shots discussed in section 5. The code provides for adjustment of altitudes to be relative to GL even though they may be input relative to some other origin.

Effective fallout wind is a weighted-average wind, the average being taken between the stabilized cloud cap center height and the surface, and the weighting being taken according to settling time of the nominal particle (sec. 2.4) through each wind stratum. The calculations are done in subroutine EFWIND.

Define $\vec{U}_i$ to be the wind vector in the $i^{th}$ stratum. Then the effective fallout wind is

$$\vec{v} = \frac{\sum_{i=1}^{J-1} \vec{U}_i \left(z_{b,i+1} - z_{b,i}\right)/f(z_i) + \vec{U}_{z_J'}\left(z_c - z_{b,J}\right)/f(z_J')}{\sum_{i=1}^{J-1} \left(z_{b,i+1} - z_{b,i}\right)/f(z_i) + \left(z_c - z_{b,J}\right)/f(z_J')} \tag{34}$$

where the summation begins at the ground, $z_i$ and $z_{b,i}$ are as defined above, but

$$z_c = \left(z_T + z_B\right)/2$$

$$z_J' = \left(z_c + z_{b,J}\right)/2 \quad ; \quad z_{b,J} \leq z_c$$

and $\vec{U}_{z_J'}$ is the wind vector at altitude $z_J'$ as determined by linear interpolation. $f(z)$ is the settling speed of the nominal particle at altitude z determined by linear interpolation in Table 1.

Actually, the code uses the magnitude of the effective fallout wind,

$$v = \sqrt{v_E^2 + v_N^2} \quad , \tag{35}$$

and the sine and cosine of its direction angle $\phi$ defined as

$$\begin{aligned} \sin \phi &= v_E/v \\ \cos \phi &= v_N/v \end{aligned} \tag{36}$$

where $v_E$ and $v_N$ are the easterly and northerly directed components of $\vec{v}$.

Theoretical and practical considerations impose a lower limit on the acceptable value of v. While occasionally a calm condition may be observed at the surface, this is never the case throughout the transport air space, and therefore a zero value for v is never acceptable. Very low values of v may cause certain unrealistic results to appear: for example, the upwind hotline activity may fall off less rapidly than the downwind activity.*

Accordingly, the code will not accept a value of v less than 0.5 m $s^{-1}$. An input value of v = 0 is used as a flag to signal input of a vertical profile of wind data. When the code encounters a value v less than 0.5 m $s^{-1}$ (which is not interpreted as the value 0.0 used to signal input of the vertical profile) this value is printed along with a comment, and v is reset to 0.5 m $s^{-1}$.

*This anomalous behavior is caused by interaction of several features of the code. First, the horizontal variance of deposited fallout, $\sigma^2$ (secs. 3.6 and 3.7) is held constant upwind of ground zero, whereas it increases downwind. Second, the upwind correction (sec. 3.4) is, unfortunately, not a function of v, but was determined from test shot results for which v is always substantially greater than zero. Consequently, both of these features depend on use of realistically large values of v to give realistic results.

## 4.3 SHEAR PARAMETER

Vertical wind shear is defined as

$$\vec{S} = \frac{d\vec{U}}{dz} \quad , \tag{37}$$

where $\vec{U}$ is wind and z is the vertical coordinate. We make the customary assumption that advective transport will overwhelm effects of shear dispersion in the alongwind direction, and, therefore, we are interested only in the crosswind component of $\vec{S}$, $S_Y$.

In this model, $S_Y$ is taken to be the root-mean-square value of the crosswind components of $\Delta\vec{U}/\Delta z$ computed at intervals of $\Delta z = (z_T - z_B)$ from the cloud top to the ground. The final $\Delta z$ value is adjusted as required to avoid reaching below the ground.

In terms of the variables defined in the preceding section,

$$S_Y = \left[ \frac{1}{K-T} \sum_{j=1}^{K-1} \left\{ \left[ \sin\phi \left( U_{N,z_j} - U_{N,z_{j+1}} \right) - \cos\phi \left( U_{E,z_j} - U_{E,z_{j+1}} \right) \right] \Big/ \left( z_j - z_{j+1} \right) \right\}^2 \right]^{1/2} \tag{38}$$

Here the summation begins at the cloud top such that we have

$$z_j = z_T - \left(j - 1\right)\left(z_T - z_B\right) \quad ; \quad j = 1,2, - - -, K-1$$

and

$$z_K = 0.$$

Wind components for arbitrary z are determined by linear interpolation in the wind data tables. The calculations are done in function SYWND.

## 5. VALIDATION

### 5.1 DISCUSSION OF RESULTS

Predictions are compared with observed H + 1 hour normalized* exposure rate maps for the first five test shots described in Table 2. For the sixth shot, Bravo, there are not enough observed data to construct a complete fallout map. Thus, for this case we compare our prediction against a special "reconstruction" calculation made by the Naval Radiological Defense Laboratory shortly after the event[19].

Three methods of comparison of fallout patterns are used:

1. Visual comparison of contour maps.
2. Comparison of contour areas, and hotline lengths and azimuths.**

TABLE 2

TEST SHOT DATA

| Shot | Total Yield (KT) | Fission Yield (KT) | HOB (m) | Altitude of GZ (m) | Site |
|---|---|---|---|---|---|
| Johnie Boy | 0.5 | 0.5 | -0.584 | 1570.6 | NTS+ |
| Jangle-S | 1.2 | 1.2 | 1.067 | 1284.7 | NTS |
| Small Boy | low | - | 3.048 | 938.2 | NTS |
| Koon | 150. | - | 4.145 | 0.0 | Bikini |
| Zuni | 3380. | - | 2.743 | 0.0 | Bikini |
| Bravo | 15000. | - | 2.134 | 0.0 | Bikini |

+Nevada Test Site

*A "normalized" exposure rate map is constructed on the assumption that all local fallout is down at the specified time, regardless of its actual deposition time.

**Hotline length is defined as the furthest distance from ground zero on a contour, and hotline azimuth is the angle, measured clockwise from north, to the point of furthest distance from ground zero on a contour.

3. The Rowland-Thompson Figure-of-Merit (FM)[20] which is a measure of contour overlap. (See Appendix C.)

These are roughly in order of importance.

Statistical data are in Table 3 and the contour plots are on pp. 58 through 80. Contours were drawn by a 30-inch Calcomp plotter, and each observed-predicted pair are to the same scale. Contour maps and statistical data are included for predictions by DELFIC and WSEG-10 as well as by DNAF-1.

Prediction accuracy is seen to be good. Perhaps the best quantitative measure of accuracy is provided by the mean absolute percent error, E, which for n observed-predicted data pairs is

$$E = \frac{100}{n} \sum_{i=1}^{n} \left| x_{obs,i} - x_{pred,i} \right| / x_{obs,i} \quad .$$

Values of E for each prediction (excluding Bravo) by each of the three models are given under the solid lines in Table 3. The values in parentheses are computed with the data for the highest level contours excluded. The highest level contours are particularly difficult to predict since usually they are dominated by the region most affected by induced activity in the ground and throwout from the crater, neither of which are addressed by the fallout models. Overall mean absolute percent errors are given in Table 4. (Bravo prediction data are excluded.) As one might expect, DNAF-1 errors are intermediate between those of DELFIC, which are best, and WSEG-10, which are worst, though the differences between the DNAF-1 and DELFIC errors are less than between DNAF-1 and WSEG-10. Note that the most obvious problem with the WSEG-10 predictions is a tendency to overpredict the low level contours at the expense of the higher levels, to the extent that frequently the higher level contours are completely absent.

TABLE 3

COMPARISON OF OBSERVED AND PREDICTED FALLOUT PATTERN STATISTICS

Observed/DNAF-1/DELFIC*/WSLG-10‡

| Test Shot | FM DNAF-1 DELFIC WSLG-10 | Contour (Roentgen $hr^{-1}$) | Area ($km^2$) | Hotline Length (km) | Azimuth (deg.) |
|---|---|---|---|---|---|
| Johnie Boy | 0.245 | 1000 | 0.278/0.038/0.029/---- | 1.38/0.38/0.032/---- | 359/351/ 0/--- |
| | 0.182 | 100 | 0.539/1.00 /0.77 /1.17 | 2.73/2.18/2.58 /3.7 | 345/351/344/344 |
| | 0.187 | 50 | 1.27 /1.90 /1.79 /4.57 | 4.10/3.21/4.13 /8.9 | 343/351/343/344 |
| | | | 74(68)/58(42)/159(188)** | 38(21)/28(3)/84(76) | |
| Jangle-S | 0.70 | 500 | 0.117/0.390/0.144/---- | 0.69/1.64/1.00 /---- | 342/ 15/353/--- |
| | 0.483 | 300 | 0.386/0.821/0.316/---- | 1.50/2.49/1.23 /---- | 346/ 15/354/--- |
| | 0.080 | 100 | 1.44 /2.64 /2.24 /0.55 | 3.74/4.97/5.37 /2.8 | 1/ 15/355/ 10 |
| | | 35 | 3.11 /6.99 /5.08 /5.45 | 5.66/9.07/7.68/10.2 | 6/ 15/355/ 10 |
| | | | 138(106)/40(46)/84(79) | 79(59)/43(42)/82(76) | |
| Small Boy ‡ | 0.582 | 1000 | 0.216/0.302/0.047 | 1.00/0.92/0.25 | 71/ 64/ 66 |
| | 0.308 | 500 | 0.528/0.703/0.135 | 1.62/1.49/0.56 | 73/ 64/ 80 |
| | ----- | 200 | 0.942/1.75 /0.564 | 2.22/2.62/1.69 | 72/ 64/ 73 |
| | | 100 | 3.75 /3.35 /1.10 | 5.66/3.90/3.72 | 72/ 64/ 74 |
| | | 50 | 9.03 /6.45 /4.38 | 8.10/5.69/6.47 | 75/ 64/ 72 |
| | | | 40(40)/63(59) | 19(22)/44(36) | |
| Koon | 0.515 | 500 | 32.0 /55.9 /26.0 /5.7 | 10.2/14.8/12.5 /5.0 | 18/11.3/ 0/ 9 |
| | 0.287 | 250 | 122 /13.8 /87 /70 | 17.3/22.7/24.2 /18.4 | 15/11.3/ 4/ 9 |
| | 0.340 | 100 | 550 /387 /261 /384 | 41.0/39.8/39.5 /45.6 | 17/11.3/ 3/ 9 |
| | | | 39(21)/33(41)/52(36) | 26(17)/22(22)/23(9) | |
| Zuni | 0.163 | 150 | 474 /537 /2239 /2659 | 98 /32 /78 /82 | 12/340/337/349 |
| | 0.105 | 100 | 2761 /1088 /3619 /4684 | 125 /44 /96 /110 | 17/340/337/349 |
| | 0.180 | 50 | 6187 /3055 /6660 /10760 | 138 /74 /121 /168 | 27/340/338/349 |
| | | 30 | 10950/5791 /9913 /18200 | 177 /103 /153 /216 | 33/340/340/349 |
| | | | 43(53)/105(16)/168(70) | 55(51)/17(16)/18(19) | |
| Bravo (NRDL) | 0.054 | 3000 | 5373 /-----/188 /---- | 177 /----/31 /---- | 72/---/ 90/--- |
| | 0.069 | 2000 | 13520/122 /413 /219 | 198 /24 /43 /30 | 69/ 94/ 90/ 89 |
| | 0.070 | 1000 | 23660/1074 /1798 /2613 | 237 /46 /73 /121 | 78/ 94/ 90/ 89 |
| | | 500 | 40480/4113 /5444 /9056 | 298 /103 /112 /259 | 75/ 94/ 90/ 89 |
| | | 100 | 76320/41590/27550/41620 | 559 /445 /268 /597 | 90/ 94/ 92/ 89 |

*Data taken from reference 1.

‡Data taken from reference 7

‡A comparable Small Boy prediction by WSLG-10 is not available.

**Mean absolute percent errors: DNAF-1/DELFIC/WSLG-10. The values in parentheses are calculated without including the data for the highest activity level contours. See p. 53.

TABLE 4

OVERALL MEAN ABSOLUTE PERCENT ERRORS*

| | Contour Area | Hotline Length |
|---|---|---|
| DNAF-1 | 66(58) | 43(35) |
| DELFIC | 62(42) | 32(26) |
| WSEG-10 | 117(90) | 51(45) |

The Figure-of-Merit (FM) results do not show a consistent order of capabilities for the models. This is typical of past experience as well, and we have concluded that in its present form, FM does not provide a very useful measure of prediction capability. Details are given in Appendix C.

## 5.2 DISCUSSION OF THE TEST SHOT DATA AND PREDICTIONS

The three low yield shots were executed at the Nevada Test Site, and their fallout patterns were measured over land. For this reason, observed patterns for these shots, though not highly accurate, may be considered to be superior to the patterns of the high yield shots which were executed on Bikini Atoll in the South Pacific. Not only are the fallout fields of the high yield shots very large, which adds to measurement problems, but most of the fallout from these shots fell into water. Even so, most of the Koon pattern area was covered by an array of fallout collection stations, so this pattern is probably reasonably accurate. Zuni, on the other hand, is a special case. The fallout pattern used here is exclusively downwind of the atoll and was determined by an oceanographic survey method that was known to be inaccurate. The close-in pattern in the region of the atoll is available, but contains no closed contours so it could not be used here; thus the high-activity portion of the observed pattern for this shot is ignored

*Values in parentheses are calculated with data for the highest level contours excluded.

and this alone must account for a substantial portion of the disagreement between observation and prediction for this shot, particularly with regard to contour areas and contour overlap (Table 3). As already mentioned, we have no observed pattern for the Bravo shot. In addition, we have the following problem.

DNAF-1 and DELFIC predictions for the high yield shots are expected to be inferior to those for the low yield shots. This is because the high yield shots were detonated over coral soil, and in the cases of Zuni and Bravo, large but uncertain amounts of sea water were lifted by the clouds. The particle size distribution used for these predictions is typical of fallout produced from the siliceous soil found at the Nevada Test Site. We have not succeeded in developing a distribution appropriate for coral and coral-sea water mixtures.

DNAF-1 predictions were made using the H hour winds tabulated in reference 7. DELFIC predictions were made using all of the reference 7 wind profiles, from H hour onward in time. WSEG-10 calculations were done using $\vec{v}$ and $S_\gamma$ values supplied by the DoD Command and Control Technical Center as determined by them from the H hour wind profiles; these data also are tabulated in referen 7 (Appendix A.3). For shots Small Boy and Bravo, the published wind data have been found to be not pertinent to transport of the nuclear clouds. For both of these cases, we have used reconstructed wind data: for Small Boy the reconstruction is described in Appendix B of reference 7, and for Bravo we have used the winds developed by Dean and Olmstead. Values of $\vec{v}$, $\phi$ and $S_\gamma$ computed for the DNAF-1 predictions are given in Table 5.

TABLE 5

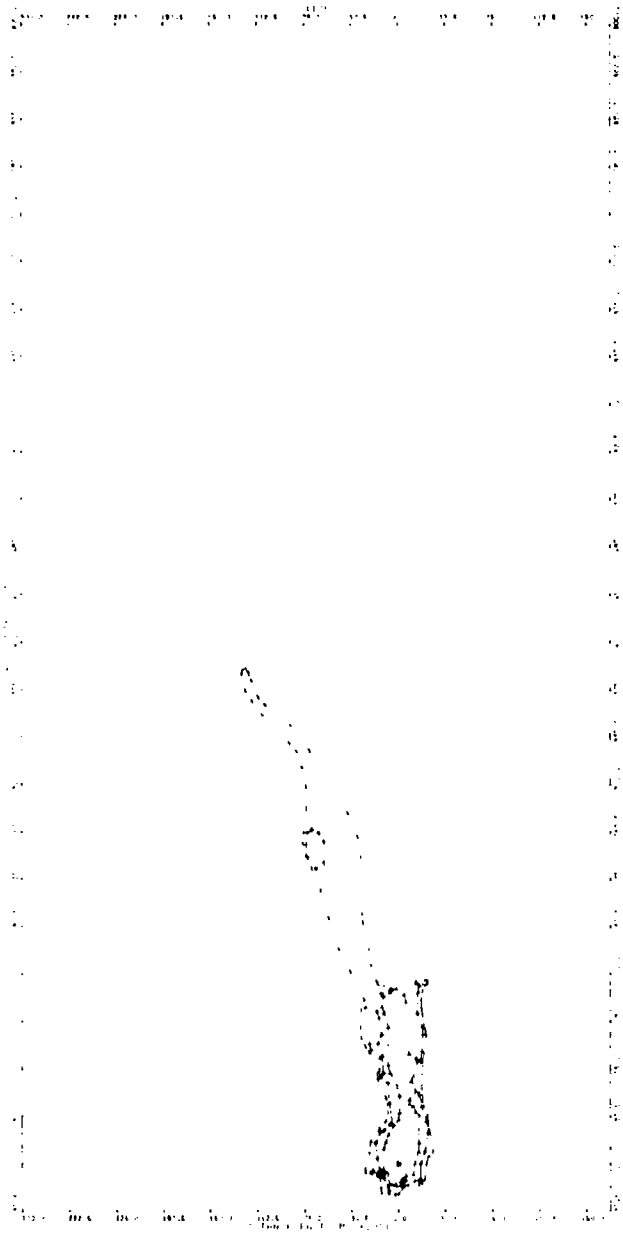
EFFECTIVE FALLOUT WINDS AND SHEAR PARAMETERS
COMPUTED FROM H HOUR WIND PROFILES FOR USE BY DNAF-1

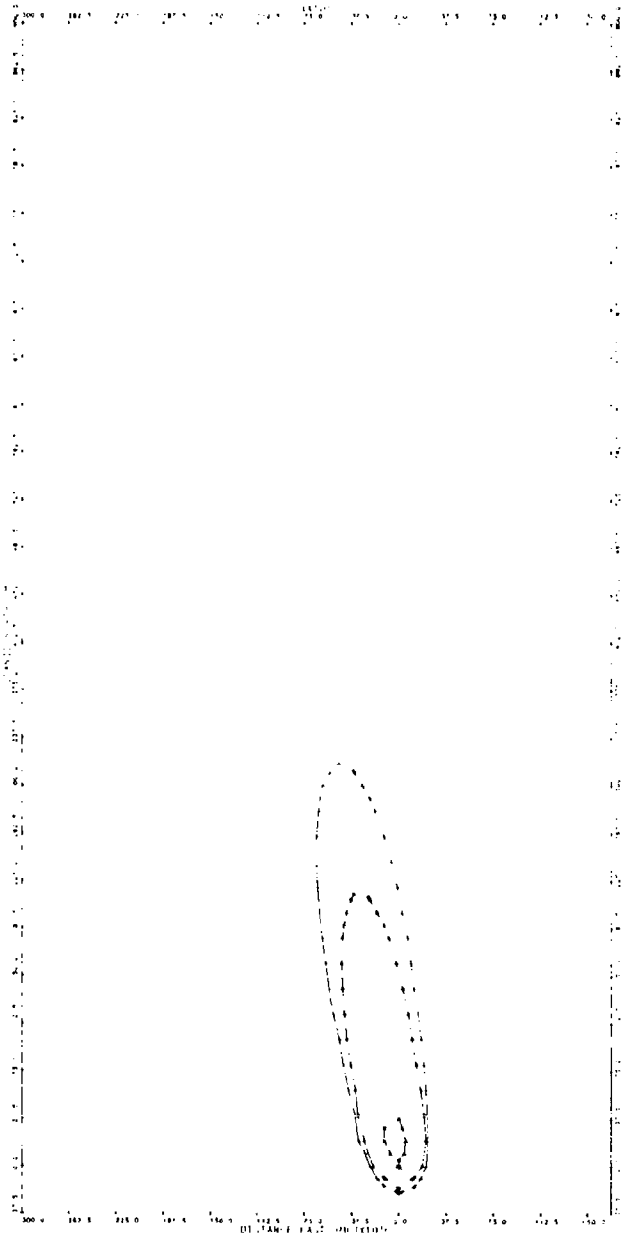
| Test Shot | $v$ ($m\ s^{-1}$) | $\phi$ (deg.) | $S_{Y_1}$ ($s^{-1}$) |
|---|---|---|---|
| Johnie Boy | 6.0 | - 8.6 | 0.00323 |
| Jangle-S | 13.1 | 14.6 | 0.00311 |
| Small Boy | 3.8 | 64.0 | 0.00066 |
| Koon | 6.2 | 11.3 | 0.00133 |
| Zuni | 4.9 | -20.0 | 0.00225 |
| Bravo | 5.8 | 93.6 | 0.00044 |

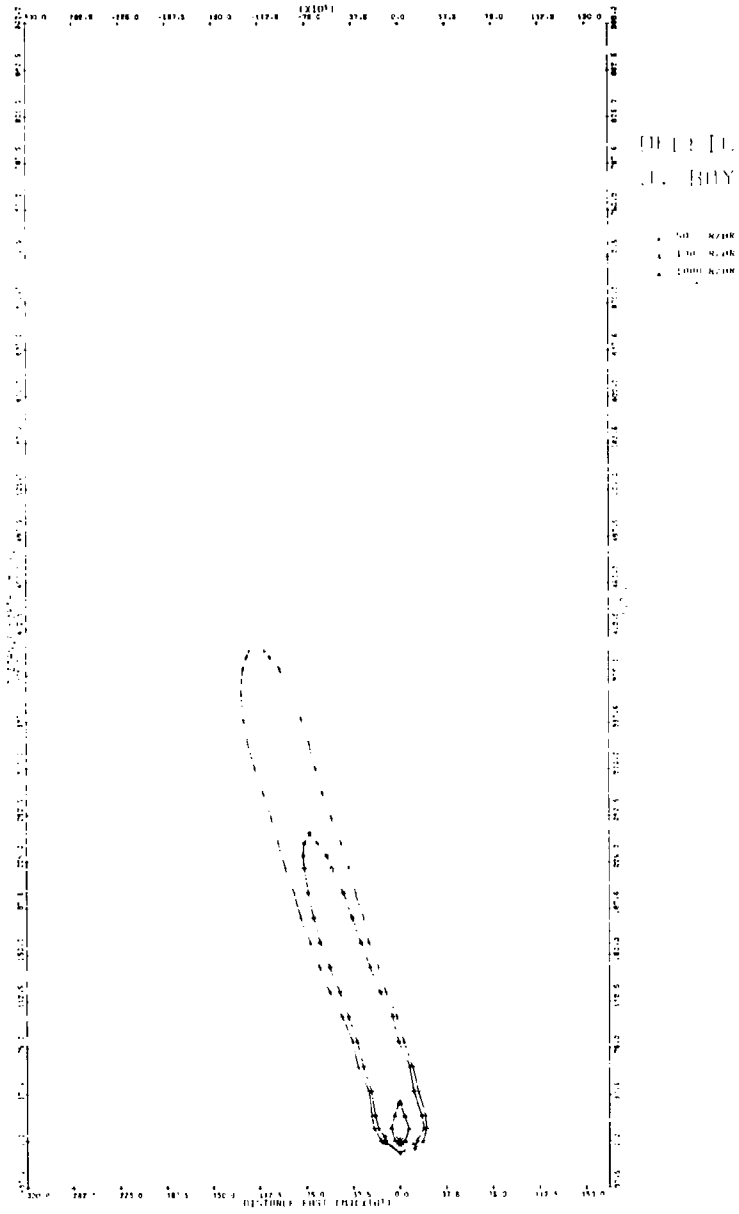
## 5.3 OBSERVED AND PREDICTED FALLOUT PATTERNS

