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WIND-WEIGHTING FACTORS FOR FALLOUT CALCULATIONS

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WIND-WEIGHTING FACTORS FOR FALLOUT CALCULATIONS

REVIEWED BY:

R. E. HARSHBARGER
Technical Director,
NMCSSC

APPROVED BY:

EMMETT GOSNELL
Colonel, USAF
Chief, NMCSSC

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ABSTRACT

Particle rate of fall, available actual wind data, and total fallout radioactivity as a function of particle size have been critically reviewed as a basis for determining wind-weighting factors (WWF). Based on recently published analyses of fallout particle data, the recalculated typical (or nominal) diameter of radioactive local-fallout particles is 137 microns. A set of WWF for calculating mean effective wind vectors has been determined for use with actual wind data in predicting the location and military significance of radioactive fallout deposition. The WWF are used with fallout models such as the Weapons Systems Evaluation Group (WSEG) model.

ACKNOWLEDGEMENTS

This study was performed by Dr. Fritz A. Hedman, Physicist, and Major Ralph C. Simmons, USAF, Advanced Weather Officer, of the Operations Analysis Division, Directorate for Development and Analysis.

The Appendix A gives empirical equations of the cumulative fall-time of nominal fallout particles as a function of elevation at the start of fall. These are based on the use of the method of least squares by Mrs. Judith R. Richards, Mathematician, of the Operations Analysis Division, Directorate for Development and Analysis.

FOREWORD

This study was undertaken as part of the program for identifying and carrying out the technological research required to support the attack hazard, vulnerability analysis, and joint war gaming functions of the National Military Command System Support Center (NMCSSC)[1].

The Department of Defense Land Fallout Prediction System (DELFIC) has been developed as a research tool, and is, of necessity, long and complex (see references 1 and 2). The NMCSSC, when performing computerized vulnerability analyses, uses, instead, a modification of the relatively simple mathematical model developed by the Weapons Systems Evaluation Group (WSEG). Calculations by means of the WSEG model, as well as calculations performed by certain army field units, are based on the effective fallout wind (see references 3 and 4). There has been no available literature on the determination and credibility of the effective fallout wind based on any specific set of wind data.

This document critically reviews the pertinent data, and presents methodology for determining the nominal radioactive fallout particle (diameter and density). The wind-weighting factors (WWF) are based on the fraction of the total particle fall-time the nominal particle spends in each wind layer above a given point on the ground.

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1 Defense Communications Agency, National Military Command System Support Center, Organization and Functions, 20 October 1966.

WIND-WEIGHTING FACTORS FOR
FALLOUT CALCULATIONS

INTRODUCTION

Discussion of Problem

General discussions of radioactive fallout deposition usually assume a constant wind velocity of 15 m.p.h. regardless of altitude. For specific situations, credible estimates of the time and place of deposition require knowledge of the length of time that particles, in the diameter range of interest, are under the influence of the wind at each applicable increment of altitude. The Department of Defense Land Fallout Prediction System (DELFIC), newly developed as a research tool (1)* uses a complex computer program to study the air transport of radioactive fallout particles. DELFIC is not designed to provide real-time predictions (2).

Certain field army units (3) and the National Military Command System Support Center must make rapid, reasonably precise estimates of radioactive fallout deposition. This requires the use of simple approximations in place of the more accurate, complex relationships. Pugh and Galiano (4) in presenting the comparatively simple WSEG Fallout Model define the effective fallout wind as an appropriate average of the winds through which a typical particle falls, without giving the size and effective density of this particle, nor its use in calculating the effective wind speed and direction.

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* Refers to Reference 1.

Equations for Particle Rate of Fall

Particle rate of fall depends upon the equilibrium between the force of gravity and the opposing effect of the resistance or drag due to the relative motion between the particles and the surrounding air. The dimensionless drag coefficient (C) and the corresponding Reynolds number (Re) are calculated from the experimentally determined rate of fall under various known conditions. Re is defined, using any consistent units, by

$$Re = DU \rho_a / \mu_a \qquad (1)$$

where D = particle diameter

U = particle free-fall velocity

ρ_a = density of air

μ_a = coefficient of viscosity of air[2]

The usual presentation of C vs. Re either in tabular form or as an irregular shaped curve is not directly usable in particle-fall calculations, because it does not give the rate of fall of a particle of predetermined size. For a given set of conditions, such as at a specific altitude in the standard atmosphere, there will be a particle diameter and corresponding rate of fall for each value of the Reynolds number, assuming fallout particles with a specific density, shape, and surface roughness. See Figures 1 and 2 (from reference 6).