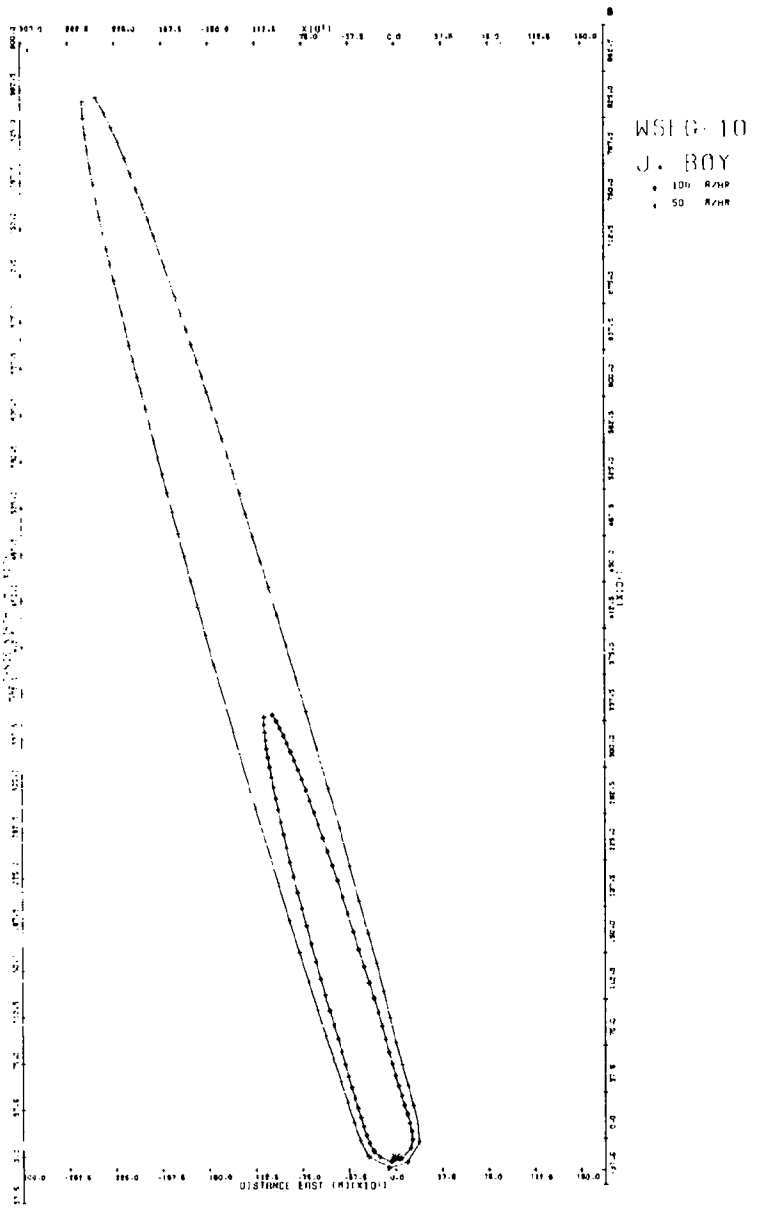
Contours are in units of Roentgens per hour for gamma radiation at a height of one meter above ground at H + 1 hour. All activity is assumed to be deposited at H + 1 hour. For all but the Zuni shot, for which fallout activity was measured by an oceanographic method, predicted activities are multiplied by a combined ground roughness-instrument response correction factor of 0.5. (See Appendix B.)

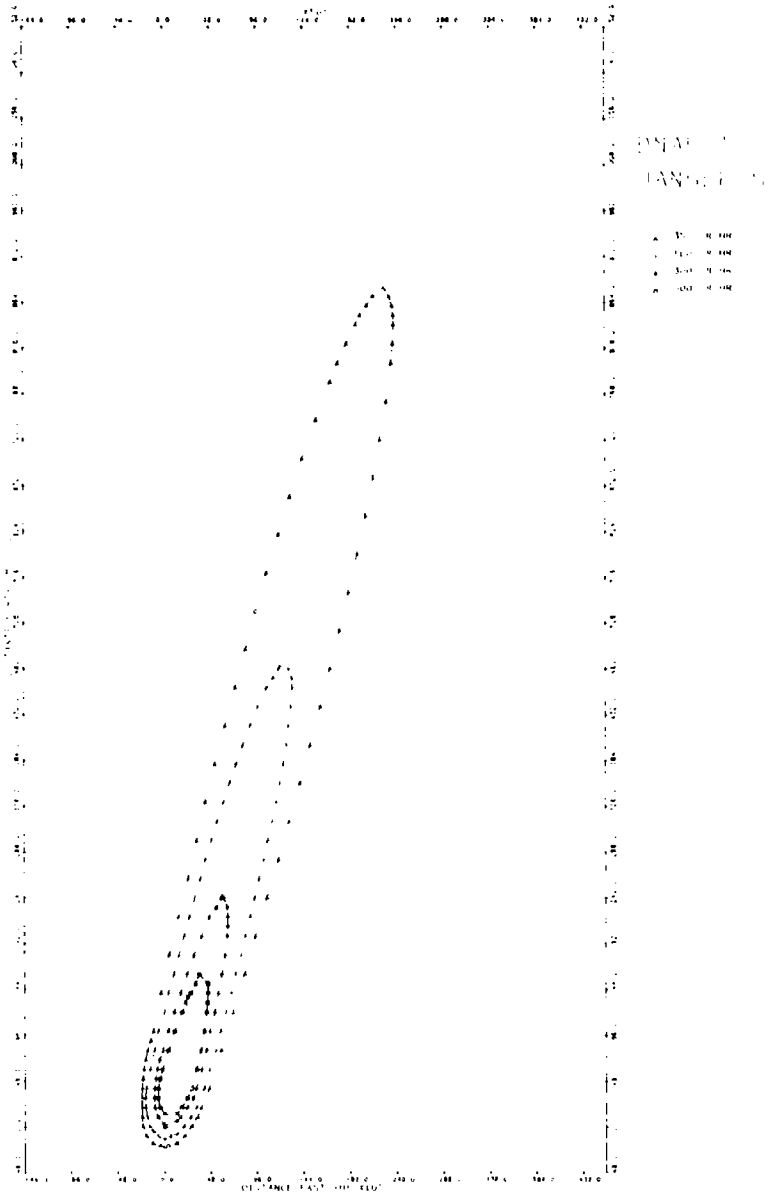
Observed and predicted patterns for each case are plotted to the same scale. North is up the pages and east is across the pages toward the right. Visual comparisons are best made by superimposing electrostatic copies of the plots.

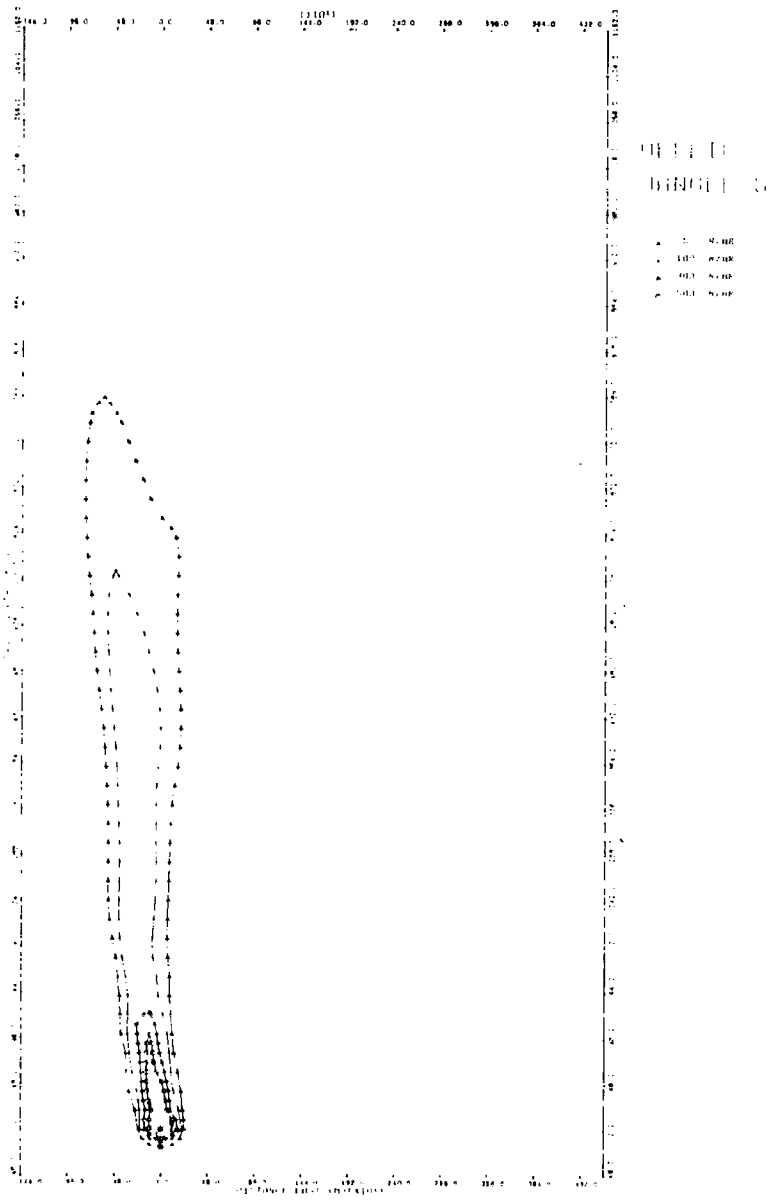


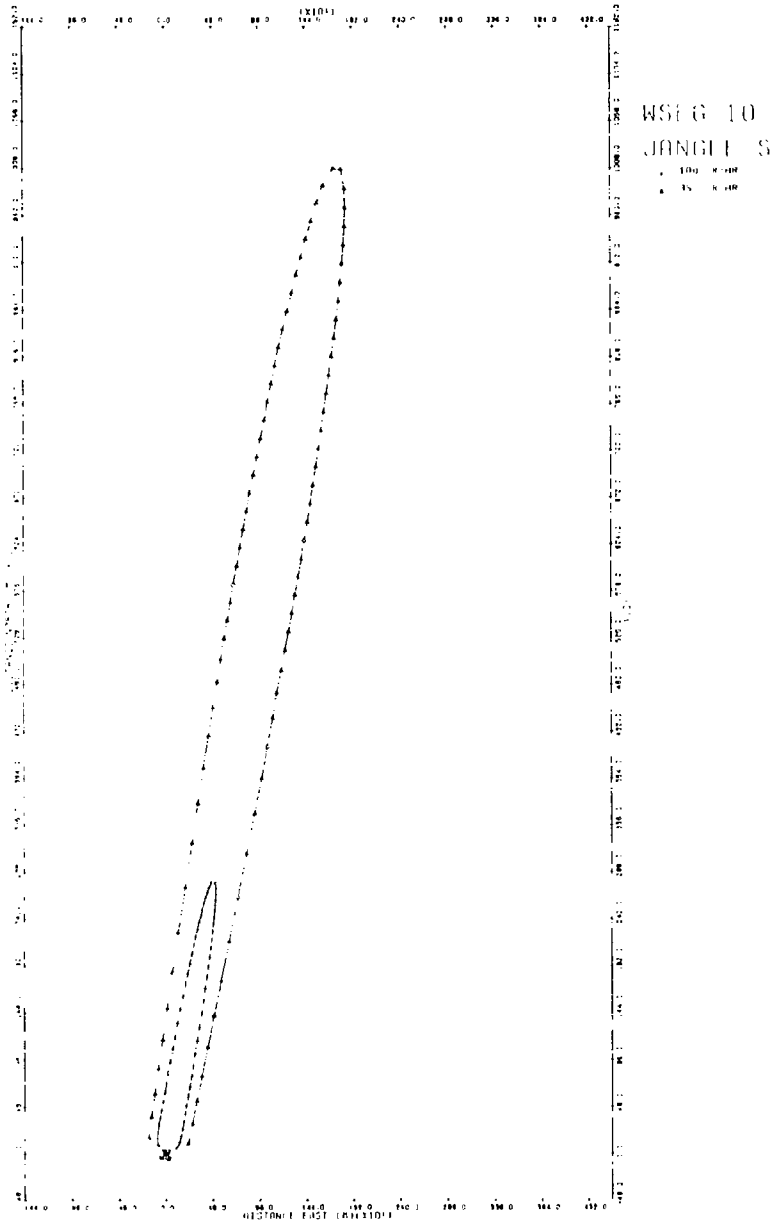


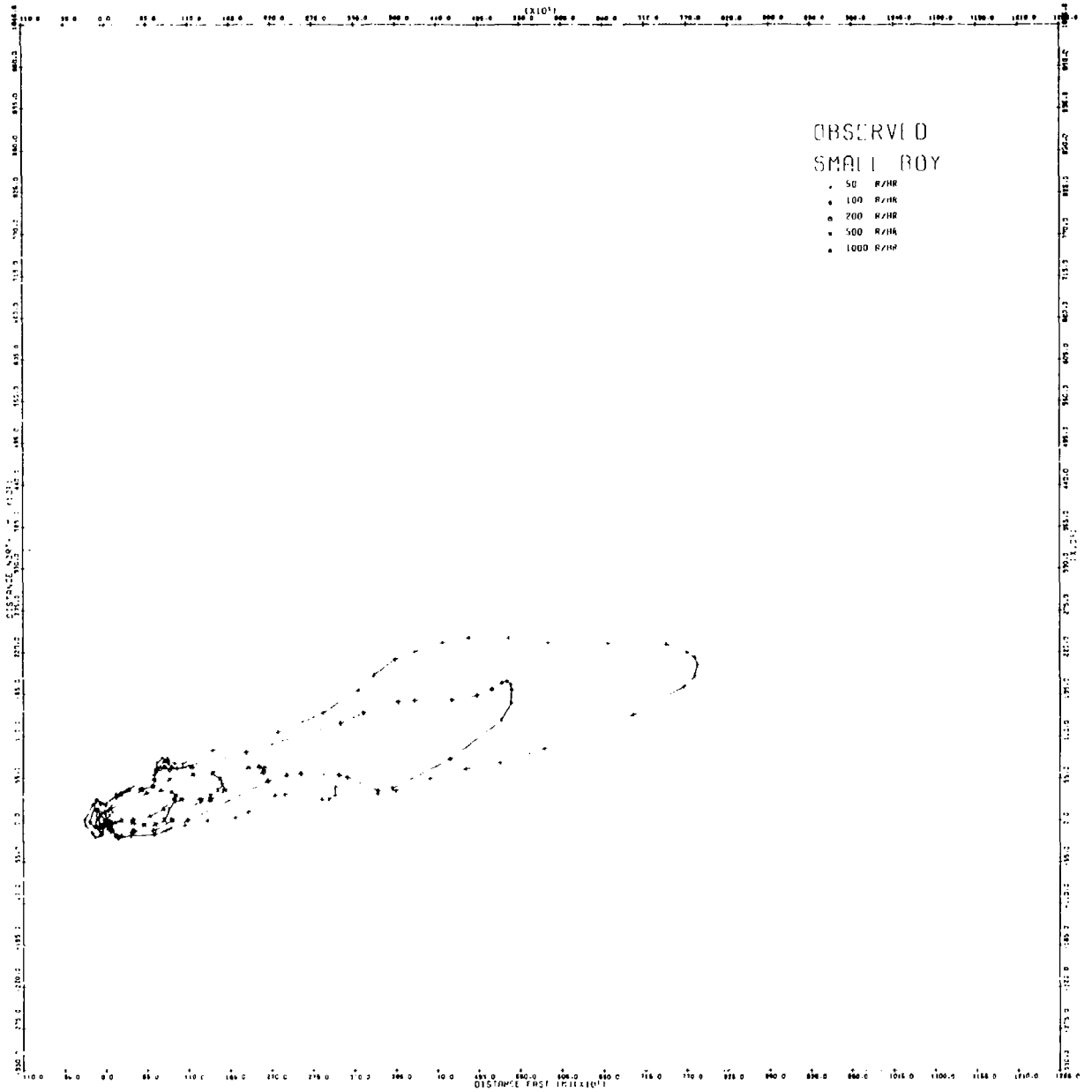


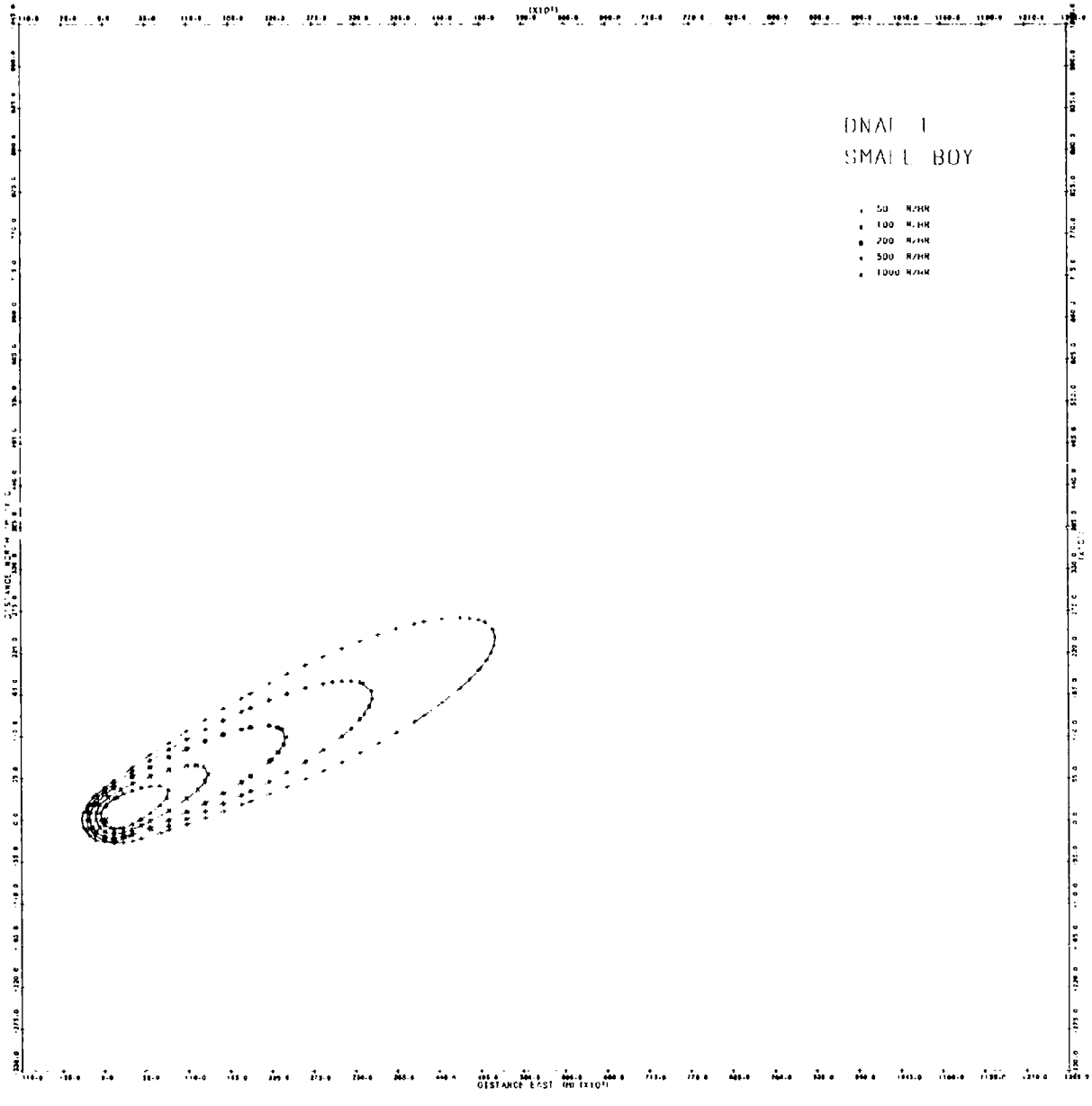

WSEG-10
J. BOY
100 R/HR
50 R/HR
DISTANCE EAST (M)X10[1]

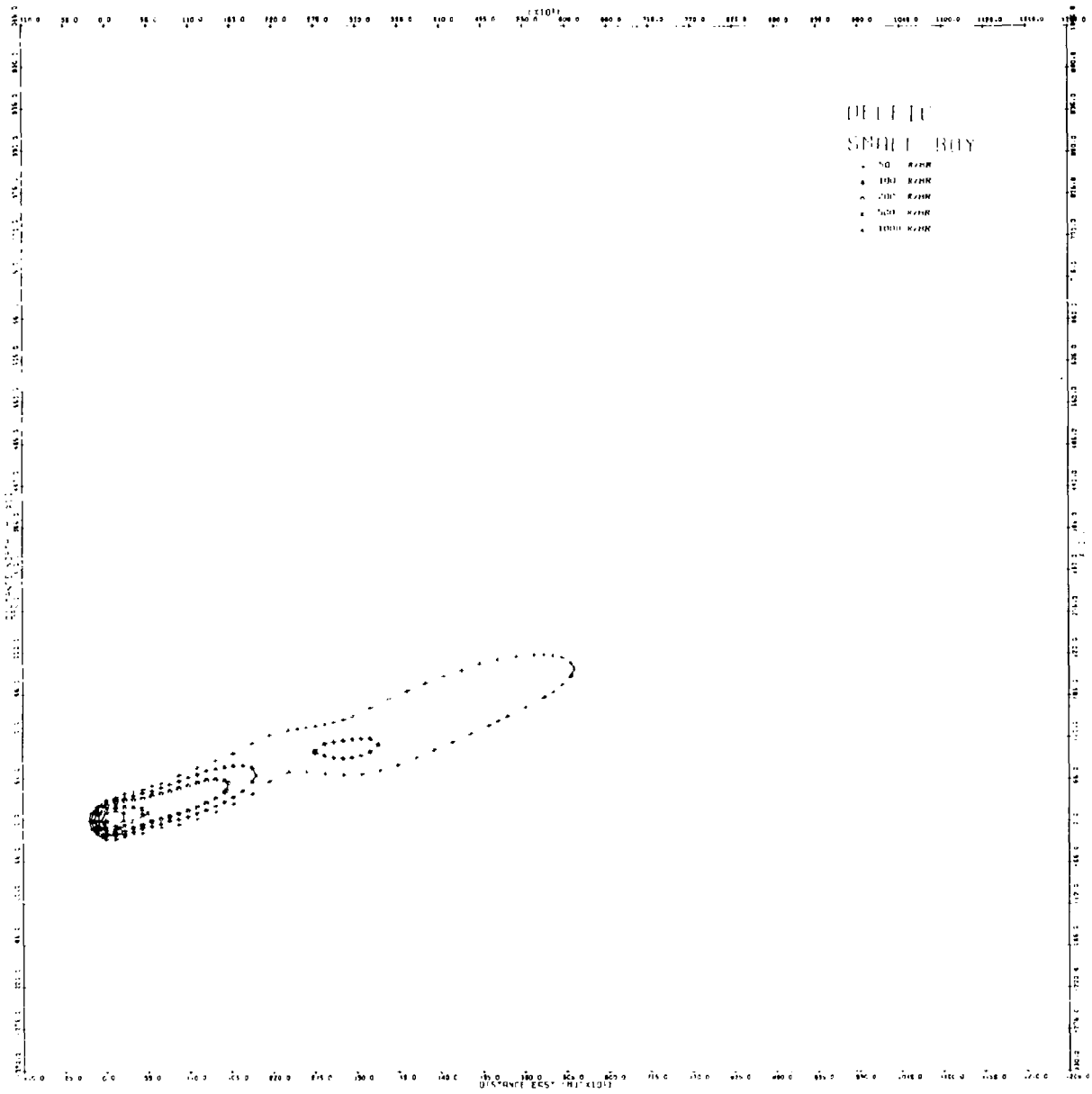


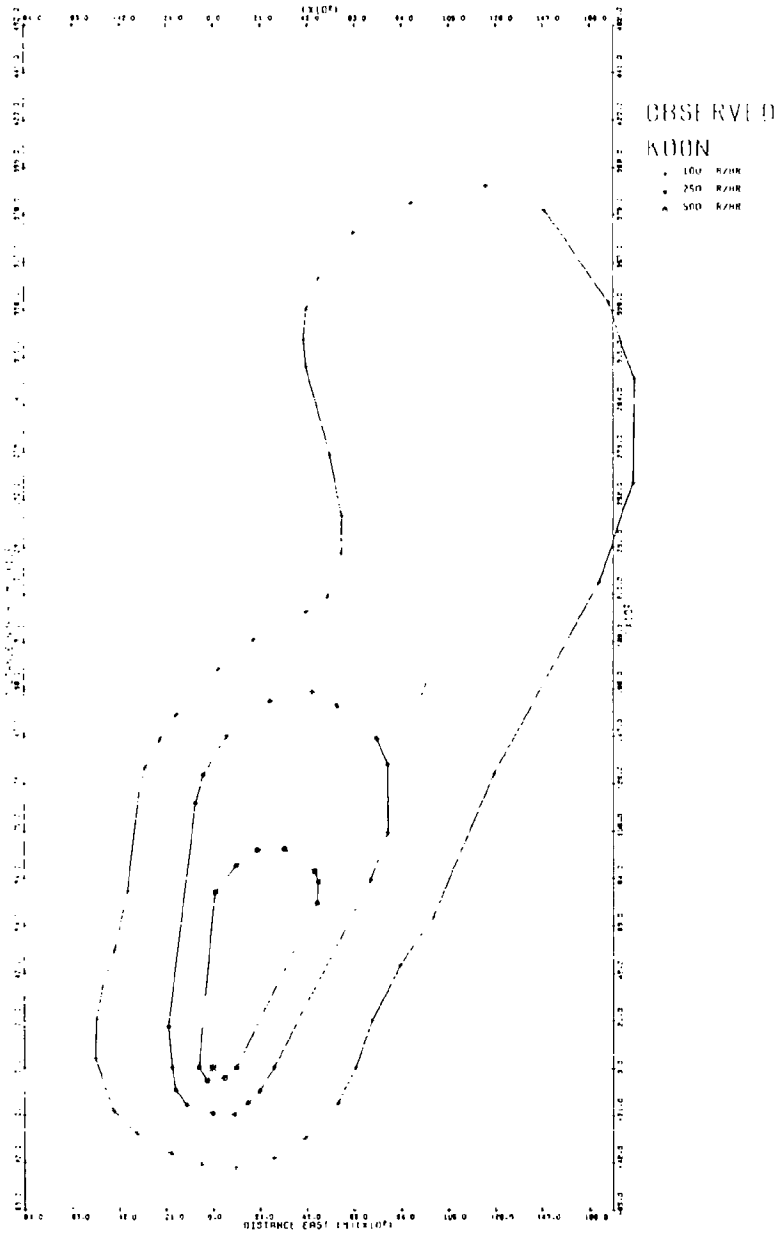


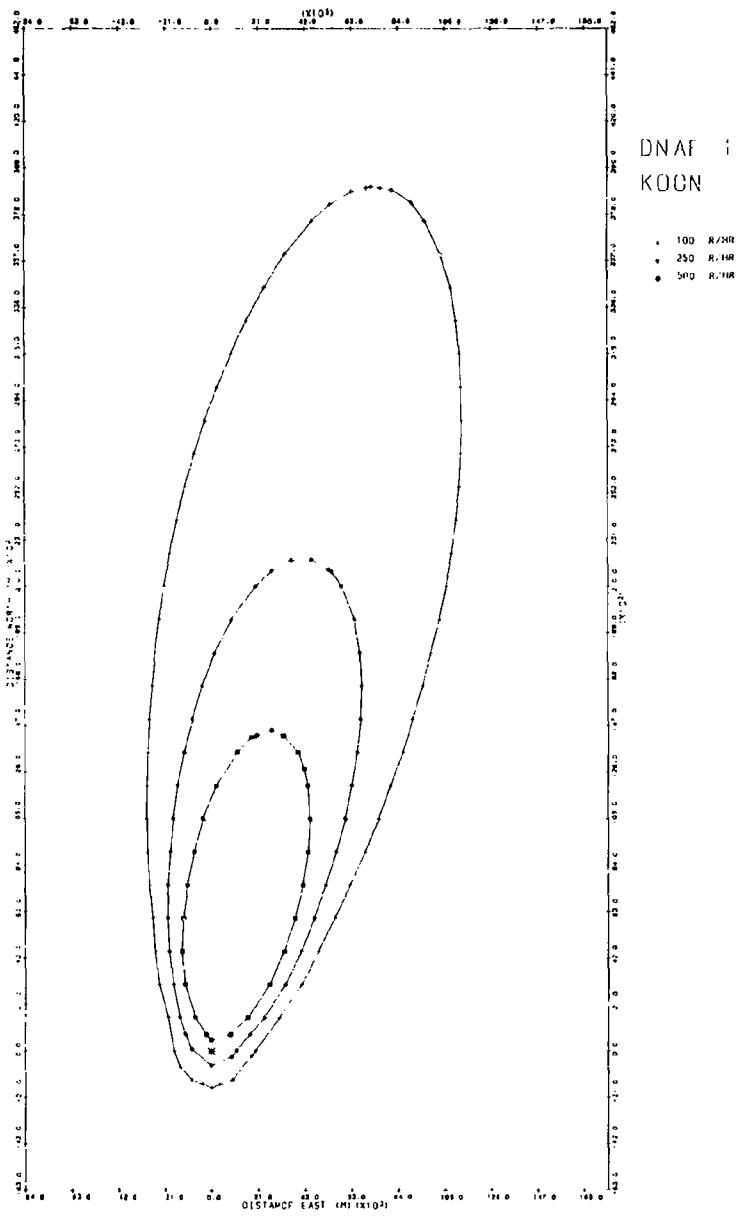

WSEG 10
JANGLE S

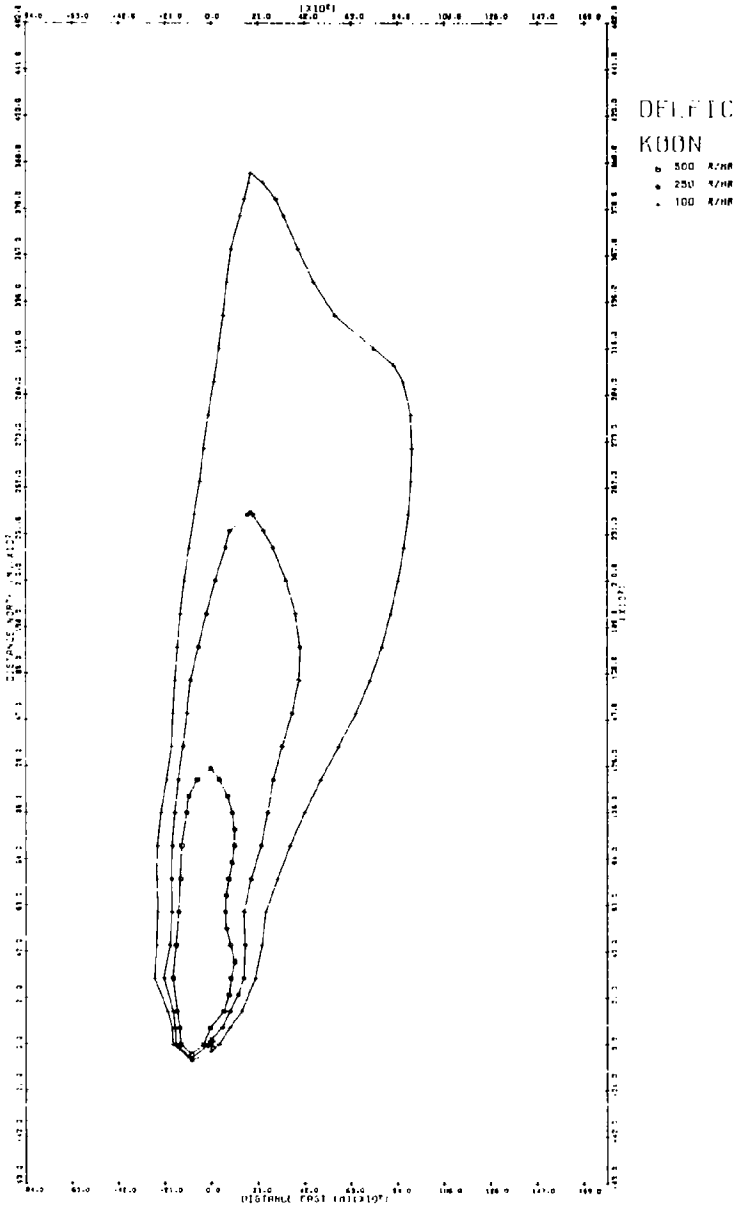

OBSERVED
SMALL BOY
50 R/HR
100 R/HR
200 R/HR
500 R/HR
1000 R/HR

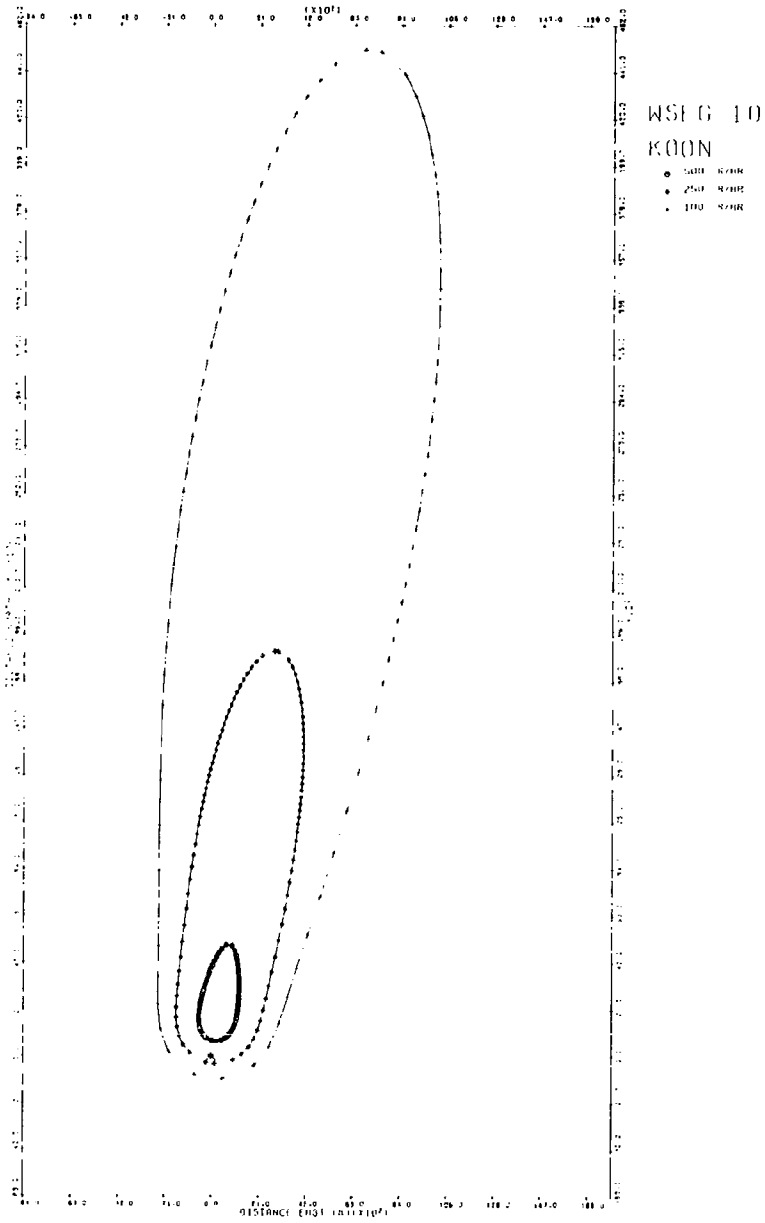

DNAL 1
SMALL BOY
50 R/HR
100 R/HR
200 R/HR
500 R/HR
1000 R/HR
DISTANCE EAST (NM (X10))

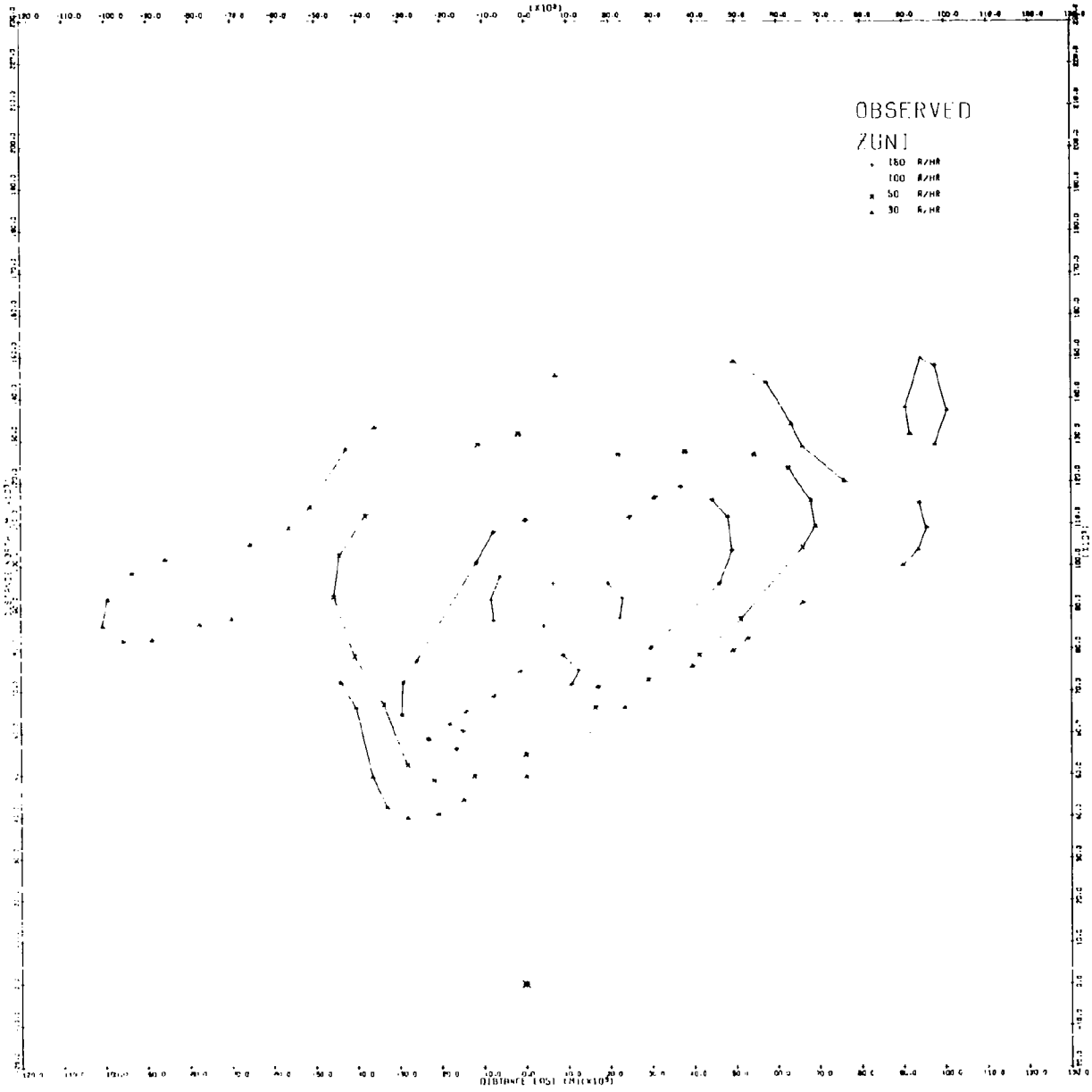

DELETE
SMALL BOY
50 R/HR
100 R/HR
200 R/HR
500 R/HR
1000 R/HR
DISTANCE EAST (M) X10[1]

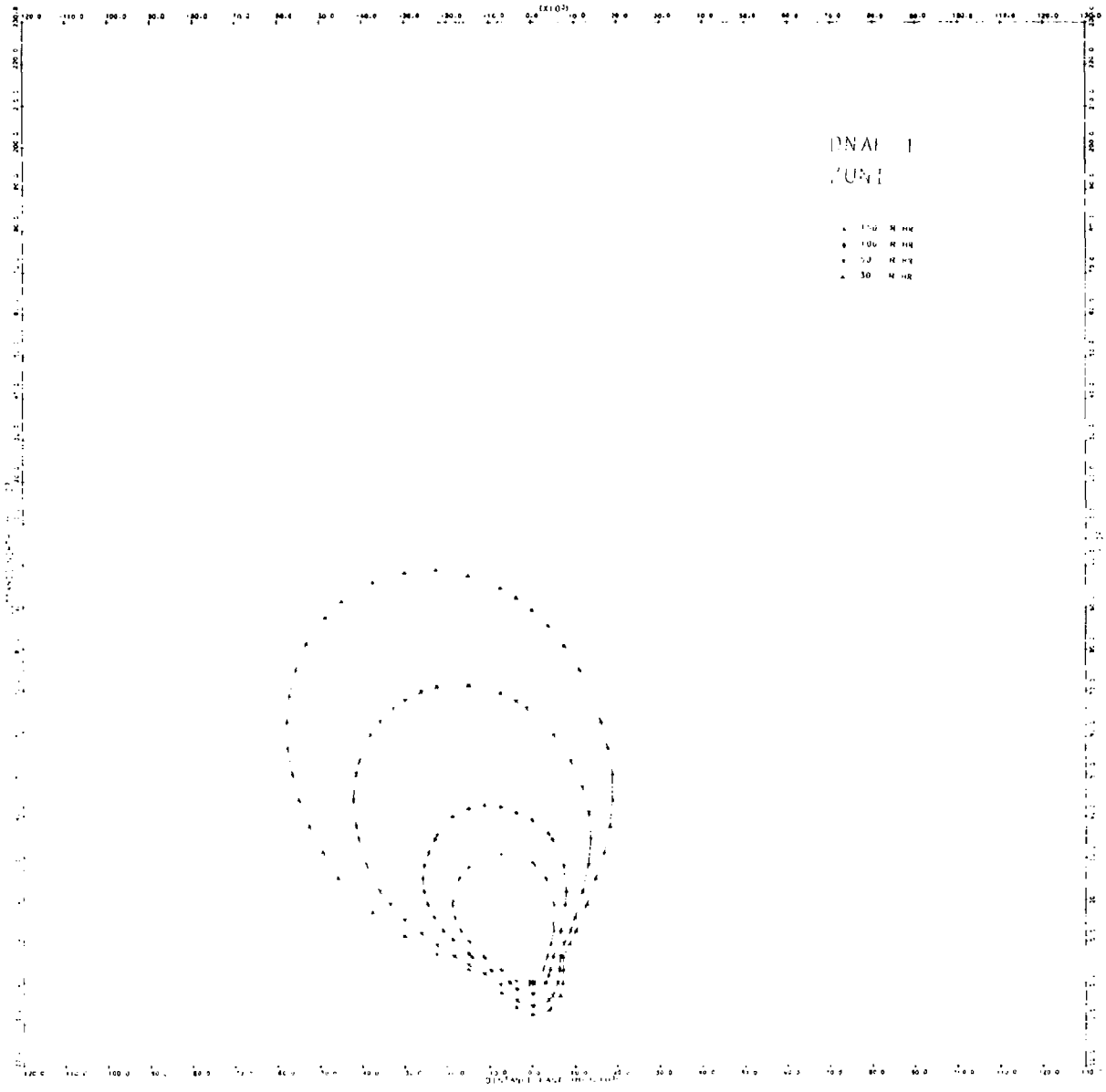

OBSERVED
KDON
100 R/HR
250 R/HR
500 R/HR
DISTANCE EAST (X10M)