For a free-falling particle of known density, ρ_p, at any point in space (of interest in local fallout calculations) with known gravitational attraction, G, and air properties (coefficient of viscosity,

2. The symbol μ and this terminology for viscosity are used in the U.S. Standard Atmosphere, 1962 (5). The same symbol is also commonly used as a unit of length ($10{,}000\mu$ = 1 centimeter). In this report, μ_a refers to viscosity of air.

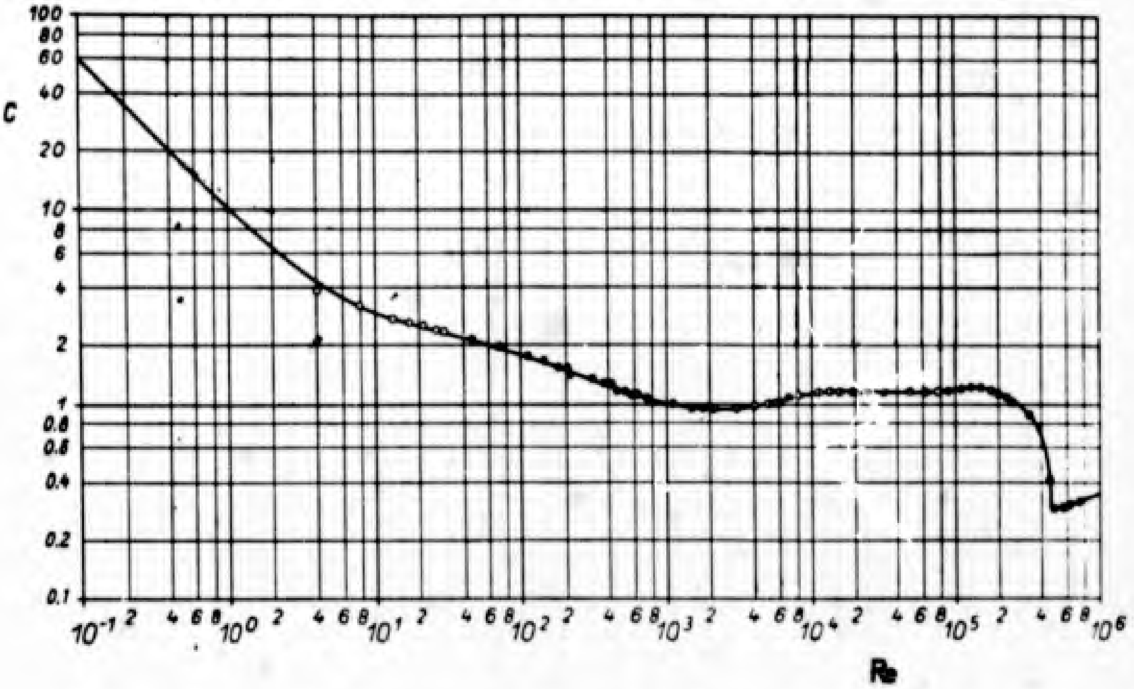

Fig. 1 Drag coefficient for circular cylinders as a function of the Reynolds number