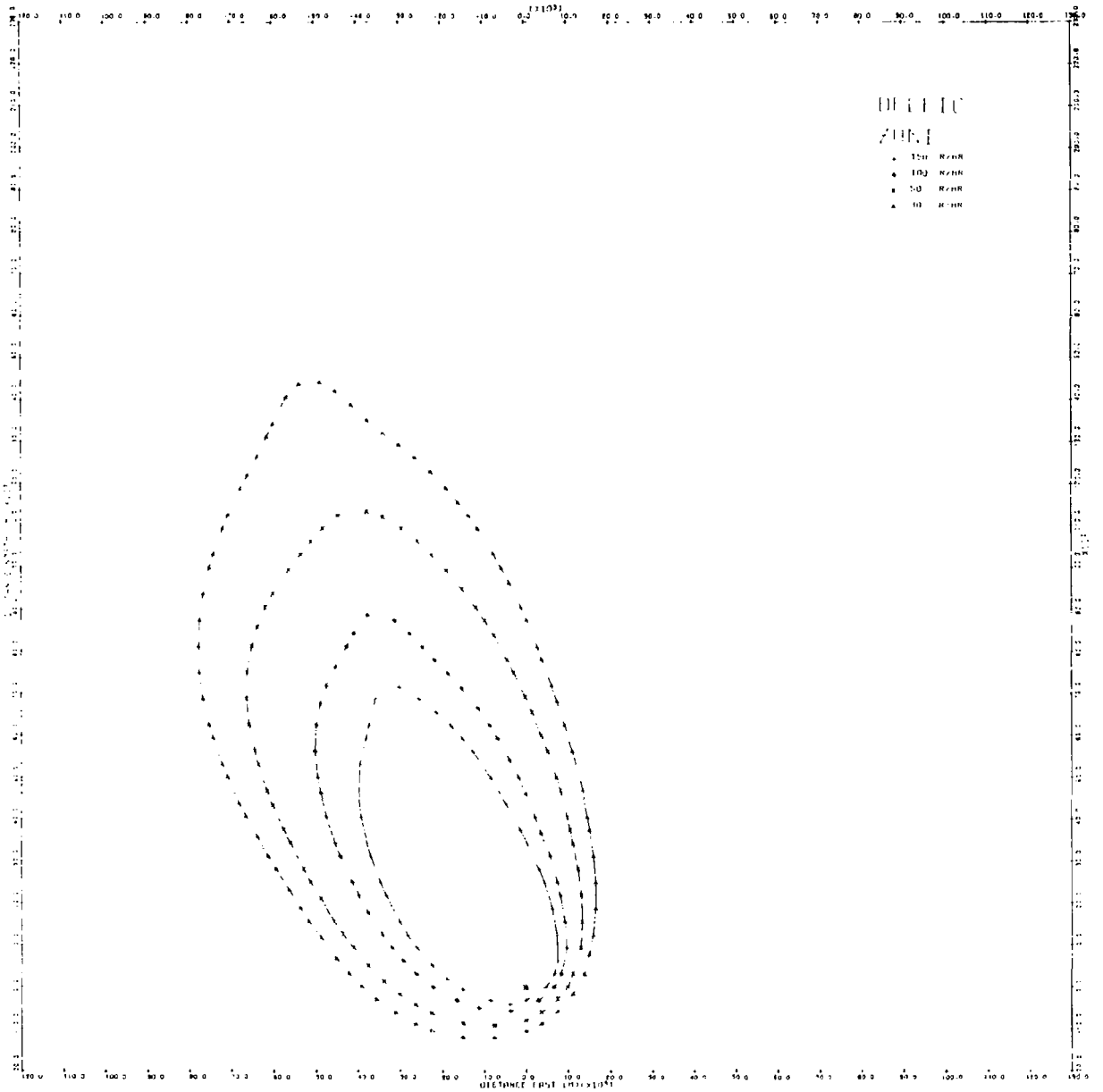

DNAF 1
KOON
100 R/HR
250 R/HR
500 R/HR
DISTANCE EAST (MI)(X10³)

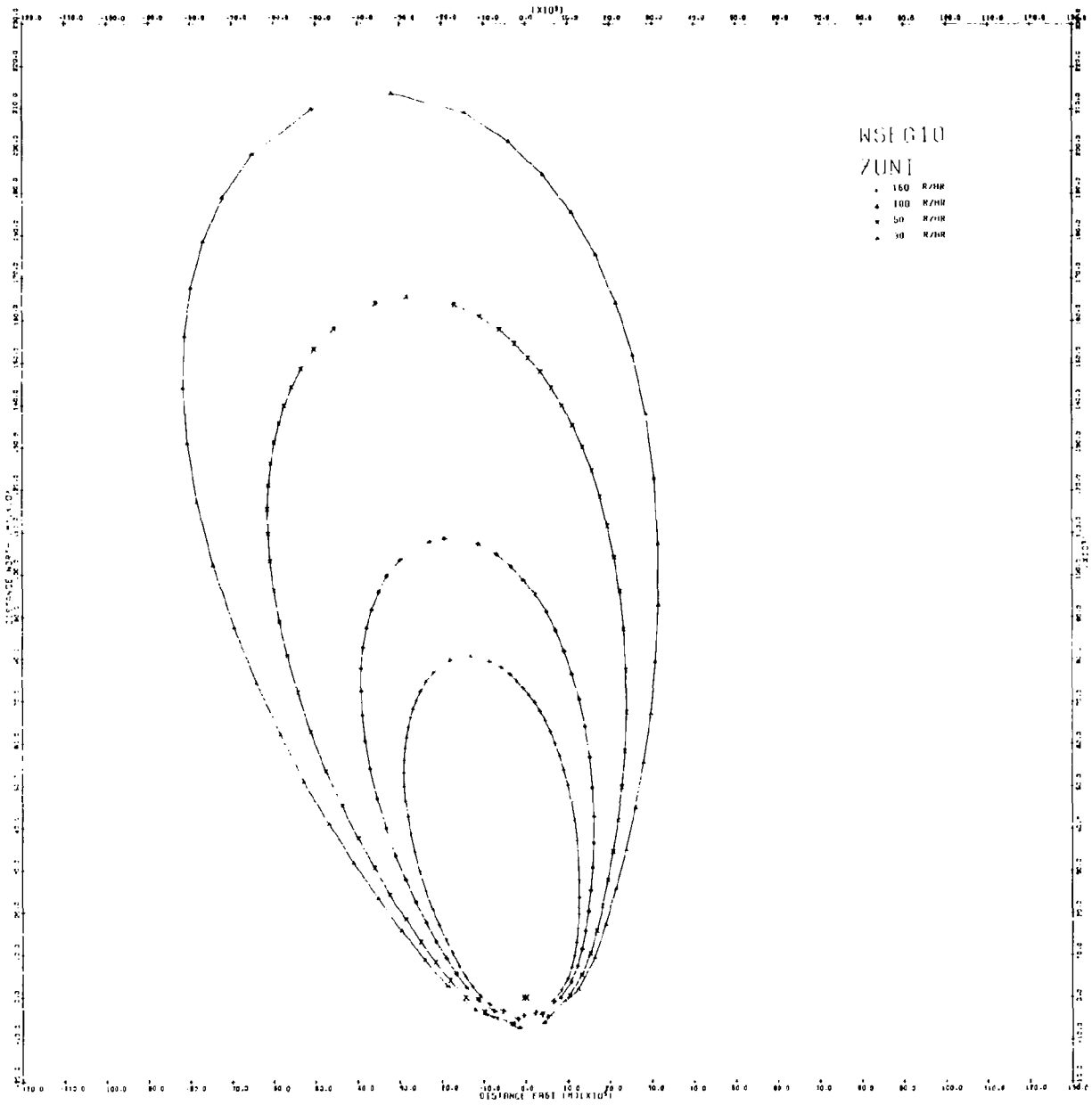

DELFTC
KOON
500 R/HR
250 R/HR
100 R/HR

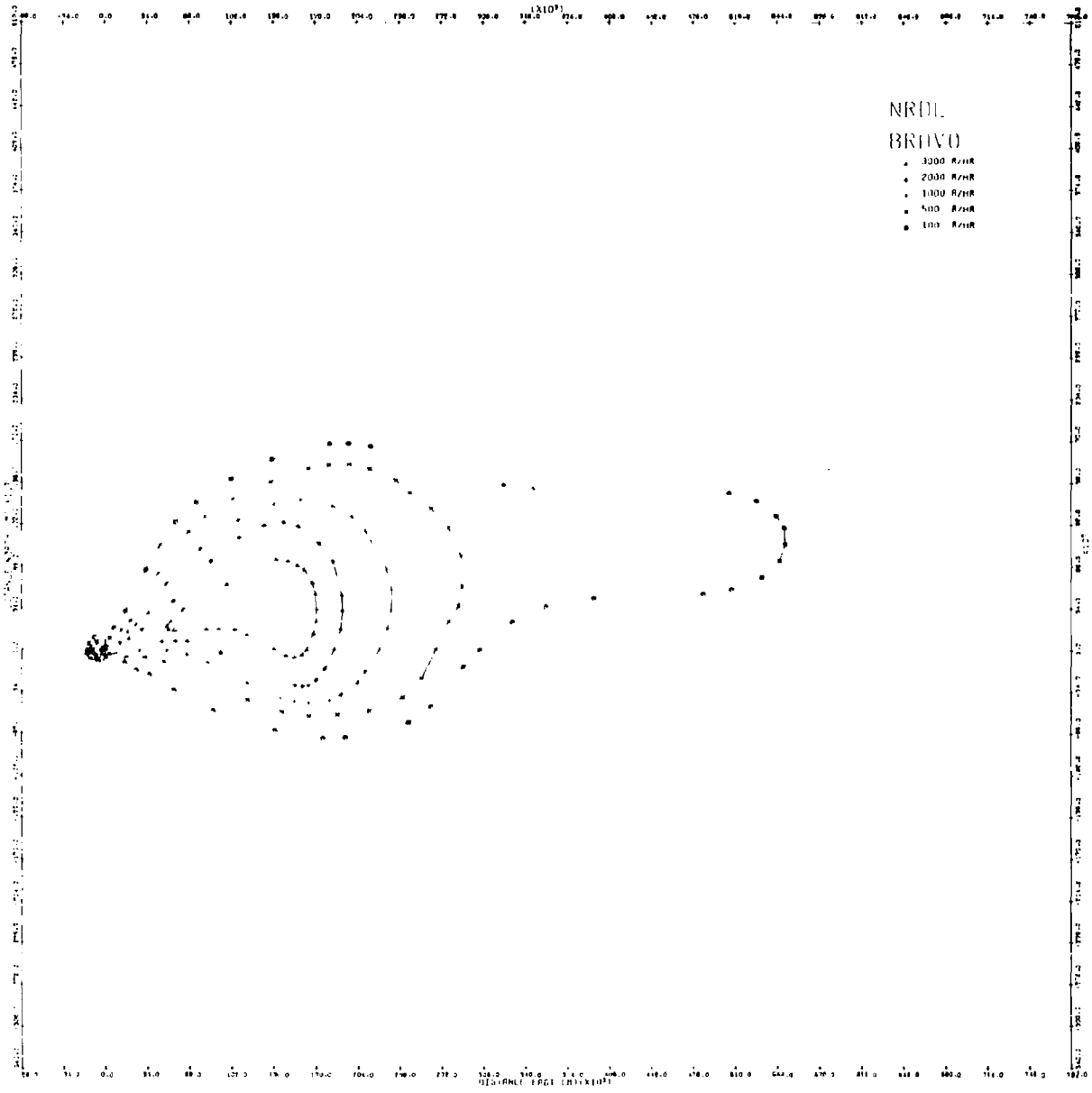

WSEG 10
KOON
DISTANCE EAST

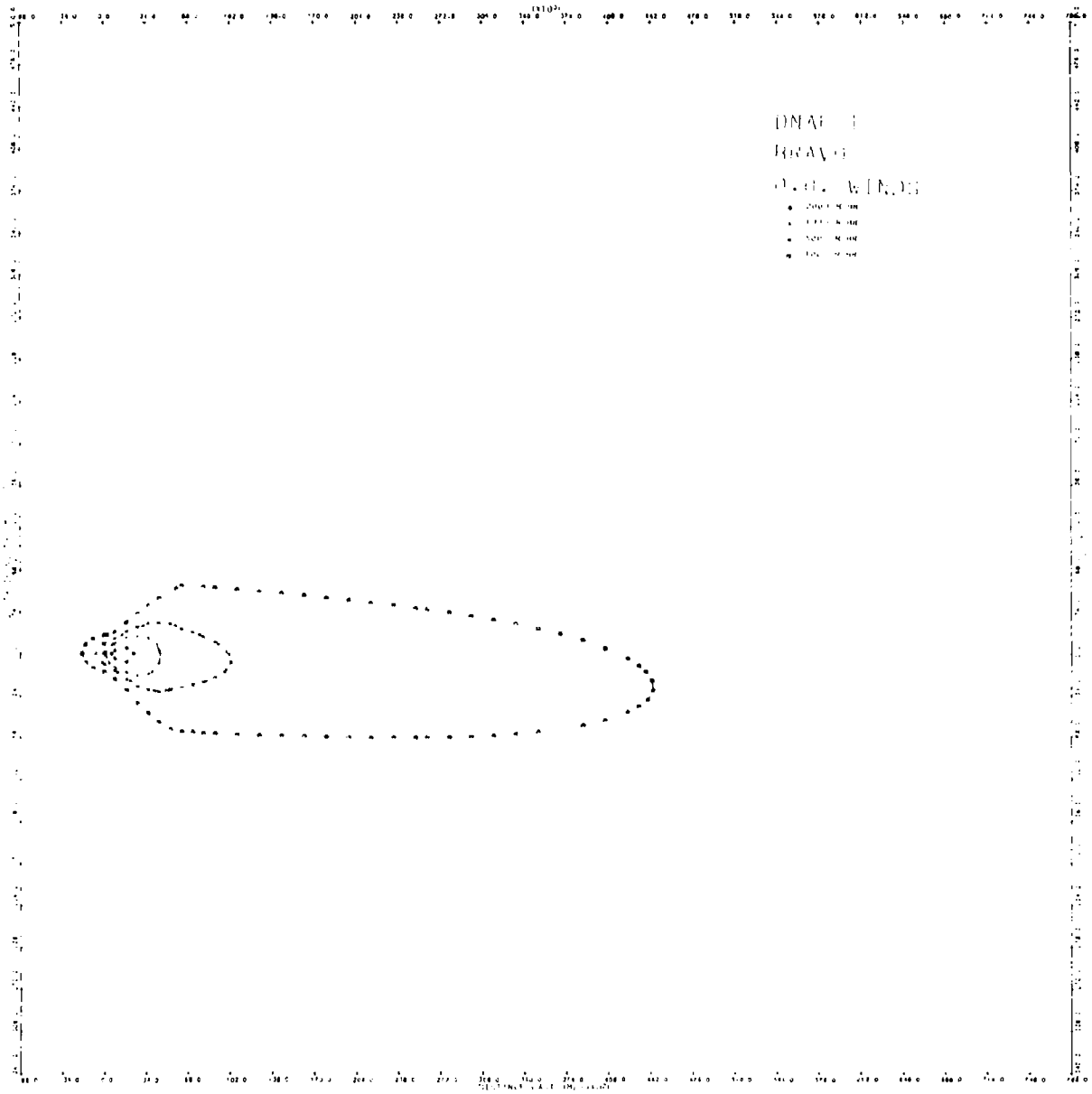

OBSERVED
ZUNI
150 R/HR
100 R/HR
50 R/HR
30 R/HR

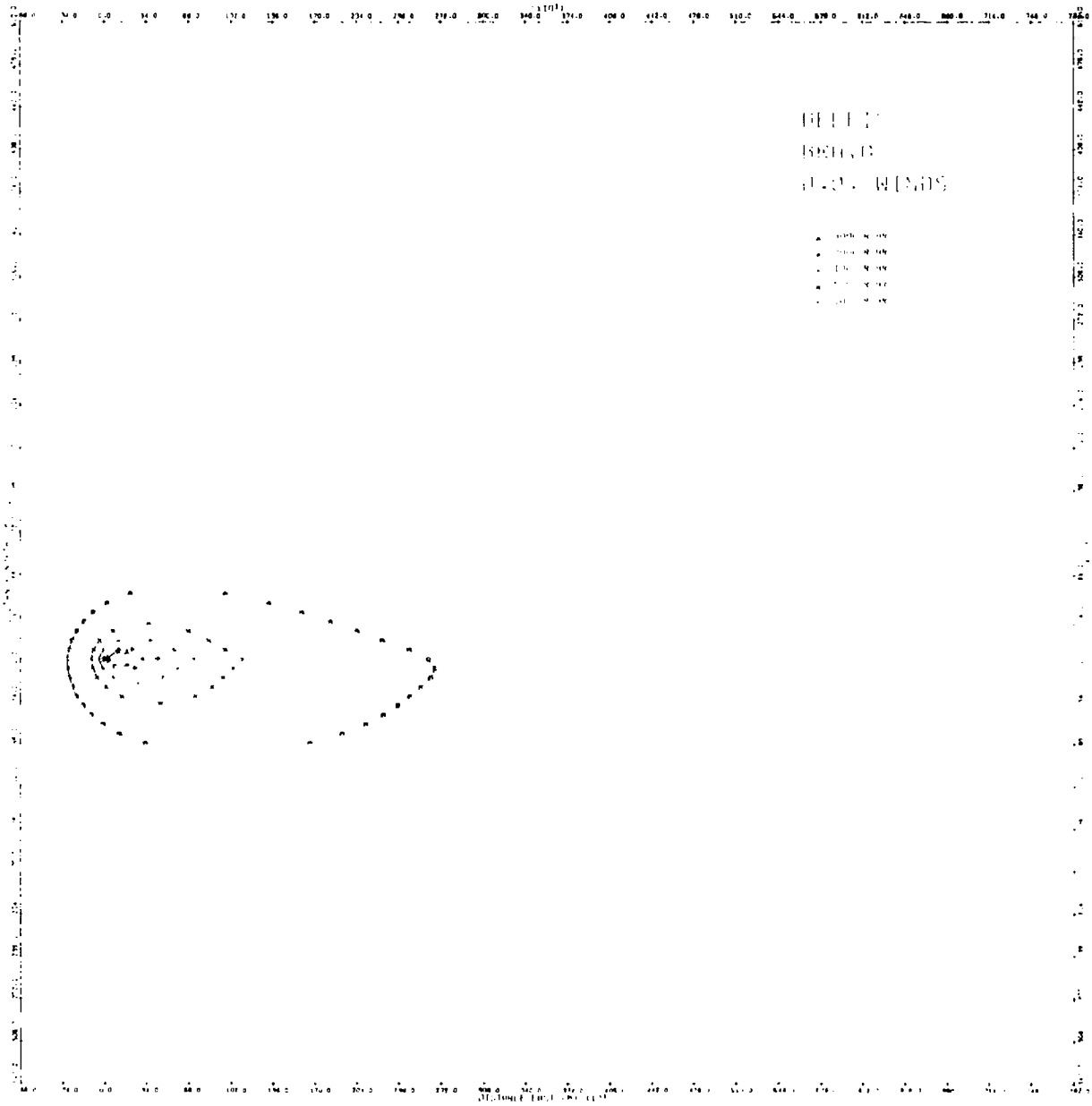


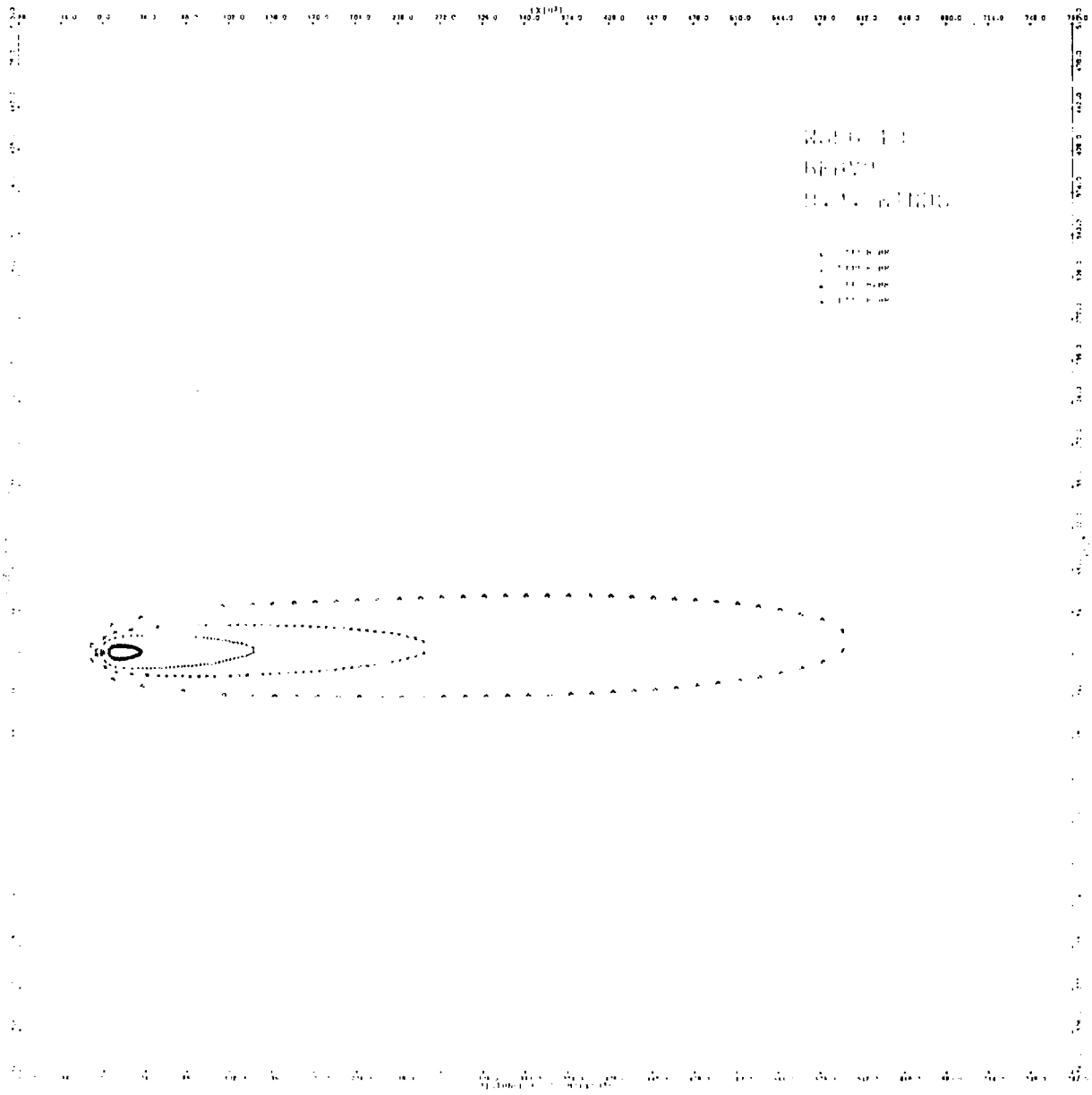

150 R/HR
100 R/HR
50 R/HR
10 R/HR


WSEG10
ZUNI
160 R/HR
100 R/HR
50 R/HR
10 R/HR
DISTANCE EAST (MI)(X10³)


NRDL
BRAVO
3000 R/HR
2000 R/HR
1000 R/HR
500 R/HR
100 R/HR







# 6. COMPUTER CODE

## 6.1 GENERAL DISCUSSION

Coding is entirely in ANSI FORTRAN and complete listings are presented in Appendix D. Glossaries of mnemonics are in subroutines DNAF and INWIND, and the Appendix A glossary relates symbols used in the report text to the FORTRAN mnemonics. The code was originally developed and exercised on the CDC 6600 computer, but also has been extensively tested and exercised on the Honeywell Information Systems 6080 computer used by the DoD Command and Control Technical Center.*

Data is input via system unit 5 and output via unit 6. These unit specifications can be changed by changing the values of parameters IN and IO (lines 69 and 70, subroutine DNAF). No other peripheral storage units are addressed.