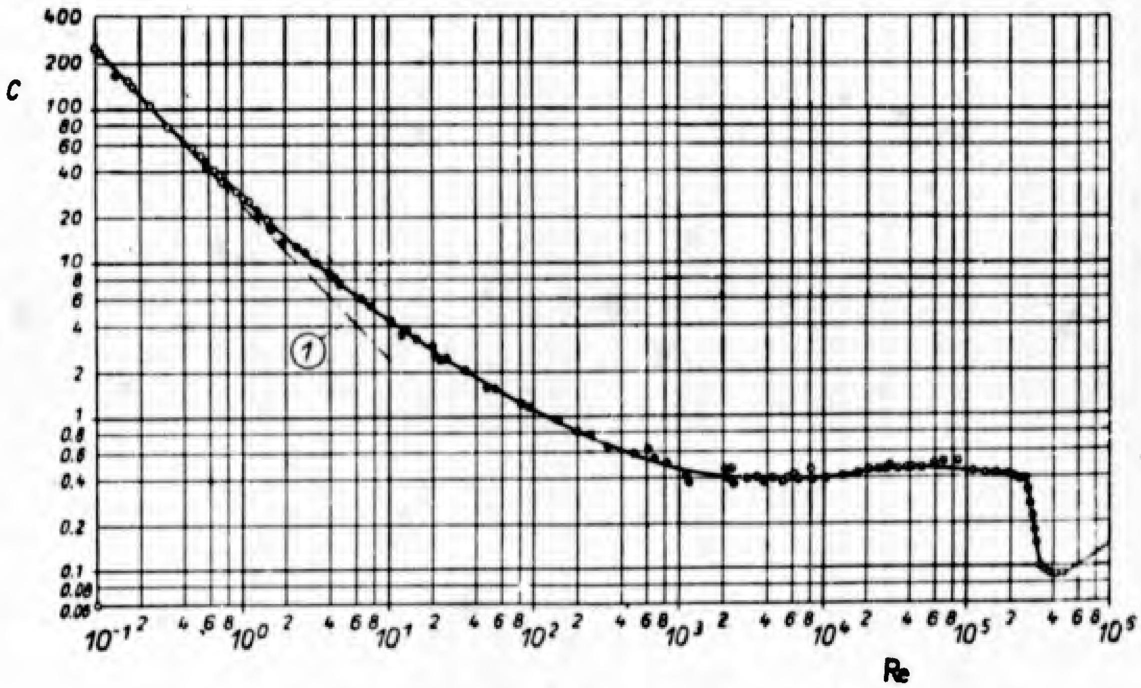

Fig. 2 Drag coefficient for spheres as a function of the Reynolds number
Curve (1): Stokes theory

μ_a, and density, ρ_a), the following equations (from reference 7) give the particle diameter and rate of fall for any specified Re and corresponding C:

$$D = (.75\ C\ Re^2\ \mu_a^2/G\ \rho_a\ \rho_p)^{1/3} \quad (2)$$

$$U = (G\ \mu_a\ \rho_p\ Re/.75C\ \rho_a^2)^{1/3} \quad (3)$$

For Re $\leq$ 0.3, falling particles obey Stokes law[3]:

$$U = B\ \rho_p D^2 \quad (4)$$

The constant B depends on the gravitational attraction and the properties of the air. Lavrenchik (8) uses Stokes law for Re $\leq$ 0.5. Stokes law gives dotted line 1 of Figure 2 (from reference 6). Note that the upper limit of Stokes law applicability depends upon the desired accuracy and/or the accuracy of the data being used. Usually equation 4 is sufficiently accurate for Re $\leq$ 1 (from reference 9).

In 1945 Davies (10) studied the available data and drafted the following equations for Re as functions of CRe^2 based on critically selected data:

$$Re = CRe^2/24 - 2.3363 \times 10^{-4}\ (CRe^2)^2 + 2.0154 \times 10^{-6}\ (CRe^2)^3 - 6.9105 \times 10^{-9}\ (CRe^2)^4 \quad \text{for } Re < 4 \text{ or } CRe^2 < 140 \quad (5)$$

$$\log Re = -1.29536 + 0.986\ (\log CRe^2) - 0.046677\ (\log CRe^2)^2 + 0.0011235\ (\log CRe^2)^3 \quad \text{for } 3 < Re < 10{,}000 \text{ or } 100 < CRe^2 < 4.5 \times 10^7 \quad (6)$$

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3 For particles with diameters of about 40μ at the top of clouds from megaton-yield weapons, the particle is small relative to the mean free path (L) between air molecules. This increases rate of fall but does not significantly affect calculations of local fallout deposition. See references 7 and 11 for functions of L/D which may be used to modify equation 4. The rate of fall of a 2-micron diameter particle at an altitude of 90,000 feet is 3.5 times that given by equation 4; near the earth's surface there is no significant deviation from equation 4.