All subroutine and function names are listed, with a brief description, in Table 6.

There are two optional modes of code operation:

Mode 1. H + 1 hour exposure rate map preparation

Mode 2. H + 1 hour exposure rate, and maximum effective biological dose at user specified points.

Map calculation is discussed in detail in section 6.2. For the Mode 2 calculation, the user simply specifies ground points in terms of X,Y coordinates relative to ground zero, and the H + 1 hour normalized exposure rates (Roentgens $nr^{-1}$) and maximum effective biological doses (Roentgens), at a height of one meter above the point are printed.

Wind data may be specified in either of two ways:

1. Effective fallout wind speed, v ($m\ s^{-1}$), wind direction, $\phi$ (degrees clockwise from north in the direction of the wind vector), and crosswind shear parameter, $S_Y$ ($s^{-1}$), are input directly.

---

*In addition to the FORTRAN code, the Texas Instruments TI 59, a sophisticated pocket calculator, has been programmed to compute A(X,0) (see eq. 31)).

TABLE 6

DESCRIPTION OF DNAF-1 CODE SUBROUTINES AND FUNCTIONS

| Subroutine or Function | Description |
|---|---|
| DNAF | Executive. Controls calculation flow and calls most of the following programs. |
| SCLOD | Computes stabilized cloud heights and radius plus fireball radius: $z_B$, $z_T$, $R_s$, $R_i$. |
| INWIND | Reads in and processes a vertical profile of wind data if the effective fallout wind speed, v, is not specified by input. |
| EFWIND | Computes effective fallout wind, $\bar{v}$, from data input via subroutine INWIND. |
| SYWND | Computes the wind shear parameter, $S_y$, from the wind data input via subroutine INWIND. |
| ONSET | Computes fallout onset time, $t_o$. |
| DOSE | Computes the factor which when multiplied by H + 1 hour exposure rate gives the maximum effective biological dose, M(X,Y). |
| DNAFI | Computes crosswind-integrated H + 1 hour activity fraction deposited at distance X along the hotline from ground zero. |
| SIGTA | Computes deposition variance, $\sigma^2$, crosswind pattern standard deviation, $\sigma_y$, and fallout arrival time, $t_a$, all at alongwind distance X from ground zero. |
| MAPP | Prints a two-dimensional map of H + 1 hour exposure rate. |
| SETMP | Sets fallout map boundaries and grid intervals for the user. This subroutine is called only if parameter USETMP is false, and the resulting map is intended to provide the user with a preliminary look at the fallout pattern. |
| TRPI | Linear interpolation between table entries. |
| ERROR | Error condition printout. |

2. A vertical profile of winds are input from which the code computes v and $S_y$ as described in sections 4.2 and 4.3.

The effective fallout wind speed is limited to values greater than or equal to 0.5 m $s^{-1}$. A zero input value is used to signal input of a vertical profile of wind data. If a value of $v < 0.5$ m $s^{-1}$, other than the signal value of 0.0, is encountered, a comment is printed and v is reset to 0.5 m $s^{-1}$. (See the end of section 4.2.)

## 6.2 FALLOUT MAPS

Selection of the mode 1 calculation option (logical parameter IFMAP, card 3, is true) causes calculation of H + 1 hour normalized exposure rates (Roentgens $hr^{-1}$) at a height of one meter above a two-dimensional array of points on the ground. The points are spaced at grid intervals DGX and DGY (meters) in the x and y coordinate directions. Here the x axis is in the west-to-east direction (positive east of ground zero), and the y axis is in the south-to-north direction (positive north of ground zero).

Ordinate values are output in rectangular arrays, and it is assumed that the arrays are printed by a standard line printer. The x axis is across the printed page, west-to-east from left-to-right, and the y axis is up the page, south-to-north from bottom-to-top. A two-line, power of ten format is used. Thus, the activity for each point appears as

```
±NNNNN
      V.VVV
```

which is interpreted as

$$V.VVV \times 10^{\pm NNNNN} \quad \text{(Roentgens hr}^{-1}\text{)}.$$

Printing is done in units of map strips, each strip consisting of a sufficient number of connected printer sheets to cover the entire y axis range.

Each row (across the page) of each strip contains a maximum of nineteen ordinate points in the x direction. Enough strips are produced to cover the entire x axis range. These strips can be attached side-by-side such as to construct the complete map, and contours may then be drawn by hand. x and y values are printed at regular intervals on each strip.

If logical parameter USETMP is true (card 3), the user must specify boundaries and grid increments for the map. Otherwise, the code sets these parameters (via subroutine SETMP) automatically, using both yield and wind as criteria. The result is a small, rather poorly resolved map which may not satisfy the particular needs of the user. It is intended to provide the user with a preliminary view of the map. From the information gained from this quick look, the user may devise his own map specifications as described next.

To specify his own map, the user must supply the following information:

1. Logical parameter USETMP = .TRUE. (card 3, sec. 6.5)
2. Coordinates ($x_{min}$, $y_{min}$ or XMIN, YMIN) of the southwest corner of the map, and ($x_{max}$, $y_{max}$ or XMAX, YMAX) of the northeast corner of the map. (card 6)
3. Grid increments DGX, or DGX and DGY, in the x and y axis directions. (card 6)

If only DGX is specified, the code computes DGY such as to produce a spatially undistorted map on a standard line printer: that is, one with 10 characters per inch across the page and 6 characters per inch down the page. To adjust for nonstandard character spacing, parameters IH and IV (lines 69 and 70 in subroutine DNAF and 13 and 14 in subroutine SETMP) must be changed.

The values of XMIN and YMIN specified on card 6 should be one grid increment less than the values actually expected on the printed map.

The code presented in Appendix D provides for a maximum of 5000 map points. If the map specified by card 6 input requires more than this number of points, DGX and DGY are adjusted such that no more than 5000 map points are required, a comment to the effect that the adjustment has been made is printed, and calculation then proceeds. Map point ordinates are stored in array OMAP, and parameter NMAP is used as a variable dimension for OMAP. To change the maximum number of points, change the dimension of the OMAP array and the value of NMAP as desired (lines 67, 69 and 70 of subroutine DNAF).

## 6. INPUT OF WIND PROFILE DATA

If parameter WIND (which is the effective fallout wind speed, v) on card 2 is zero, the code calls subroutine INWIND which reads in a vertical profile of wind data as described by cards 4a-4n (sec. 6.5). This input is designed for maximum versatility.

Card 4a is used to specify whether the wind data are input in resolved form (i.e., vector components in the easterly and northerly directions), or in terms of speed and direction angle.

Card 4b is an object-time format to be used to read the data.

Card 4c contains scale and translation factors, and card 4d contains data field pointers. Cards 4e to 4n-1 each contain altitude and wind vector data for a wind stratum, and the last card, 4n, is the data set terminator.

Use of the scale-translation data and the field pointers deserves some explanation.

In combination with the object-time format, the field pointers, N1, N2, N3, allow any arrangement of the data on the cards; the only restriction being that all of the data cards have the same arrangement. Each card contains three items of data:

1. Altitude of the wind measurement
2. x component of the wind vector
3. y component of the wind vector

} FORM = RESO

or

2. Wind direction angle
3. Wind speed

} FORM = METE

Pointer N1 is associated with the altitude, N2 with the x wind component or direction angle, and N3 with the y wind component or wind speed. Collectively N1, N2, N3 consist of some permutation of the integers 1, 2, 3. The object-time format specifies three data fields, and N1 specifies which of the three contains the altitude, N2 specifies which contains the x wind component or the direction angle, etc. For example, if we have N1 = 1, N2 = 3, N3 = 2, then the altitude is in the first field (from the left), the x wind component or direction angle is in the third field, and the y wind component or wind speed is in the second field.

The scale and translation data input via card 4c allows input of data in any units, and allows certain common data translations to be made. Scale factors are in fields 1-3 and translations are in fields 4-5 of card 4c. After application of these translations and scale factors, altitude must be in meters with origin at the ground, and the wind must be expressed in terms of components ($m\ s^{-1}$) in the x (easterly) and y (northerly) directions. If it is used, the wind direction angle must be, after scaling and translating, the angle of the wind vector measured clockwise from north.

Scale and translation data are read from card 4c into array SCALE( ). The three data items on each wind data card are read into array AP( ). For the altitude, SCALE(4) is a translation, which is applied before scaling, to adjust the origin to be at ground level, and SCALE(1) is a scale factor used to adjust the units to meters. Thus the altitude, ZCH, is

$$ZCH = (AP(N1) + SCALE(4))*SCALE(1).$$

If FORM = RESO (card 4a), the wind vector data are input in component form. In this case, the only other card 4c datum used is SCALE(2), which is a scale factor applied to both components to adjust units to meters per second. Specifically, we have for the x and y wind components, WX and WY,

$$WX = AP(N2)*SCALE(2)$$

$$WY = AP(N3)*SCALE(2).$$

If FORM = METE (card 4a), the wind vector data are input in terms of direction angle and speed. As with the previous case, SCALE(2) is used to scale the wind speed to units of meters per second. SCALE(3) is a scale factor used to convert the direction angle to degrees. SCALE(5) is an angle translation (i.e., rotation) which is input in the same units as is the direction angle. The angle translation calculation is set up to convert the angle from the conventional meteorological specification of direction <u>from</u> which the wind is blowing, to direction <u>toward</u> which the wind is blowing; in other words, the code automatically rotates the wind angle through 180° unless this is circumvented by appropriate specification of SCALE(5). Specifically we have

$$WX = AP(N3)*SCALE(2)*SIN(\frac{\pi}{180}(AP(N2)*SCALE(3) + TRNS))$$

$$WY = AP(N3)*SCALE(2)*COS(\frac{\pi}{180}(AP(N2)*SCALE(3) + TRNS))$$

where

$$TRNS = SCALE(5)*SCALE(3) - 180.$$

Default values for the scale factors, SCALE(1) through SCALE(3), are unity. That is, if any or all of the first three fields on card 4c are left blank, the code sets the corresponding scale factors to unity.

The wind data should extend at least up to the cloud top height, $z_T$ (eq. (4)), but if it does not, the code simply assumes that the data in the highest wind stratum is constant up to $z_T$.

The wind data are sorted by the code and arranged in sequence of increasing altitude; thus it is not necessary that they be input in any particular order.

An example of a common situation will illustrate how to set up the data cards. Suppose the wind data are available in the form shown in Table 7. Ground zero is at an altitude of 4215 feet, and we assume that the surface wind was measured at a height of 10 meters above the ground. Thus, the actual altitude of the surface wind is 4248 feet. Figure 9 shows how cards 4a-4n might be punched for this set of data.

TABLE 7

EXAMPLE WIND DATA LISTING

Site Elevation is 4215 Feet

| Altitude (kft relative to MSL) | Speed (mph) | Direction Angle* (degrees) |
|---|---|---|
| Surface | 2 | 190 |
| 6 | 15 | 170 |
| 8 | 30 | 180 |
| 10 | 37 | 200 |
| . | . | . |
| . | . | . |
| . | . | . |
| 30 | 80 | 210 |

*Direction from which the wind is blowing.

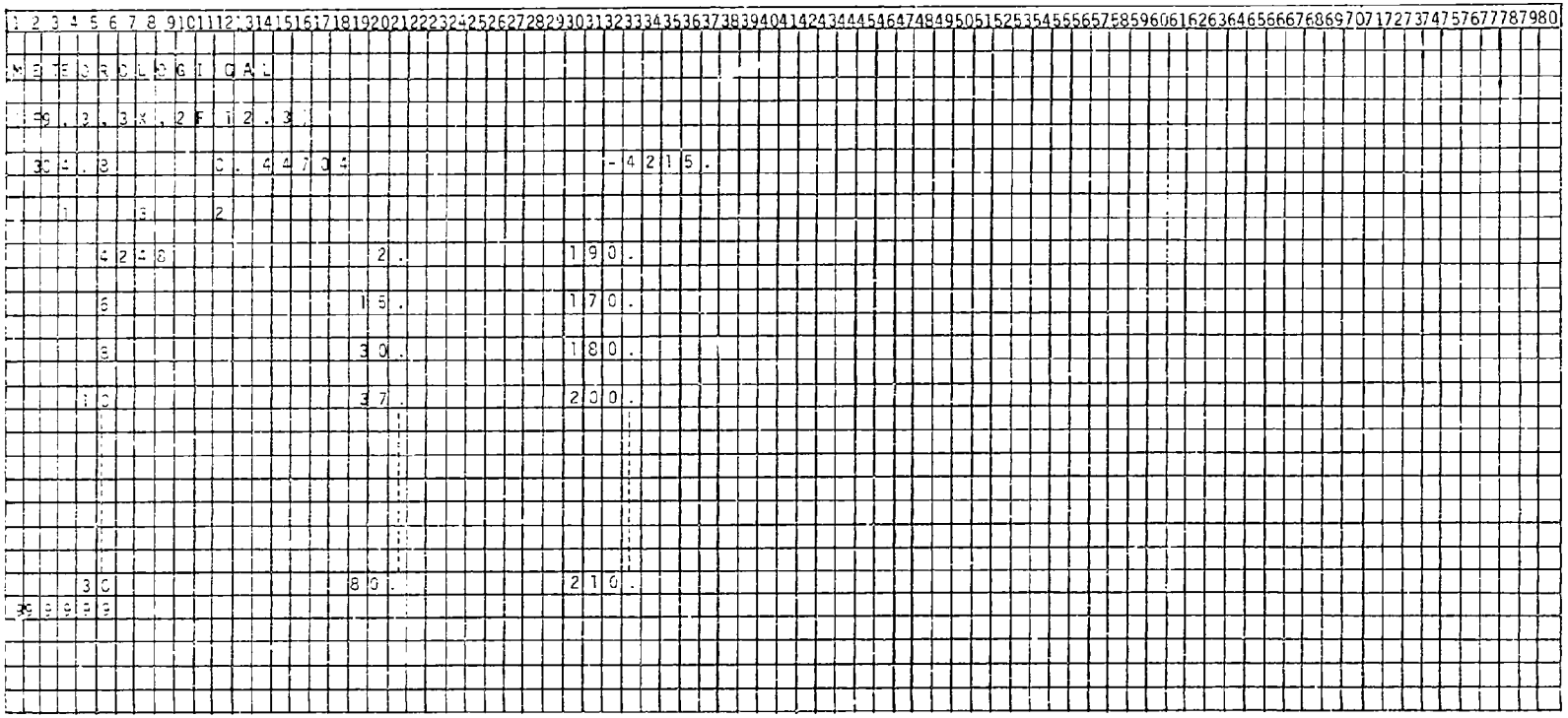



Figure 9. Wind data card input for the example data listed in Table 7.

## 6.4 STORAGE AND COMPUTATION TIME REQUIREMENTS

Approximately 15,000 (decimal) storage cells are required by the CDC 6600 computer to contain the object codes compiled from the complete package of FORTRAN codes listed in Appendix D.

Computation is quite fast. A rough estimate of computation time is derived as follows. In a single run on the CDC 6600 computer, eight complete fallout maps were calculated and printed, and for each map a vertical profile of wind data was processed. In addition to the usual calculations, contour points were calculated, printed and punched for the maps shown on pp. 58 to 80. Activities for a total of 11,242 map points were calculated, and the total CPU time was 29.469 seconds. If we simply lump all of the accessory calculations, including print and punch times, in with the activity calculation time, we get 2.6 millisecond per activity calculation.

## 6.5 DESCRIPTION OF CARD INPUTS FOR THE DNAF-1 CODE

| Card Number | Variables and Format | Data Description |
|---|---|---|
| 1 | HOLL(12), (12A6) | Run identification |
| 2 | W, FW, WIND, SY, ANG, GRUFF, (8F10.0) | W = Total explosion energy yield (KT) |
| | | FW = Fission yield (KT) |
| | | WIND = Effective fallout wind speed ($m\ s^{-1}$) (WIND $\geq$ 0.0) A blank field is used to signal input of card 4 data. |
| | | SY = Wind shear parameter ($s^{-1}$). Required only if Wind > 0.0 |
| | | ANG = Effective fallout wind vector angle, or hotline angle, clockwise relative to north (degrees). Required only if WIND = 0.0. |
| | | GRUFF = Scale factor for multiplication of all H + 1 hr exposure rate values. (See Appendix C.) Default value is unity. |
| 3 | IFMAP, USETMP (5L1) | IFMAP If true, a two-dimensional H + 1 hour exposure rate map is to be computed and printed. (See logical parameter USETMP and card number 6.) If false, H + 1 hour exposure rate and maximum biological dose are computed for user-specified points. (See cards number 5.) |
| | | USETMP If true, the user must specify the fallout map boundaries and grid intervals via input of card 6. If false, the code sets these parameters via subroutine SETMP. In any case, USETMP is applicable only if IFMAP IS TRUE. |
| 4 | Cards 4a-4n are input only if WIND = 0.0 on card 2. In that case, a wind profile in the vertical is specified as follows (see sec. 6.3) | |
| 4a | FORM, (A4) | Specifies whether wind data are input in meteorological format (i.e., speed and direction) or in resolved format (i.e., components resolved in the northerly and easterly directions). |
| | | FORM METL specifies meteorological format |
| | | FORM RESO specifies resolved format |

| Card Number | Variables and Format | Data Description |
|---|---|---|
| 4b | FMT, (12A6) | Wind data object-time format. (See cards number 4e-4n.) |
| 4c | SCALE(5), (8F10.0) | Wind data scale factors and translations. Default values for SCALE(1) through SCALE(3) = 1. (See cards 4e-4n.) |
| 4d | N1, N2, N3, (3I4) | Wind data input field pointers. N1, N2, N3 are some permutation of the integers 1, 2, 3. (See cards 4e-4n.) |
| 4e | AP(3), (FMT, see card 4b) | Altitude (m above ground) = (AP(N1) + SCALE(4))*SCALE(1)<br>For FORM METE:<br>Easterly wind component (m $s^{-1}$)<br>= AP(N3)*SCALE(2)*SIN(π/180.(AP(N2)*SCALE(3)<br>+ SCALE(3)*SCALE(5) - 180.)) |
| 4n | AP(N1) = 999999., (FMT) | Northerly wind component (m $s^{-1}$)<br>= AP(N3)*SCALE(2)*COS(π/180.(AP(N2)*SCALE(3)<br>+ SCALE(3)*SCALE(5) - 180.))<br>For FORM = RESO:<br>Easterly wind component (m $s^{-1}$) = AP(N2)*SCALE(2)<br>Northerly wind component (m $s^{-1}$) = AP(N3)*SCALE(2) |
| 5 | Cards 5a-5n are input only if parameter IFMAP = .FALSE. on card 3. | |
| 5a | X, Y, (8F10.0) | X = Distance from GZ along the hotline. Positive X is in the downwind direction (m)<br>Y = Distance normal to the hotline (m). Activity and maximum biological dose are calculated at each (X,Y) point input. |
| 5n | End of record flag. | |
| 6 | XMIN, XMAX, YMIN, YMAX, DGX, DGY, (8F10.0) | Card 6 is input only if parameters IFMAP and USETMP both are true on card 3. Map boundaries and grid increments are specified as:<br>XMIN, XMAX = minimum and maximum map coordinates relative to GZ along the easterly directed axis (m).<br>YMIN, YMAX = minimum and maximum map coordinates relative to GZ along the northerly directed axis (m).<br>DGX, DGY = map grid increments in the easterly and northerly axes directions (m). DGX must be specified, but DGY is optional. If DGY is not specified, it is computed by the program such as to provide a spatially undistorted map when printed by a standard line printer. |

## 6.6 EXAMPLE PROBLEM AND PRINTOUT DESCRIPTION

To assist the user in getting the code running on his own computer, and to illustrate the card input and the printout for a mode 1 (fallout map) case, we provide here a simple test problem. The card input is given in Figure 10, and the complete printout is given below, which is largely self-explanatory.

The raw wind data are printed as well as the processed data. The processed data have been translated and scaled according to the data specified on card 4c. Wind layer base altitudes are in meters relative to the ground. When $\vec{v}$, $\phi$ and $S_\gamma$ are supplied directly, this output is omitted.

For a mode 2 (user supplied X, Y coordinates) calculation, the output is the same except that the map strips are replaced by a tabulation of X, Y, H + 1 hour exposure rate and maximum effective biological dose.

Card No.

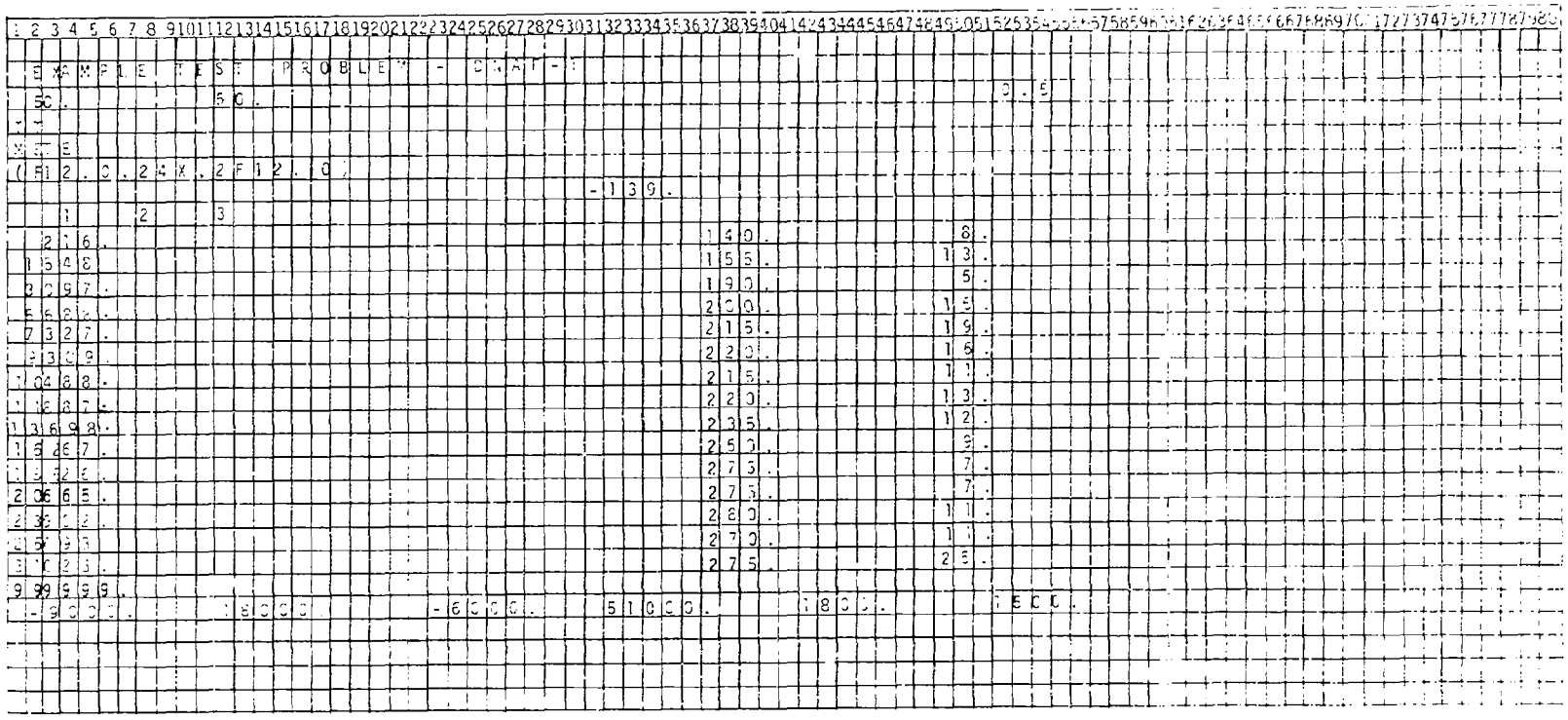



Figure 10. Test problem card input.

*************************************************************************************

* * * * * * * * * * *

D N A F - 1

T H E   D E F E N S E   N U C L E A R   A G E N C Y   F A S T   F A L L O U T

P R E D I C T I O N   S Y S T E M

* * * * * * * * * * *

PREPARED BY
ATMOSPHERIC SCIENCE ASSOCIATES
BEDFORD, MASS.

**** RUN IDENTIFICATION ****    EXAMPLE TEST PROBLEM - DNAF-1

YIELDS - TOTAL (FISSION)    5.00000E+01 ( 5.00000 +01) KT
ORDINATE SCALE FACTOR    5.00000E-01

RAW WIND DATA

| Z | VX OR DIR. | VY OR SPEED |
|---|---|---|
| 2.16000E+02 | 1.40000E+02 | 5.00000E+00 |
| 1.54500E+03 | 1.60001E+02 | 1.30000E+01 |
| 3.05700E+03 | 1.30001E+02 | 5.00000E+00 |
| 5.66300E+03 | 2.00002E+02 | 1.50000E+01 |
| 7.32700E+03 | 2.10001E+02 | 1.30000E+01 |
| 9.30300E+03 | 2.20001E+02 | 1.60000E+01 |
| 1.04360E+04 | 2.10001E+02 | 1.10000E+01 |
| 1.18670E+04 | 2.20001E+02 | 1.30000E+01 |
| 1.36530E+04 | 2.50001E+02 | 1.20000E+01 |
| 1.62570E+04 | 2.50001E+02 | 9.00000E+00 |
| 1.85210E+04 | 2.70001E+02 | 7.00000E+00 |
| 2.06590E+04 | 2.60001E+02 | 7.00000E+00 |
| 2.39020E+04 | 2.60001E+02 | 1.10000E+01 |
| 2.66330E+04 | 2.70001E+02 | 1.10000E+01 |
| 3.10230E+04 | 2.70001E+02 | 2.50000E+01 |

PROCESSED WIND DATA

| Z | VX | VY |
|---|---|---|
| 7.79000E+01 | -4.14230E+00 | 4.12830E+00 |
| 1.49900E+03 | -5.45404E+00 | 1.17220E+01 |
| 2.95900E+03 | 6.62743E-01 | 4.82404E+00 |
| 5.56300E+03 | 5.13030E+00 | 1.40554E+01 |
| 7.18800E+03 | 1.08980E+01 | 1.55439E+01 |
| 9.17000E+03 | 1.02646E+01 | 1.22567E+01 |
| 1.03430E+04 | 6.50334E+00 | 9.01067E+00 |
| 1.17450E+04 | 9.35674E+00 | 9.38552E+00 |
| 1.35590E+04 | 9.82902E+00 | 6.68292E+00 |
| 1.61280E+04 | 8.45723E+00 | 3.07818E+00 |
| 1.85670E+04 | 6.97336E+00 | -6.10050E-01 |
| 2.08250E+04 | 6.97336E+00 | -6.10090E-01 |
| 2.37530E+04 | 1.08323E+01 | -1.51013E+00 |
| 2.63540E+04 | 1.10000E+01 | 1.97430E-06 |
| 3.08840E+04 | 2.45049E+01 | -2.17089E+00 |

WIND LAYER BASE ALTITUDES

LEVELS  1 THRU  8   0.00000   243.00000  2183.50000  4257.50000  6368.50000  8179.00000  9755.50000 11046.50000
LEVELS  9 THRU 15 12563.00000 14843.50000 17267.50000 19456.00000 22144.50000 25058.00000 28613.00000

EFFECTIVE WIND SPEED    1.12963E+01 M/SEC
WIND DIRECTION (CLOCKWISE FROM NORTH)    1.47431E+01 DEG.
SHEAR PARAMETER, SY    1.13031E-03 PER SEC

GRID LIMITS AND INTERVALS

| XMIN | XMAX | YMIN | YMAX | DELTA X | DELTA Y |
|---|---|---|---|---|---|
| -9000. | 18000. | -6000. | 51000. | 1800.00 | 1500.00 |

THE QUANTITY PRESENTED IS
EXPOSURE RATE NORMALIZED TO TIME H+1 HOUR
UNITS ARE ROENTGENS PER HOUR
GROUND ZERO IS LOCATED AT  X =    0.0  , Y =    0.0

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## APPENDIX A

## GLOSSARY OF SYMBOLS AND FORTRAN MNEMONICS

| Text Symbol | FORTRAN Mnemonic | Description |
|---|---|---|
| A(X,Y) | OMAP( ),A | H + 1 hr normalized exposure rate (Roentgen $hr^{-1}$) at three meters above point X, Y. |
| C | GRUFF | Scale factor to be applied to activity calculations. |
| D(X) | GOFX<br>DNAF1 (Function) | Crosswind integrated activity fraction deposited at distance X from ground zero. ($m^{-1}$) |
| $D(X)_f$ | | Farfield corrected, crosswind integrated activity fraction deposited at downwind distance X from ground zero. ($m^{-1}$) |
| $D(X)_u$ | | Upwind corrected, crosswind integrated activity fraction deposited at upwind distance X from ground zero. ($m^{-1}$) |
| f(z) | V( ) | Settling speed of the nominal fallout particle at altitude z. ($m\ s^{-1}$) |
| F(X,t) | | Factor to account for dispersion in the hotline axis direction of fallout being deposited at time t at point X. ($m^{-1}$) |
| g(t) | | Activity fraction deposition rate function. ($s^{-1}$) |
| G(Y) | CROSS (Statement Function) | Crosswind fallout pattern dispersion factor. ($m^{-1}$) |
| M(X,Y) | DMAX | Maximum effective biological dose (Roentgens) |
| $R_i$ | RI | Early cloud radius. (m) |
| $R_s$ | RS | Stabilized cloud cap radius. (m) |
| $S_Y$ | SY | Wind shear parameter: approximation to the crosswind component of the vertical wind shear. ($s^{-1}$) |
| t | | Time. (s) |
| $t_a$ | TA | Time of arrival of the first fallout at distance X from ground zero. (s) |
| $t_B$ | TB | Time required for the nominal particle to settle from the stabilized cloud cap base to the ground. (s) |
| $t_{max}$ | TM | Yield dependent time of maximum activity deposition rate according to the g(t) function. (s) |
| $t_o$ | TO | Fallout onset time. (s) |

| Text Symbol | FORTRAN Mnemonic | Description |
|---|---|---|
| $T$ | | Yield dependent constant in the g(t) and D(X) functions. (s) |
| $U_{E,i}$ | WX(I) | Easterly directed component of the wind vector in the $i^{th}$ wind stratum. ($m\ s^{-1}$) |
| $U_{N,i}$ | WY(I) | Northerly directed component of the wind vector in the $i^{th}$ wind stratum. ($m\ s^{-1}$) |
| $v$ | WIND | Effective fallout wind speed. ($m\ s^{-1}$) |
| $\vec{v}$ | | Effective fallout wind vector. ($m\ s^{-1}$) |
| $W$ | W | Energy yield of the explosion (KT). (The KT unit is the energy released by explosion of one kiloton of TNT.) |
| $W_F$ | FW | Fission yield of the nuclear explosion. (KT) |
| $x$ | XM | Coordinate, relative to ground zero, in the easterly direction. (m) |
| $X$ | X | Hotline distance from ground zero, positive in the downwind direction. (m) |
| $y$ | YM | Coordinate, relative to ground zero, in the northerly direction. (m) |
| $Y$ | Y | Perpendicular distance to the hotline in the ground plane. (m) |
| $z_{b,i}$ | ZBH(I) | Altitude of the base of the $i^{th}$ wind stratum above ground. (m) |
| $z_B$ | ZB | Height of the base of the stabilized cloud cap above ground. (m) |
| $z_i$ | ZCH(I) | Altitude of the center of the $i^{th}$ wind stratum above ground. (m) |
| $z_T$ | ZT | Height of the top of the stabilized cloud cap above ground. (m) |
| $\alpha$ | ALPHA | Yield dependent parameter in the g(t) and D(X) functions. (dimensionless) |
| $\delta_{nom}$ | | Diameter (um) of the nominal fallout particle. |
| $\epsilon$ | | Turbulent energy density dissipation rate. ($m^2\ s^{-3}$) |
| $\sigma^2$ | SIGE | Variance of the horizontal spread of the nuclear cloud at deposition time. (Does not include the wind shear dispersion contribution.) ($m^2$) |
| $\sigma_c$ | | Standard deviation of horizontal spread of the cloud before atmospheric transport. (m) |

| Text Symbol | FORTRAN Mnemonic | Description |
|---|---|---|
| $\sigma_s^2$ | | Wind shear contribution to the crosswind fallout pattern variance. ($m^2$) |
| $\sigma_Y$ | SIGY | Crosswind standard deviation of the fallout pattern. (m) |
| $\xi$ | ANG | Direction angle (clockwise from north) of the effective fallout wind vector. (deg.) |

## APPENDIX B

## GROUND ROUGHNESS AND INSTRUMENT RESPONSE CORRECTION FACTORS

To compare predicted H + 1 hour gamma exposure rates in a fallout field with values measured over land by radiation survey meters, it is necessary to make certain adjustments to either the observed or predicted values. Conventional practice is to adjust the predictions.

Predicted exposure rates are based on laboratory measurements of fission product yields and on factors called exposure rate multipliers that convert the fission yields for individual nuclides to exposure rates at one meter height above an infinite plane on which the fission products are assumed to be uniformly distributed. One correction, the ground roughness factor, is required to account for absorption of radiation by small irregularities, or roughness elements, in an actual ground surface. The other correction is necessary to account for variation of response of survey meters to radiation over the spectrum of wave lengths encountered. Ground roughness factors for Nevada Test Site terrains are estimated to be in the range of 0.70 to 0.75, and an instrument response factor of about 0.75 is appropriate for commonly used survey meters. The product of these two factors is approximately 0.5, and this factor is applied to dose rates throughout all of the predicted test shot patterns except for Zuni as noted in section 5.3.

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## APPENDIX C

## FALLOUT PATTERN COMPARISON BY THE FIGURE-OF-MERIT METHOD

Rowland and Thompson[20] developed this method for comparison of pairs of fallout contour maps by computation of a single index, the FM, that is a measure of contour overlap between them. For each contour common to the patterns, the area overlapped and the area not overlapped is calculated. The areas are weighted by the average radiation level between successive contours. Sums over all contours of weighted overlapped areas and weighted total areas are computed, and the FM is the ratio of the two sums. For completely overlapped, perfectly matched patterns, FM = 1; for no overlap, FM = 0.

Mathematically, FM is

$$FM = \frac{\sum_{i=1}^{N} \frac{(r_i + r_{i-1})}{2} (a_i - a_{i-1})}{\sum_{i=1}^{N} \frac{(r_i + r_{i-1})}{2} (A_i - A_{i-1})}$$

where

$N$ is the number of contours in the patterns. The summations are from highest contour to lowest

$r_i$ is activity of the i th contour (Roentgen $hr^{-1}$), $r_o = 10\ r_1$

$a_i$ is common (i.e., overlapped) area for the i th contours. $a_o = 0$.

$A_i$ is total area of the i th contour. The summation in the denominator is computed for both patterns, and the largest sum is used. $A_o = 0$.

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The FM has been found to have limited utility as a measure of fallout prediction accuracy. This is mainly for two reasons. First, and most important, is that being a measure of overlap, the FM is strongly biased in favor of overprediction; that is, it favors predictions that cover a large area, and therefore overlap the observed pattern, regardless of other considerations. Second, the FM method imposes no penality for missing or extra contours; contours not common to both patterns are simply ignored.