The value of Re is found by use of equation 5 or 6 after CRe^2 has been evaluated by using equation 2 in the form

$$CRe^2 = 4\ GD^3\ \rho_p\ \rho_a /\ 3\mu_a{}^2 \qquad (2a)$$

Then the rate of fall of the particle is found by using equation 1 in the form,

$$U = \mu_a\ Re/\rho_p\ D \qquad (1a)$$

The rate of fall of any airborne particle is a function of the properties of the enveloping air, which change continuously with altitude. The Reynolds number of any falling particle is continuously increasing. The rate of fall of some radioactive particles included in local fallout would initially be calculated by use of equation 5, later by use of equation 6 (for the same particles).

The equations derived by Davies when used in a computerized fallout model, require a table which for each altitude increment of interest gives the gravitational attraction, also the viscosity and density of air. A method of determining particle fall-time between specified elevations is also required. McDonald (12) has developed a simple method of calculating particle rate of fall, using a graph by Schlichting (6) of Re vs. CRe^2, and collecting all terms involving atmospheric properties for a one-time calculation for each altitude of interest.

Lapple (13 and 14) and Schlichting (6), after independent critical analyses of the available data, in 1951 published values for Re vs. CRe^2 which differed slightly from the values obtained by Davies. Hedman and Campbell (15) derived a mathematical relationship, suitable for use in a computer, for particle rate of fall. This was based on Reynolds numbers as a function of Lapple's values of corresponding drag coefficients for the particles of unit density (1 gm/cc) falling near the earth's surface. Later this relationship was generalized for a range of particle densities and altitudes of interest in radioactive fallout calculations (7). In a computerized fallout model the latter equation would be used with auxiliary equations specific for the atmospheric conditions; there would be no requirement for storage of atmospheric data for a series of altitude increments.

The equations (7), applicable to any set of atmospheric conditions, are:

$$U = B_s \rho_p D_p^2 / D_r^x \qquad (7)$$

$$D_r = 53.17 \rho_p^{1/3} D_p / D_s' \qquad (8)$$

$$x = 0, \text{ when } D_r \leq 53.17\mu \qquad (9)$$

$$= 0.074230 (\log D_r)^2 - 0.120553 (\log D_r) - 0.013022, \text{ when}$$

$$53.17\mu < D_r \leq 800\mu$$

$$= 0.009011 (\log D_r)^2 + 0.231346 (\log D_r) - 0.483577, \text{ when}$$

$$800\mu < D_r \leq 5500\mu$$

B_s and D_s are constants dependent on atmospheric conditions, calculated by use of equations 1, 2, and 3 with Re = 0.3.

The following equations are specific for the U. S. Standard Atmosphere, 1962 (from reference 5) and give values of B_s and D_s as functions of Z, the altitude in thousands of feet (when the units of U, ρ_p, and D_p are feet/second, gm/cc, and microns, respectively):

$$B_s = 10^{-4}(0.5762 \times 10^{-4}Z^2 + 0.4938 \times 10^{-2}Z + 0.9984), \text{ for } 0 \le Z \le 36.2 \quad (10)$$
$$= 10^{-4}(0.0050 \times 10^{-4}Z^2 - 0.0165 \times 10^{-2}Z + 1.2578), \text{ for } 36.2 < Z \le 65.6$$
$$= 10^{-4}(0.0178 \times 10^{-4}Z^2 - 0.1796 \times 10^{-2}Z + 1.3593), \text{ for } 65.6 < Z \le 100$$

$$D_s = 26.92 \times 10^{-4}Z^2 + 31.67 \times 10^{-2}Z + 52.41, \text{ for } 0 \le Z \le 36.2 \quad (11)$$
$$= 106.90 \times 10^{-4}Z^2 + 28.12 \times 10^{-2}Z + 43.38, \text{ for } 36.2 < Z \le 65.6$$
$$= 185.03 \times 10^{-4}Z^2 - 62.51 \times 10^{-2}Z + 69.476, \text{ for } 65.6 < Z \le 100$$

Appendix A gives empirical equations for the cumulative fall-time of a nominal particle[4] as a function of initial altitude. Equations 1 to 9, inclusive, apply under any set of atmospheric conditions. Equations 10 and 11 and the equations in Appendix A are based on the Standard Atmosphere (5).

Table 1 shows, for altitudes of interest in local fallout calculations, the seasonal change of nominal particle rate of fall (16). The calculations were made using data for the standard atmosphere and data for the months of January and July at 45° N Latitude (17). Considering the current shortage of data needed for predicting cloud rise and particle distribution (18) equations 10 and 11 appear to be adequate for use with research models as well as with the less complex models used by the National Military Command System Support Center.