# APPENDIX D

## FORTRAN CODE FOR THE DNAF-1 FALLOUT MODEL

```
      SUBROUTINE DNAF                                                   DNAF   1
C                                                                       DNAF   2
C     EXECUTIVE PROGRAM FOR THE DNAF-1 FALLOUT PREDICTION MODEL         DNAF   3
C                                                                       DNAF   4
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1981       DNAF   5
C                                                                       DNAF   6
C * * * * * * * * * * * * * * GLOSSARY * * * * * * * * * * * * * * *    DNAF   7
C     A        H+1 HOUR GAMMA EXPOSURE RATE (ROENTGENS/HR)              DNAF   8
C     ALPHA    DNAF-1 MODEL PARAMETER                                   DNAF   9
C     ALT      HEIGHTS (M ABOVE MSL) AT WICH SETTLING SPEEDS OF THE     DNAF  10
C              NOMINAL PARTICLE ARE DEFINED                             DNAF  11
C     ANG      HOTLINE ANGLE (INPUT AS DEGREES CLOCKWISE FROM NORTH)    DNAF  12
C     B        EXPONENT PARAMETER USED FOR APPROX. PARTICLE SETTLING    DNAF  13
C              SPEED CALCULATION                                        DNAF  14
C     CAY      K FACTOR ((R-M**2)/(HR-KT))                              DNAF  15
C     COSA     COSINE OF HOTLINE ANGLE = WINDY/WIND                     DNAF  16
C     DGX,DGY  MAP INCREMENTS (SEE XMAX, ETC)  (M)                      DNAF  17
C     DMAX     MAXIMUM EFFECTIVE BIOLOGICAL DOSE (ROENTGENS)            DNAF  18
C     FW       FISSION YIELD (KT)                                       DNAF  19
C     GRUFF    SCALE FACTOR TO BE APPLIED TO ACTIVITY VALUES            DNAF  20
C              (E.G. GROUND ROUGHNESS + INSTRUMENT RESPONSE FACTOR)     DNAF  21
C     IFMAP    LOGICAL FLAG WHICH WHEN TRUE SPECIFIES THAT A FALLOUT MAP DNAF  22
C              BE PREPARED                                              DNAF  23
C     IH       NUMBER OF CHARACTERS/INCH HORIZONTALLY ON THE PRINTED MAP DNAF  24
C     IN       SYSTEM INPUT UNIT                                        DNAF  25
C     INTL1,INTL2    FLAGS TO SIGNAL FIRST PASS THROUGH SIGTA & DNAF1   DNAF  26
C     IO       SYSTEM PRINT UNIT                                        DNAF  27
C     IP       SYSTEM PUNCH UNIT                                        DNAF  28
C     IV       NUMBER OF CHARACTERS/INCH  VERTICALLY  ON THE PRINTED MAP DNAF  29
C     NHODO    NUMBER OF HEIGHTS AT WICH WIND DATA ARE INPUT            DNAF  30
C     NMAP     MAX. NO. OF POINTS ALLOWED IN A MAP. (DIMENSION OF OMAP) DNAF  31
C     NXMAP    NUMBER OF MAP INCREMENTS IN THE X DIRECTION (SEE XMAX ETC)DNAF  32
C     NYMAP    NUMBER OF MAP INCREMENTS IN THE Y DIRECTION (SEE XMAX ETC)DNAF  33
C     OMAP     FALLOUT MAP ORDINATE ARRAY                               DNAF  34
C     RI       FIRLBALL RADIUS (M)                                      DNAF  35
C     RS       STABILIZED CLOUD RADIUS (M)                              DNAF  36
C     SIGE     GAUSSIAN VARIANCE OF CLOUD DISPERSION (M**2)             DNAF  37
C     SIGY     CROSS-WIND GAUSSIAN STANDARD DEVIATION OF THE FALLOUT    DNAF  38
C              PATTERN (M)                                              DNAF  39
C     SINA     SINE OF HOTLINE ANGLE = WINDX/WIND                       DNAF  40
C     SY       SHEAR PARAMETER OR RMS SHEAR PARAMETER FROM ZO TO GROUND DNAF  41
C     TA       TIME OF ARRIVAL OF FALLOUT (S)                           DNAF  42
C     TB       ARRIVAL TIME OF FALLOUT FROM THE STABILIZED CLOUD BASE (S)DNAF  43
C     TLL,TLS  ARRIVAL TIMES AT WHICH RATE OF GROWTH OF CLOUD TURBULENT DNAF  44
C              DISPERSION VARIANCE BECOMES CONSTANT  (S)                DNAF  45
C     TM       TIME OF MAXIMUM ACTIVITY DEPOSITION RATE (S)             DNAF  46
C     TO       FALLOUT ONSET TIME (S)                                   DNAF  47
C     USETMP   LOGICAL FLAG WHICH WHEN TRUE REQUIRES THE USER TO SPECIFY DNAF  48
C              MAP BOUNDRIES AND GRID                                   DNAF  49
C     V        SETTLING SPEEDS (M/S) OF THE NOMINAL PARTICLE AT HEIGHTS DNAF  50
C              ALT                                                      DNAF  51
C     VO       SETTLING SPEED AT SEA LEVEL OF THE NOMINAL PARTICLE (M/S) DNAF  52
C     W        TOTAL YIELD (KT)                                         DNAF  53
C     WIND     EFFECTIVE WIND SPEED (M/S)                               DNAF  54
C     WL       NAPERIAN LOGARITHM OF W                                  DNAF  55
C     WL10     BRIGGSIAN LOGARITHM OF W                                 DNAF  56
C     WX       OBSERVED WIND COMPONENTS IN THE X DIRECTION (SEE XMAX ETC)DNAF  57
C     WY       OBSERVED WIND COMPONENTS IN THE Y DIRECTION (SEE XMAX ETC)DNAF  58
C     XMAX,XMIN,YMAX,YMIN    MAP LIMITING COORDINATES.  (X IS POSITIVE  DNAF  59
C              TOWARD EAST AND Y IS POSITIVE TOWARD NORTH)  (M)         DNAF  60
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C     ZB       STABILIZED CLOUD BASE HEIGHT (M)                          DNAF  61
C     ZBH      WIND LAYER  BASE  HEIGHTS (M)                             DNAF  62
C     ZCH      WIND LAYER CENTER HEIGHTS (M)                             DNAF  63
C     ZO       STABILIZED CLOUD CENTER HEIGHT (M)                        DNAF  64
C     ZT       STABILIZED CLOUD TOP  HEIGHT (M)                          DNAF  65
C                                                                        DNAF  66
      DIMENSION HOLL(12), OMAP( 5000), CONTUR( 8)                        DNAF  67
      LOGICAL IFMAP, USETMP, CENT, CPNC                                  DNAF  68
      DATA IN , IO , IH , IV ,    CAY    ,  NMAP    ,   DIRC             DNAF  69
     1   /  5 ,  6 , 10 ,  6 , 6.97336E9,  5000    ,57.295779513/       DNAF  70
      DATA IP/ 7/, SQT2PI/2.506628275/                                   DNAF  71
C                                                                        DNAF  72
 24   FORMAT(///15X25HGRID LIMITS AND INTERVALS/20X4HXMIN10X4HXMAX10X4HYDNAF  73
     1MIN10X4HYMAX10X7HDELTA X,3X7HDELTA Y/15XF10.0,4XF10.0,4XF10.0,4XF1DNAF  74
     20.0,5XF10.2,5XF10.2)                                               DNAF  75
  47 FORMAT(//15X, 61HDGX AND DGY MUST BE ADJUSTED TO ACCOMODATE THE MADNAF  76
     1P IN STORAGE)                                                      DNAF  77
 1000 FORMAT(8F10.0)                                                     DNAF  78
 1100 FORMAT(5L1)                                                        DNAF  79
 1200 FORMAT(4(5X, 1PE11.4))                                             DNAF  80
 1300 FORMAT(///7X, 118HA MAP IS NOT PREPARED.  H+1 HOUR EXPOSURE RATE (DNAF  81
     1ROENTGENS/HR) AND MAXIMUM EFFECTIVE BIOLOGICAL DOSE (REBD) (ROENTGDNAF  82
     2ENS)/ 7X, 88HARE COMPUTED FOR USER-SPECIFIED POINTS.  X IS THE WINDNAF  83
     3DWARD DIRECTION AND Y IS CROSSWIND.//                              DNAF  84
     4 9X, 4HX(M), 12X, 4HY(M), 11X, 6HR(H+1), 11X, 4HREBD)              DNAF  85
 1400 FORMAT(12A6)                                                       DNAF  86
 1500 FORMAT( 1H1,   50(, 19H* * * * * * * * * *//55X,11HD N A F - 1//   DNAF  87
     1 25X,  72HT H E  D E F E N S E  N U C L E A R  A G E N C Y  F A S DNAF  88
     2T  F A L L O U T//              45X, 32HP R E D I C T I O N  S Y S TDNAF  89
     3 E M// 51X, 19H* * * * * * * * * *////55X,11HPREPARED BY/46X,  30HDNAF  90
     4ATMOSPHERIC SCIENCE ASSOCIATES/  54X, 14HBEDFORD, MASS.////25X,   DNAF  91
     530H****  RUN IDENTIFICATION  ****, 3X, 12A6)                      DNAF  92
 1600 FORMAT(//20X,24HYIELDS - TOTAL (FISSION), 21X, 1PE12.5, 2H (,      DNAF  93
     1 1PE12.5, 4H) KT/ 20X,21HORDINATE SCALE FACTOR, 24X, 1PE12.5)      DNAF  94
 1700 FORMAT(//20X, 20HEFFECTIVE WIND SPEED, 25X, 1PE12.5,6H M/SEC)      DNAF  95
 1800 FORMAT( 20X, 37HWIND DIRECTION (CLOCKWISE FROM NORTH),  8X,        DNAF  96
     1 1PE12.5, 5H DEG.)                                                 DNAF  97
 1900 FORMAT(20X, 19HSHEAR PARAMETER, SY, 26X, 1PE12.5, 8H PER SEC)      DNAF  98
 2000 FORMAT(//20X, 71HAN EFFECTIVE WIND SPEED LESS THAN 0.50 M/S HAS BEDNAF  99
     1EN SPECIFIED - WIND = 1PE12.5/ 20X, 21HWIND IS RESET TO 0.50)      DNAF 100
 2100 FORMAT(A6)                                                         DNAF 101
C                                                                        DNAF 102
COMPUTE THE CROSSWIND GAUSSIAN SPREAD VIA THIS FUNCTION                  DNAF 103
      CROS  /Y,SIGYY) = EXP(-0.5*(YY/SIGYY)**2)/SIGYY/SQT2PI             DNAF 104
C                                                                        DNAF 105
COPY IN RUN IDENTIFICATION                                               DNAF 106
  100 READ(IN,1400,END=300) HOLL                                         DNAF 107
C                                                                        DNAF 108
  150 INTL1=0                                                            DNAF 109
      INTL2=0                                                            DNAF 110
COPY IN BASIC DATA                                                       DNAF 111
      READ(IN, 1000) W, FW, WIND, SY, ANG, GRUFF                         DNAF 112
      READ(IN, 1100) IFMAP, USETMP                                       DNAF 113
      WL10 = ALOG10(W)                                                   DNAF 114
      ANG = ANG/DIRC                                                     DNAF 115
      SINA = SIN(ANG)                                                    DNAF 116
      COSA = COS(ANG)                                                    DNAF 117
      IF(GRUFF .EQ. 0.0) GRUFF=1.0                                       DNAF 118
      CAYFW = CAY*FW*GRUFF                                               DNAF 119
COMPUTE STABILIZED CLOUD PROPERTIES                                      DNAF 120
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      CALL        SCLOD( W, RI, RS, ZT, ZB)                                 DNAF 121
COPY OUT BASIC DATA                                                         DNAF 122
      WRITE(IO, 1500) HOLL                                                  DNAF 123
      WRITE(IO, 1600) W, FW, GRUFF                                          DNAF 124
      IF(WIND .NE. 0.0) GO TO 200                                           DNAF 125
COPY IN WIND PROFILE DATA                                                   DNAF 126
      CALL INWIND(IN, IO)                                                   DNAF 127
COMPUTE EFFECTIVE WIND, WIND                                                DNAF 128
      CALL        EFWIND(ZT, ZB, WIND, SINA, COSA)                          DNAF 129
COMPUTE WIND SHEAR PARAMETER, SY                                            DNAF 130
      SY = SYWND (ZT, ZB, SINA, COSA)                                       DNAF 131
CHECK WIND FOR THRESHOLD AND SET WIND=0.50 IF IT IS BELOW THE THRESHOLD DNAF 132
  200 IF(WIND .GE. 0.50) GO TO 205                                          DNAF 133
      WRITE(IO,2000) WIND                                                   DNAF 134
      WIND = 0.50                                                           DNAF 135
COMPUTE FALLOUT ONSET TIME, TO                                              DNAF 136
  205 TO = ONSET(W)                                                         DNAF 137
COPY OUT MODEL PARAMETERS                                                   DNAF 138
      WRITE(IO, 1700) WIND                                                  DNAF 139
      IF( .NOT. IFMAP) GO TO 210                                            DNAF 140
      DIR = DIRC * ATAN(SINA/COSA)                                          DNAF 141
      IF(COSA .LT. 0.0) DIR = DIR - SIGN(180.0, DIR)                        DNAF 142
      WRITE(6, 1800) DIR                                                    DNAF 143
  210 WRITE(IO, 1900) SY                                                    DNAF 144
CHECK IF A MAP IS TO BE PREPARED                                            DNAF 145
      IF(IFMAP) GO TO 300                                                   DNAF 146
      WRITE(IO, 1300)                                                       DNAF 147
COPY IN COORDINATES AT WHICH ACTIVITY IS TO BE COMPUTED                     DNAF 148
  250 READ(IN,1000,END=100) X, Y                                            DNAF 149
C                                                                           DNAF 150
COMPUTE CLOUD DISPERSION PARAMETERS AND FALLOUT ARRIVAL TIME                DNAF 151
  275 CALL        SIGTA(Q, W, TO, WIND,SY, RI, RS, ZB, ZT, WL10,            DNAF 152
     1  INTL1, SIGE, SIGY, TA)                                              DNAF 153
COMPUTE CROSSWIND-INTEGRATED ACTIVITY FRACTION ON THE HOTLINE AT X          DNAF 154
      GOFX = DNAF1(X, WIND, SIGE, W, INTL2)                                 DNAF 155
COMPUTE H+1 ACTIVITY (R/HR) AT POINT (X,Y)                                  DNAF 156
      A = CAYFW * CROSS(Y,SIGY) * GOFX                                      DNAF 157
COMPUTE MAXIMUM EFFECTIVE BIOLOGICAL DOSE                                   DNAF 158
      DMAX = A * DOSE(T1)                                                   DNAF 159
COPY OUT RESULTS                                                            DNAF 160
      WRITE(IO, 1200) X, Y, A, DMAX                                         DNAF 161
      GO TO 250                                                             DNAF 162
C                                                                           DNAF 163
CHECK IF MAP IS SPECIFIED BY THE USER OR BY THE PROGRAM                     DNAF 164
  300 IF(USETMP) GO TO 400                                                  DNAF 165
      CALL        SETMP(W, FW, WIND, SINA, COSA, GRUFF, XMIN, XMAX,         DNAF 166
     1 YMIN, YMAX, DGX, DGY)                                                DNAF 167
      GO TO 450                                                             DNAF 168
  400 READ(IN, 1000) XMIN, XMAX, YMIN, YMAX, DGX, DGY                       DNAF 169
  410 IF(DGY .EQ. 0.0) DGY = DGX*IH/IV/2.0                                  DNAF 170
  450 NXMAP = (XMAX - XMIN)/DGX                                             DNAF 171
      NYMAP = (YMAX - YMIN)/DGY                                             DNAF 172
      MMAP = NXMAP*NYMAP                                                    DNAF 173
      IF( MMAP .LE. NMAP)  GO TO 460                                        DNAF 174
      WRITE(IO,47)                                                          DNAF 175
      DGX = SQRT( 2.0*IV*MMAP*DGX*DGY/(NMAP*IH))                            DNAF 176
      DGY=0.0                                                               DNAF 177
      GO TO 410                                                             DNAF 178
  460 WRITE(IO,  24) XMIN, XMAX, YMIN, YMAX, DGX, DGY                       DNAF 179
COMPUTE ACTIVITY AT MAP POINTS                                              DNAF 180
```

```
      YM = YMIN                                                         DNAF 181
      INDEX = 0                                                         DNAF 182
      DO 500 J=1,NYMAP                                                  DNAF 183
      YM = YM + DGY                                                     DNAF 184
      XM = XMIN                                                         DNAF 185
      DO 500 I=1,NXMAP                                                  DNAF 186
      XM = XM + DGX                                                     DNAF 187
      IF(WIND .GT. 1.0E-02) GO TO 470                                   DNAF 188
      X = SQRT(XM**2 + YM**2)                                           DNAF 189
      Y = 0.0                                                           DNAF 190
      GO TO 472                                                         DNAF 191
  470 X = XM*SINA + YM*COSA                                             DNAF 192
      Y =-XM*COSA + YM*SINA                                             DNAF 193
COMPUTE CLOUD DISPERSION PARAMETERS AND FALLOUT ARRIVAL TIME            DNAF 194
  472 CALL        SIGTA(X, W, TO, WIND,SY, RI, RS, ZB, ZT, WL10,        DNAF 195
     1  INTL1, SIGE, SIGY, TA)                                          DNAF 196
      INDEX = INDEX + 1                                                 DNAF 197
COMPUTE MAP ORDINATE - 4+1 HOUR EXPOSURE RATE (NORMALIZED)              DNAF 198
  475 OMAP(INDEX) =CAYEW*DNAF1(X, WIND, SIGE, W, INTL2) * CROSS(Y,SIGY) DNAF 199
  500 CONTINUE                                                          DNAF 200
COPY OUT MAP                                                            DNAF 201
  600 CALL        MAPP(   ID,  HOLL, DGX, DGY, NXMAP, NYMAP, OMAP,      DNAF 202
     1  XMAX, XMIN, YMAX, YMIN)                                         DNAF 203
      GO TO 100                                                         DNAF 204
  900 RETURN                                                            DNAF 205
      END                                                               DNAF 206
```

```
      SUBROUTINE SCLOD( W, RI, RS, ZT, ZB)                              SCLOD  2
C                                                                       SCLOD  3
COMPUTES STABILIZED CLOUD PROPERTIES                                    SCLOD  4
C                                                                       SCLOD  5
C     H. G. NORMINT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1980       SCLOD  6
C                                                                       SCLOD  7
      RI=103.0*W**(0.33)                                                SCLOD  8
      WL=ALOG(W)                                                        SCLOD  9
      RS = EXP(6.7553 + WL*(0.32055 + WL*0.01137478))                   SCLOD 10
      IF(W .GT. 4.07) GO TO 10                                          SCLOD 11
      ZB = 2223. * W**(0.3463)                                          SCLOD 12
      GO TO 20                                                          SCLOD 13
   10 ZB = 2661. * W**(0.2198)                                          SCLOD 14
   20 IF(W .GT. 2.29) IF(W - 19.0)30,30,40                              SCLOD 15
      ZT = 3537. * W**(0.2553)                                          SCLOD 16
      GO TO 50                                                          SCLOD 17
   30 ZT = 3170. * W**(0.4077)                                          SCLOD 18
      GO TO 50                                                          SCLOD 19
   40 ZT = 6474. * W**(0.1650)                                          SCLOD 20
   50 CONTINUE                                                          SCLOD 21
      RETURN                                                            SCLOD 22
      END                                                               SCLOD 23
```

```
      SUBROUTINE INWIND(IN, IO)                                         INWIN  2
C                                                                       INWIN  3
COPIES IN AND PROCESSES OBSERVED WIND DATA                              INWIN  4
C                                                                       INWIN  5
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1980       INWIN  6
C                                                                       INWIN  7
C ***********************************************************************INWIN  8
C                                                                       INWIN  9
C     READS AND PROCESSES WIND DATA FOR A HORIZONTALLY                  INWIN 10
C     HOMOGENIOUS FIELD.  VERTICAL COMPONENTS ARE NOT CONSIDERED.       INWIN 11
C                                                                       INWIN 12
C  * * * * * * * * * * * * * * GLOSSARY * * * * * * * * * * * * *       INWIN 13
C     FMT      OBJECT-TIME FORMAT OF WIND DATA                          INWIN 14
C     FORM     INPUT PARAMETER TO INDICATE FORMAT OF WIND DATA TO FOLLOW-INWIN 15
C              EITHER - METEOR OR RESOLV                                INWIN 16
C     N1,N2,N3  DATA FIELD POINTERS                                     INWIN 17
C     SCALE    DATA SCALE FACTORS AND TRANSLATIONS                      INWIN 18
C     SEE GLOSSARY IN PROGRAM DNAF FOR OTHER QUANTIES                   INWIN 19
C ***********************************************************************INWIN 20
C                                                                       INWIN 21
      REAL METEOR                                                       INWIN 22
      COMMON /WDAT/ NHODO, ZBH(50), ZCH(50), WX(50), WY(50)             INWIN 23
      DIMENSION SCALE( 3), AP( 3), FMT(12)                              INWIN 24
C                                                                       INWIN 25
      DATA ALIMIT  , BAIC      , PROGRM  , METEOR ,RESOLV               INWIN 26
     1  /  999999. , 01'4532925, 6HINWIND, 4HMETE ,4HRESO/              INWIN 27
      DATA IREC/0/                                                      INWIN 28
C                                                                       INWIN 29
    1 FORMAT(  4X,  6HLEVELS,I4, 5H THRU,I4, 8F12.5)                    INWIN 30
    3 FORMAT( ////33X, 25HWIND LAYER BASE ALTITUDES/)                   INWIN 31
C   4 FORMAT(1H03X31HMAXIMUM WIND SPACE ALTITUDE IS E12.5,7H METERS)    INWIN 32
 1000 FORMAT (12A6)                                                     INWIN 33
 1100 FORMAT (3F10.0)                                                   INWIN 34
 1200 FORMAT (20I4)                                                     INWIN 35
 1300 FORMAT(////  26X, 13HRAW WIND DATA,33X,19HPROCESSED WIND DATA/18X,INWIN 36
     11HZ, 9X, 10HVX OR DIR., 3X, 11HVY OR SPEED, 14X, 1HZ, 12X,        INWIN 37
     2 2HVX, 12X, 2HVY)                                                 INWIN 38
 1400 FORMAT (10X, 3(2X, 1PE12.5))                                      INWIN 39
 1500 FORMAT (1H+,57X, 3(2X, 1PE12.5))                                  INWIN 40
 1800 FORMAT( 1H0, 5X, 34HWIND STRATA ALTITUDES INCONSISTENT)           INWIN 41
 1900 FORMAT(A4)                                                        INWIN 42
C                                                                       INWIN 43
COPY IN DATA SPECIFICATION                                              INWIN 44
      READ(IN,1900) FORM                                                INWIN 45
CHECK FORM                                                              INWIN 46
      IF(FORM .EQ. METEOR) GO TO 25                                     INWIN 47
   20 IF(FORM .NE. RESOLV)CALL ERROR(PROGRM,-20,IO)                     INWIN 48
COPY IN FORMAT, SCALE & FIELD POINTERS                                  INWIN 49
   25 READ ( IN , 1000)FMT                                              INWIN 50
      READ ( IN , 1100) SCALE                                           INWIN 51
      READ ( IN , 1200) N1, N2, N3                                      INWIN 52
      DO 50 I = 1,3                                                     INWIN 53
   50     IF(SCALE(I).EQ. 0.0) SCALE (I) = 1.0                          INWIN 54
      IF(FORM .EQ. METEOR) TRNS=SCALE(5)*SCALE(3) - 180.                INWIN 55
      WRITE (IO,1300)                                                   INWIN 56
      NHODO=0                                                           INWIN 57
COPY IN, PRINT RAW DATA, TRANSLATE AND SCALE DATA, AND PRINT PROCESSED  INWIN 58
C     DATA                                                              INWIN 59
  100 READ ( IN , FMT) AP                                               INWIN 60
      IF(AP(N1).GE.ALIMIT)GO TO 250                                     INWIN 61
```

```
      WRITE(IO,1400)AP(N1), AP(N2), AP(N3)                              INWIN 62
      NHODO=NHODO+1                                                     INWIN 63
      ZCH(NHODO)=(AP(N1)  + SCALE(4))*SCALE(1)                          INWIN 64
      IF(FORM.EQ.RESOLV) GO TO 150                                      INWIN 65
      WX(NHODO)      =AP(N3)*SCALE(2)*SIN(RADC*(AP(N2)*SCALE(3) + TRNS)) INWIN 66
      WY(NHODO)      =AP(N3)*SCALE(2)*COS(RADC*(AP(N2)*SCALE(3) + TRNS)) INWIN 67
      GO TO 200                                                         INWIN 68
  150 WX(NHODO)       = AP(N2)*SCALE(2)                                 INWIN 69
      WY(NHODO)       = AP(N3)*SCALE(2)                                 INWIN 70
  200 WRITE(IO,1500) ZCH(NHODO),WX(NHODO), WY(NHODO)                    INWIN 71
      GO TO 100                                                         INWIN 72
COMMINGLE DATA TO ARRANGE IT IN ORDER OF ASCENDING ALTITUDE             INWIN 73
  250 NHODM1=NHODO-1                                                    INWIN 74
      DO 255 I=1,NHODM1                                                 INWIN 75
      IP1=I+1                                                           INWIN 76
      DO 255 J=IP1,NHODO                                                INWIN 77
      IF( ZCH(I) .LE.  ZCH(J)) GO TO 255                                INWIN 78
      TEMP= ZCH(I)                                                      INWIN 79
       ZCH(I)= ZCH(J)                                                   INWIN 80
       ZCH(J)=TEMP                                                      INWIN 81
      TEMP=WX(I)                                                        INWIN 82
      WX(I)=WX(J)                                                       INWIN 83
      WX(J)=TEMP                                                        INWIN 84
      TEMP=WY(I)                                                        INWIN 85
      WY(I)=WY(J)                                                       INWIN 86
      WY(J)=TEMP                                                        INWIN 87
  255 CONTINUE                                                          INWIN 88
CONSTRUCT WIND LAYER  BASE  ALTITUDES IN ARRAY ZBH                      INWIN 89
  259 ZBH(1) = 0.0                                                      INWIN 90
      DO 260 I=2,NHODO                                                  INWIN 91
  260 ZBH(I) = (ZCH(I-1) + ZCH(I))/2.0                                  INWIN 92
C     ZMAX=2.0*ZCH(NHODO)) - ZBH(NHODO)                                 INWIN 93
COPY OUT WIND LAYER BASE DATA                                           INWIN 94
      WRITE(  IO ,3)                                                    INWIN 95
      DO 270 IGO=1,NHODO,IREC                                           INWIN 96
      ISTOP=IGO+IREC-1                                                  INWIN 97
      IF(ISTOP.GT.NHODO) ISTOP=NHODO                                    INWIN 98
  270 WRITE(  IO ,1)IGO,ISTOP,(ZBH(K),K=IGO,ISTOP)                      INWIN 99
C     WRITE(  IO ,4)ZMAX                                                INWIN100
      RETURN                                                            INWIN101
      END                                                               INWIN102
```

```
      SUBROUTINE EFWIND(ZT, ZB, WIND, SINA, COSA)
C
COMPUTES THE EFFECTIVE WIND SPEED, WIND, AND ITS DIRECTION ANGLE FROM
C     OBSERVED WIND DATA
C
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - JULY 1991
C
      COMMON /WDAT/ NHODO, ZBH(50), ZCH(50), WX(50), WY(50)
      DIMENSION ALT( 39), V( 39)
      DATA ALT/0.,1000.,2000., 3000., 4000., 5000., 6000., 7000., 8000.,
     1 9000., 10000., 11000., 12000., 13000., 14000., 15000., 16000.,
     2 17000., 18000., 19000., 20000., 21000., 22000., 23000., 24000.,
     3 25000., 26000., 28000., 30000., 32000., 34000., 36000., 38000.,
     4 40000., 42000., 44000., 46000., 48000., 50000./
      DATA V/ 1.6538, 1.7124, 1.7744, 1.8401, 1.9097, 1.9836, 2.0621,
     1 2.1453, 2.2350, 2.3303, 2.4324, 2.5419, 2.6446, 2.7483, 2.8551,
     2 2.9630, 3.0723, 3.1831, 3.2951, 3.4082, 3.5222, 3.6322, 3.8122,
     3 3.9243, 3.9994, 4.0806, 4.1746, 4.3565, 4.5326, 4.7063, 4.8517,
     4 5.0023, 5.1767, 5.3910, 5.6632, 6.0155, 6.4727, 7.0778, 7.8819/
C
COMPUTE CLOUD CENTER HEIGHT, ZO
      ZO = (ZT + ZB)/2.0
COMPUTE LOCATION OF ZO IN ZBH ARRAY
      NHODO = NHODO+1
      DO 100 I=1,NHODO
      J = NHODO - I
      IF(ZO.GT. ZBH(J)) GO TO 150
  100 CONTINUE
  150 Z = (ZO + ZBH(J))/2.0
      CALL TRPL(Z, 39, ALT, V, VP)
      WGT = (ZO - ZBH(J))/VP
      SWGT = WGT
      CALL TRPL(Z, NHODO, ZCH, WX,WNDX)
      CALL TRPL(Z, NHODO, ZCH, WY,WNDY)
      WNDX = WNDX*WGT
      WNDY = WNDY*WGT
      J = J - 1
      IF(J .EQ. 0) GO TO 250
      DO 200 I=1,J
      CALL TRPL(ZCH(I), 39, ALT, V, VP)
      WGT =(ZBH(I+1) - ZBH(I))/VP
      SWGT = SWGT + WGT
      WNDX =  WNDX + WX(I)*WGT
  200 WNDY =  WNDY + WY(I)*WGT
  250 WIND = SQRT(WNDX**2 +  WNDY**2)
      IF(WIND .EQ. 0.0) GO TO 300
      SINA = WNDX/WIND
      COSA = WNDY/WIND
      WIND = WIND/SWGT
      RETURN
  300 SINA = 1.0
      COSA = 0.0
      RETURN
      END
```

```
      FUNCTION DOSE(TA)                                                 DOSE   1
C                                                                       DOSE   2
COMPUTES THE FACTOR WHICH WHEN MULTIPLIED BY A PROVIDES MAXIMUM         DOSE   3
C     EFFECTIVE BIOLOGICAL DOSE                                         DOSE   4
C                                                                       DOSE   5
      IF(TA .LT. 1157.9) GO TO 100                                      DOSE   6
      ZEE = 2.0 * ALOG(TA/3600.0) + 4.0                                 DOSE   7
      DOSE = 4.6182 - ZEE * (0.53587 - 0.016923 * ZEE)                  DOSE   8
      RETURN                                                            DOSE   9
  100 ZEE = 0.8685833 * ALOG(TA)                                        DOSE  10
      DOSE = 15.2891 - ZEE * (2.903225 - 0.16623215 * ZEE)              DOSE  11
      RETURN                                                            DOSE  12
      END                                                               DOSE  13
```

```
      FUNCTION SYWND(ZT, ZB, SINA, COSA)                                SYWND   2
C                                                                       SYWND   3
COMPUTES RMS SHEAR PARAMETER BETWEEN ZO AND THE GROUND                  SYWND   4
C                                                                       SYWND   5
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1980       SYWND   6
C                                                                       SYWND   7
      COMMON /WDAT/ NHODO, ZBH(50), ZCH(50), WX(50), WY(50)             SYWND   8
COMPUTE CLOUD CENTER HEIGHT AND HALF CLOUD THICKNESS                    SYWND   9
      ZO = (ZT + ZB)/2.0                                                SYWND  10
      DH = (ZT - ZB)/2.0                                                SYWND  11
      N = 0                                                             SYWND  12
      SY = 0.0                                                          SYWND  13
      ZU = ZO + DH                                                      SYWND  14
      ZL = ZO - DH                                                      SYWND  15
COMPUTE SQUARE OF SHEAR PARAMETER AND INCREMENT SUM AND COUNTER         SYWND  16
  100 CALL TRPL(ZU, NHODO, ZCH, WX, WXU)                                SYWND  17
      CALL TRPL(ZU, NHODO, ZCH, WY, WYU)                                SYWND  18
      CALL TRPL(ZL, NHODO, ZCH, WX, WXL)                                SYWND  19
      CALL TRPL(ZL, NHODO, ZCH, WY, WYL)                                SYWND  20
      SY = SY + ((-COSA*(WXU - WXL) + SINA*(WYU - WYL))/(ZU-ZL))**2     SYWND  21
      N = N + 1                                                         SYWND  22
CHECK IF DONE                                                           SYWND  23
      IF(ZL .EQ. 0.0) GO TO 200                                         SYWND  24
      ZU = ZL                                                           SYWND  25
      ZL = ZU - 2.0*DH                                                  SYWND  26
CHECK IF THIS IS LAST SUMMAND                                           SYWND  27
      IF(ZL .LT. ZBH(2)) ZL=0.0                                         SYWND  28
      GO TO 100                                                         SYWND  29
  200 SYWND = SQRT(SY/N)                                                SYWND  30
      RETURN                                                            SYWND  31
      END                                                               SYWND  32
```

```
      FUNCTION ONSET(W)
C
COMPUTES FALLOUT ONSET TIME (S)
C
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1980
C
      IF(W .LT. 1.0E4) GO TO 100
      ONSET = 1147.54
      RETURN
  100 WL = ALOG(W)
      ONSET = EXP(1.527667 + WL*(0.4089466 + WL*2.064322E-2))
      RETURN
      END
```

```
      SUBROUTINE SIGTA(X, W, TO, WIND,SY, PI, RS, ZB, ZT, WL10,
     1  INTL1, SIGE, SIGY, TA)
C
COMPUTES GAUSSIAN VARIANCE SIGE AND STANDARD DEVIATION SIGY, AND TIME
C     OF ARRIVAL OF FALLOUT AT DISTANCE X FROM GZ ALONG THE HOTLINE
C
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1981
C
      DATA      BXVO      ,      B      ,        EX
     1   /  4.79602E-5  ,  2.9E-5  , 0.66666666667 /
C
      IF(INTL1 .GT. 0) GO TO 100
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
COMPUTE  INITIALIZATION PARAMETERS ON FIRST PASS
      TB = (1.0 - EXP(-3*ZB))/BXVO
      WTO = WIND * TO
      TOPRIW = TO + RI/WIND
      RSD2 =RS/2.0
      IF(WL10 .GT. 1.0) IF(WL10-3.0)10,20,20
      SIGOP = RI
      GO TO 50
   10 SIGOP = RI*(1.0 + 3.0*WL10)/4.0
      GO TO 50
   20 SIGOP = 2.5*RI
   50 CINT = (RSD2-SIGOP )/(TB - TO)
      SIGC1S = SIGOP**EX
      SIGC1L = RSD2**EX
      SIGC2S = 3.0E6*SIGC1S - 2.0E9
      SIGC2L = 3.0E6*SIGC1L - 2.0E9
      EPSC1 = 0.016522*W**(-0.10233)
      EPSC2 = 3.0E6*EPSC1
      TLS = (1000.0 - SIGC1S)/EPSC1
      TLL = (1000.0 - SIGC1L)/EPSC1
      SHEARC = SY*(ZT - ZB)/10.0
      INTL1 = 1
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
COMPUTE FALLOUT TIME OF ARRIVAL
  100 XIM1 = X/WIND - TOPRIW
      TA = TO + (XIM1 + SQRT(XIM1**2 + 0.01*TOPRIW))/2.0
COMPUTE CLOUD HORIZONTAL DISPERSION VARIANCE, SIGE
  125 IF(X .GT. WTO) IF(TA - TB)300,200,200
      IF(TA .GT. TLS) GO TO 150
```

```
      SIGE = (SIGC1S + TA*EPSC1)**3                                     SIGTA 44
      GO TO 500                                                         SIGTA 45
  150 SIGE = SIGC2S +TA*EPSC2                                           SIGTA 46
      GO TO 500                                                         SIGTA 47
  200 IF(TA .GT. TLL) GO TO 250                                         SIGTA 48
      SIGE = (SIGC1L +TA*EPSC1)**3                                      SIGTA 49
      GO TO 500                                                         SIGTA 50
  250 SIGE = SIGC2L +TA*EPSC2                                           SIGTA 51
      GO TO 500                                                         SIGTA 52
  300 SIGO = (SIGOP+ (TA - TO)*SINT)**EX                                SIGTA 53
      IF(TA.GT. (1000.0 - SIGO)/EPSC1) GO TO 350                        SIGTA 54
      SIGE = (SIGO +TA*EPSC1)**3                                        SIGTA 55
      GO TO 500                                                         SIGTA 56
  350 SIGE = 3.0E6*SIGO +TA*EPSC2- 2.0E9                                SIGTA 57
CORRECT CLOUD HORIZONTAL DISPERSION VARIANCE FOR WIND SHEAR DISPERSION  SIGTA 58
C     AND RETURN THE STANDARD DEVIATION                                 SIGTA 59
  500 SIGY = SQRT(SIGE + (SHEARC*TA)**2)                                SIGTA 60
      RETURN                                                            SIGTA 61
      END                                                               SIGTA 62


      FUNCTION DNAF1(X, WIND, SIGE, W, INTL2)                           DNAF1  2
C                                                                       DNAF1  3
COMPUTES TOTAL FALLOUT FRACTION (INTEGRATED IN THE CROSSWIND DIRECTION) DNAF1  4
C     DEPOSITED AT DISTANCE X FROM GZ ALONG THE HOTLINE  (PER M)        DNAF1  5
C                                                                       DNAF1  6
C     M. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1981       DNAF1  7
C                                                                       DNAF1  8
      DATA PI/3.141592654/                                              DNAF1  9
      IF(INTL2)10,10,500                                                DNAF1 10
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * DNAF1 11
COMPUTE  INITIALIZATION PARAMETERS ON FIRST PASS                        DNAF1 12
   10 INTL2 =1                                                          DNAF1 13
      WL = ALOG(W)                                                      DNAF1 14
      IF(W .GT. 10.0) GO TO 30                                          DNAF1 15
      A = 570.0                                                         DNAF1 16
      B = 0.0176                                                        DNAF1 17
      GO TO 50                                                          DNAF1 18
   30 A = -3179.62 + 3800.0*WL                                          DNAF1 19
      B = 0.03045*W**(-0.66)                                            DNAF1 20
   50 IF(W .GT. 1.0E3) GO TO 200                                        DNAF1 21
      IF(W .GT. 0.1) GO TO 60                                           DNAF1 22
      ALPHA = 1.06                                                      DNAF1 23
      GO TO 100                                                         DNAF1 24
   60 ALPHA = 1.0875 + 0.0119431*WL                                     DNAF1 25
  100 IF(W .GT. 1.0) GO TO 150                                          DNAF1 26
      TM = 30. * W**(0.1956)                                            DNAF1 27
      GO TO 400                                                         DNAF1 28
  150 TM = 30. * W**(0.0407)                                            DNAF1 29
      GO TO 400                                                         DNAF1 30
  200 ALPHA = 1.17                                                      DNAF1 31
      IF(W .GT. 1.0E4) GO TO 300                                        DNAF1 32
      TM = 933.616*W**(0.16273)                                         DNAF1 33
      GO TO 400                                                         DNAF1 34
  300 TM = 2437.18*W**(0.05115)                                         DNAF1 35
  400 X1= TM*SQRT(ALPHA/(4.0 - ALPHA)) * WIND                           DNAF1 36
      COF = 2.0*SIN(PI*(3.0 - ALPHA)/2.0)/(3.0 - ALPHA)/PI**2           DNAF1 37
      PIX1 = PI*X1                                                      DNAF1 38
      X1S = X1**2                                                       DNAF1 39
      FX1F = 4.0*X1S**2                                                 DNAF1 40
      FX1S = 4.0*X1S                                                    DNAF1 41
      TX1S = 3.0*X1S                                                    DNAF1 42
      VOK = WIND*W**(0.26945)/9.867E-5                                  DNAF1 43
```

```
      VTAU = 3160.0*W**(0.2483) * WIND                                  DNAF1 44
      IF(W - 38.7868)450,450,420                                        DNAF1 45
  420 VATC = -1.443*WIND*EXP( 10.124706 + WL*(0.166176 -                DNAF1 46
     1 8.660449E-3*WL))                                                 DNAF1 47
      GO TO 500                                                         DNAF1 48
  450 VATC = -1.443*WIND*14667.0*W**(0.26203)                           DNAF1 49
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * DNAF1 50
COMPUTE G(X)                                                            DNAF1 51
  500 XS = X**2                                                         DNAF1 52
      X2S = XS + SIGF                                                   DNAF1 53
      X3S = X2S - X1S                                                   DNAF1 54
      X3F = X3S**2                                                      DNAF1 55
      SRSIG = SQRT(SIGE)                                                DNAF1 56
      XDSIG = X/SRSIG                                                   DNAF1 57
      FXSX1S = XS*FX1S                                                  DNAF1 58
      FXSX1F = XS*FX1F                                                  DNAF1 59
      IF(X3F .GT. 1.0) GO TO 510                                        DNAF1 60
      F1 = X3S                                                          DNAF1 61
      F2 = X3F                                                          DNAF1 62
      GO TO 550                                                         DNAF1 63
  510 F1 = 1.0/X3S                                                      DNAF1 64
      F2 = 1.0                                                          DNAF1 65
      FXSX1S = FXSX1S/X3F                                               DNAF1 66
      FXSX1F = FXSX1F/X3F                                               DNAF1 67
  550 DNAF1 = SRSIG * COF*(-X*PIX1*(( 3.0*X2S + X1S)*F1  + FXSX1S) -    DNAF1 68
     1  (F2  + FXSX1S)*X3S + (X2S*F2  - FXSX1F)*ALOG(X2S/X1S) +         DNAF1 69
     2  XDSIG*((X2S + TX1S)*X2S*F1  + FXSX1F)*(PI + 2.0*ATAN(XDSIG)))/  DNAF1 70
     3  ((F2 + 2.0*FXSX1S)*X3F + 4.0*XS*FXSX1F)                         DNAF1 71
CHECK FOR UPWIND OR DOWNWIND CORRECTION                                 DNAF1 72
      IF(X)600,800,700                                                  DNAF1 73
COMPUTE UPWIND CORRECTION                                               DNAF1 74
  600 DNAF1 = DNAF1 * EXP( B*X*(1.0 - EXP(X/A)))                        DNAF1 75
      RETURN                                                            DNAF1 76
COMPUTE DOWNWIND CORRECTION                                             DNAF1 77
  700 DNAF1 = DNAF1 * EXP(-(ALOG(VOK*DNAF1) + (X/VTAU)**2) *            DNAF1 78
     1  (1.0 - EXP(X/VATC)))                                            DNAF1 79
  800 RETURN                                                            DNAF1 80
      END                                                               DNAF1 81
```

```
      SUBROUTINE SETMP(W, FW, WIND, SINA, COSA, GRUFF, XMIN, XMAX,
     1 YMIN, YMAX, DGX, DGY)
C
C     AUTOMATIC MAP SETUP FOR PURPOSE OF PRELIMINARY LOOK AT PATTERN
C
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - AUGUST 1981
C
C     THIS CODE ESTIMATES UPWIND AND DOWNWIND HOTLINE DISTANCES TO THE
C     1 R/HR CONTOUR LEVEL, AND SETS UP THE MAP ACCORDINGLY.
C     THE MAP IS SPATIALLY UNDISTORTED.
C
      DATA  NGRIDX  ,  NGRIDY  ,  IH  ,  IV
     1   /    37    ,    44    ,  10  ,   6  /
C
COMPUTE APPROXIMATE HOTLINE DISTANCES TO THE 1 R/HR CONTOUR LEVEL
      TENWND = 10.0*WIND
      XDN = (2.5153 *  TENWND**(0.6834)) * (W**( 0.27125 + 0.031124 *
     1 ALOG(TENWND)))
      IF(W .GT. 10.0) GO TO 100
      XUP = -340.0 * (TENWND**(0.1062)) * (W**(0.15))
      GO TO 200
  100 XUP = -125.3 * (TENWND**(0.1062)) * (W**(0.5833))
COMPUTE MAXIMUM AND MININUM MAP COORDINATES
  200 IF(SINA)300,400,400
  300 XMAX = XUP * SINA
      XMIN = XDN * SINA
      GO TO 500
  400 XMAX = XDN * SINA
      XMIN = XUP * SINA
  500 IF(COSA)600,700,700
  600 YMAX = XUP * COSA
      YMIN = XDN * COSA
      GO TO 800
  700 YMAX = XDN * COSA
      YMIN = XUP * COSA
COMPUTE GRID INCREMENTS AND ADJUST MAP BOUNDARIES
  800 XLNGH = XMAX - XMIN
      YLNGH = YMAX - YMIN
      IF(XLNGH .GT. YLNGH) GO TO 900
      DGY = YLNGH/NGRIDY
      DGX = 2.0*DGY*IV/IH
      DG = (0.667*YLNGH - XLNGH)/2.0
      IF(DG)1000,1000,850
  850 XMAX = XMAX + DG
      XMIN = XMIN - DG
      GO TO 1000
  900 DGX = XLNGH/NGRIDX
      DGY = DGX*IH/IV/2.0
      DG = (0.667*XLNGH - YLNGH)/2.0
      IF(DG)1000,1000,950
  950 YMAX = YMAX + DG
      YMIN = YMIN - DG
 1000 XMIN = XMIN - DGX
      YMIN = YMIN - DGY
      RETURN
      END
```

```
      SUBROUTINE MAPP( ISOUT, HOLL, DGX, DGY, NXMAP, NYMAP, OMAP,
     1  XMAX, XMIN, YMAX, YMIN)
C
COPIES OUT THE FALLOUT MAP FROM THE  ARRAY OMAP
C
C     T. W. SCHWINKL  28 FEBRUARY 1967
C     H. G. NORMENT, ATMOSPHERIC SCIENCE ASSOCIATES - JULY 1981
C
C ***********************************************************************
C
C     DNAF-1 MAP PRINTER
C
C ***********************************************************************
C
      DIMENSION JMAP(20), ABSSA(10), HOLL(12), OMAP( 5000)
      DATA INC/ 13/, XGZ,YGZ/0.0,0.0/
 2    FORMAT(/12X,19I6)
 4    FORMAT(1X,F13.0,2X,19F6.3)
 8    FORMAT(//15X,25HTHE QUANTITY PRESENTED IS)
 10   FORMAT(15X,42H_XPOSURE RATE NORMALIZED TO TIME H+1 HOUR.)
 1    FORMAT(1H1,5HSTRIPI3,5X, 12A6)
 16   FORMAT(/ 3X, 4H*** , 10F12.0, 3H **/)
 20   FORMAT(15X,31HGROUND ZERO IS LOCATED AT  X = F10.1,8H  , Y = F10.1
     1)
 29   FORMAT(15X,28HUNITS ARE ROENTGENS PER HOUR)
C
      MAPRUN=0
      TINC=2.0*DGX
      XCOORD=XMIN+DGX
      XCINC= INC*DGX
      KKL=1
      NX=NXMAP
C     LEFT IS USED HERE AS A TEMPORARY STORAGE
      LEFT=(XMAX-XMIN)/DGX
C 102   PRINT ORDINATE DESCRIPTION
C
 102  WRITE (ISOUT,8)
 162  WRITE (ISOUT,10)
      WRITE (ISOUT,29)
C
 170  WRITE (ISOUT,20) XGZ,YGZ
 1702 IF(LEFT-NX) 1021,1022,1022
 1021 NX=LEFT
 1022 MM=NX/(INC)
      M=MM+1
C     LEFT IS USED HERE AS THE NUMBER OF PRINT COLUMNS IN THE LAST
C     PRINTER STRIP
      LEFT=NX-MM*(INC)
      IF (LEFT.NE.0) GO TO 2023
      M = MM
      LEFT = INC
C     STRIPS
 2023 DO 110 ISTRIP=1,M
      MAPRUN=MAPRUN+1
      ABSSA(1)=XCOORD
      DO 3023 IAB=2,10
 3023 ABSSA(IAB)=ABSSA(IAB-1)+TINC
      WRITE (ISOUT,1)MAPRUN,HOLL
      WRITE (ISOUT,16)ABSSA
 1023 KL=KKL+(NYMAP-1)*NXMAP
```

```
      IF(ISTRIP-M)103,104,103                                           MAPP  62
 104  KINC=LEFT-1                                                       MAPP  63
      VLEFT=LEFT                                                        MAPP  64
      XCIN=VLEFT*DGX                                                    MAPP  65
      GO TO 1031                                                        MAPP  66
 103  KINC=INC-1                                                        MAPP  67
      XCIN=XCINC                                                        MAPP  68
 1031 CONTINUE                                                          MAPP  69
C                                                                       MAPP  70
C     ROWS                                                              MAPP  71
      YY=YMIN+DGY*FLOAT(NYMAP)                                          MAPP  72
      DO 200 J=1,NYMAP                                                  MAPP  73
      KH=KL+KINC                                                        MAPP  74
      KDC=0                                                             MAPP  75
C                                                                       MAPP  76
C     NUMBERS WITHIN ROWS                                               MAPP  77
      DO 300 K=KL,KH                                                    MAPP  78
      KDC=KDC+1                                                         MAPP  79
C                                                                       MAPP  80
C 150 CODE FOR POWER OF TEN DISPLAY                                     MAPP  81
 150  IF(OMAP(K))105,106,107                                            MAPP  82
 105  ASSIGN 121 TO N3                                                  MAPP  83
      OMAP(K)=-OMAP(K)                                                  MAPP  84
      GO TO 109                                                         MAPP  85
  105 JMAP(KDC)=0                                                       MAPP  86
      GO TO 300                                                         MAPP  87
 107  ASSIGN 300 TO N3                                                  MAPP  88
  109 H = ALOG10(OMAP(K))                                               MAPP  89
      H1=AMOD(H,1.0)                                                    MAPP  90
      JMAP(KDC)=H-H1                                                    MAPP  91
 1090 OMAP(K) = 10.0**H1                                                MAPP  92
      IF(OMAP(K)-9.999)115,115,1091                                     MAPP  93
 1091 OMAP(K)=OMAP(K)/10.0                                              MAPP  94
      JMAP(KDC)=JMAP(KDC)+1                                             MAPP  95
 115  GO TO N3,(300,121)                                                MAPP  96
C 121  RESET SIGN OF MAP COORDINATE                                     MAPP  97
 121  OMAP(K)=-OMAP(K)                                                  MAPP  98
 300  CONTINUE                                                          MAPP  99
      WRITE(ISOUT,2      ) (JMAP(K),K=1,KDC)                            MAPP 100
      WRITE(ISOUT,4    )YY,(OMAP(K),K=KL,KH)                            MAPP 101
      YY=YY-DGY                                                         MAPP 102
 200  KL=KL-NYMAP                                                       MAPP 103
      WRITE (ISOUT,16)ABSSA                                             MAPP 104
      XCOORD=XCOORD+XCIN                                                MAPP 105
 110  KKL=KKL+INC                                                       MAPP 106
 111  RETURN                                                            MAPP 107
      END                                                               MAPP 108
```

```
      SUBROUTINE TRPL (                                                 TRPL   2
     1  ARG, NPR, PARA, PARB, VRB)                                      TRPL   3
C                                                                       TRPL   4
C ***********************************************************************TRPL   5
C                                                                       TRPL   6
C     TRPL USES LINEAR INTERPOLATION TO LOCATE POSITION OF ARG WITHIN   TRPL   7
C     THE ONE-DIMENSIONAL ARRAY PARA AND COMPUTES FOR THE CORRESPONDING TRPL   8
C     POSITION IN THE ONE-DIMENSIONAL ARRAY PARB, VRB. NPR IS THE       TRPL   9
C     DIMENSION OF PARA AND PARB (WHOSE ELEMENTS CORRESPOND ONE TO ONE).TRPL  10
C     IF ARG IS OUTSIDE THE TABULATED VALUES OF PARA, VRB IS SELECTED   TRPL  11
C     FROM THE CORRESPONDING END OF PARB.                               TRPL  12
C     PARA IS ORDERED FROM LEAST (PARA (1)) TO GREATEST (PARA (NPR))    TRPL  13
C                                                                       TRPL  14
C ***********************************************************************TRPL  15
C                                                                       TRPL  16
      DIMENSION                                                         TRPL  17
     1  PARA ( NPR), PARB (NPR)                                         TRPL  18
C                                                                       TRPL  19
C ***********************************************************************TRPL  20
C ***********************************************************************TRPL  21
C                                                                       TRPL  22
  020 IF (ARG - PARA (1)) 022, 022, 040                                 TRPL  23
  022 MB = 1                                                            TRPL  24
  024 VRB = PARB (MB)                                                   TRPL  25
  026 RETURN                                                            TRPL  26
  040 DO 054 MA =2, NPR                                                 TRPL  27
      IF (ARG - PARA (MA)) 048, 044, 054                                TRPL  28
  044 MB = MA                                                           TRPL  29
      GO TO 024                                                         TRPL  30
  048 VRB = (ARG - PARA (MA - 1)) * (PARB (MA) - PARB (MA - 1)) /       TRPL  31
     1  (PARA (MA) - PARA (MA - 1)) + PARB (MA - 1)                     TRPL  32
      GO TO 026                                                         TRPL  33
  054 CONTINUE                                                          TRPL  34
      MB = NPR                                                          TRPL  35
      GO TO 024                                                         TRPL  36
      END                                                               TRPL  37
```

```
      SUBROUTINE ERROR (PROGRM,IRROR,ISOUT)                             ERROR  2
C     T. W. SCHWENKE                                                    ERROR  3
C     1 MARCH 1966                                                      ERROR  4
C                                                                       ERROR  5
C ***********************************************************************ERROR  6
C                                                                       ERROR  7
C     THIS PROGRAM WRITES A GENERALIZED ERROR COMMENT OF THE FOLLOWING  ERROR  8
C     FORM ON TAPE ISOUT AND THEN RETURNS IF THE SIGN OF IRROR IS       ERROR  9
C     POSITIVE OR STOPS IF ITS SIGN IS NEGATIVE.                        ERROR 10
C                                                                       ERROR 11
C         ERROR SENSED IN PROGRAM (PROGRM) AT OR NEAR STATEMENT NUMBER  ERROR 12
C         (IRROR).  PLEASE REFER TO THE PROGRAM LISTING.                ERROR 13
C                                                                       ERROR 14
C     PRIOR TO CALLING ERROR  THE PARAMETER  PROGRM  MUST BE SET        ERROR 15
C                                  WITH THE BCD NAME OF THE CALLING     ERROR 16
C     PROGRAM AND PARAMETER  IRROR  MUST BE SET WITH THE NUMBER OF THE  ERROR 17
C     FORTRAN STATEMENT WHICH BEST IDENTIFIES THE ERROR CONDITION.      ERROR 18
C                                                                       ERROR 19
C ***********************************************************************ERROR 20
C                                                                       ERROR 21
 1    FORMAT(//26H ERROR SENSED IN PROGRAM  A6,30H  AT OR NEAR STATEMENTERROR 22
     1 NUMBER I6,40H .  PLEASE REFER TO THE PROGRAM LISTING.)           ERROR 23
C                                                                       ERROR 24
C ***********************************************************************ERROR 25
C ***********************************************************************ERROR 26
C                                                                       ERROR 27
      IRR= IABS(IRROR)                                                  ERROR 28
      WRITE(ISOUT,1)PROGRM,IRR                                          ERROR 29
      IF(IRROR)101,100,100                                              ERROR 30
  100 RETURN                                                            ERROR 31
  101 STOP                                                              ERROR 32
      END                                                               ERROR 33
```

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