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4 These calculations are based on a spherical particle with a density of 2.35 gm/cc and a diameter of 137μ. According to an earlier definition (see reference 3) a nominal particle has a diameter of 143μ and requires 3 hours to fall to the ground from an altitude of 11,000 meters.

TABLE 1

Seasonal Change of Nominal Particle Rate of Fall

Altitude	Fall Rate		
	Summer	Standard	Winter
km	km/hr	km/hr	km/hr
5	3.37	3.43	3.47
10	3.96	4.07	4.12
15	4.62	4.66	4.68
20	5.10	5.17	5.21

Wind Data - Required and Available

Pugh and Galiano (4) give the following equation for the initial height[5] of the nominal (or typical) fallout particle as a function of weapon yield:

$$ho = 44 + 6.1 \ln Y - .205(\ln Y + 2.42) \left| \ln Y + 2.42 \right| \quad (12)$$

Where ho = height in thousands of feet

ln = natural logarithm

Y = weapon yield in megatons

Accordingly the initial height of the nominal particle from a 100-megaton weapon is about 60,000 feet, roughly the upper limit of the 100-millibar (mb) wind layer (see Table 2).

Routinely available current wind data include 36-hour forecasts for the constant pressure surfaces of 700 mb, 500 mb, 300 mb, 200 mb, and 100 mb. The average altitudes of these five pressure surfaces are given in Table 2.

5 Reference 4 uses the term "center of radioactive cloud."

The relationships developed in this report are based on the assumption that the wind velocity at each constant pressure surface is also the wind velocity throughout an altitude range extending above and below the average surface altitude. Table 2 gives for each pressure surface the corresponding altitude range or wind layer. This differs from the assumption, used in reference 3, that the wind velocity at each constant pressure surface applies throughout an altitude range extending below, but not appreciably above, the average surface altitude. If reference 3 were used, column 2 of Table 2 would give both the average altitude and the upper limit of the corresponding wind layer.

Table 2

Wind Layers for Five Wind Levels

Wind Level mb	Average Altitude ft	Wind Layer ft
700	9,882	0 - 14,086
500	18,289	14,086 - 24,177
300	30,065	24,177 - 34,364
200	38,662	34,364 - 45,873
100	53,083	45,873 - 60,293

The wind layers corresponding to each of the five wind levels were determined by use of the following assumptions:

a. The wind layer for each wind level, except 100-mb, extends upwards to an altitude midway to the next wind level; the upper limit of the 700-mb wind layer is therefore midway between 9,882 and 18,289 feet.

b. The 100-mb wind layer has the 100-mb level as its mid-altitude and extends downward midway to the 200-mb level and upward an equal distance.

Wind-Weighting Factors and Their Use

Wind-weighting factors (WWF), used with specific winds in calculating weighted wind vectors (or effective fallout wind), are based on the length of time the typical (or nominal) radioactive fallout particle is under the influence of the wind in each of five altitude increments (wind layers). As used in this report, the WWF for a given wind layer is the fraction of total fall-time the particle spends falling through that layer.

ADEQUACY OF AVAILABLE DATA

The relationships for particle rate of fall previously discussed are sufficiently accurate (18) for use with DELFIC (1) or other research models. However, for routine, repetitive use, where computer time and capacity are severely limited, the relationships given by equations 7 to 11 are preferable.

Equation 12 gives the initial height of the nominal particle as a function of weapon yield. The accuracy of calculations based on this equation may be questioned because of the shortage of data needed for predicting cloud rise and particle distribution (18). The DELFIC model is based arbitrarily on the pre-shot soil particle size distribution modified by 20% of the soil vaporizing, later condensing with concurrent agglomeration.

There is no generally accepted simple relationship between particle diameter and total associated radioactivity[6]. Considerable work related to this problem is in progress (19). Recent publications (20 and 21) describe some of the work accomplished since 1958 (22) when the nominal fallout particle had already been assigned a diameter of 143μ. In subsequent sections of this report the available pertinent data are analyzed, and the approximate diameter of the nominal particle determined. While a small change in particle diameter makes a significant change in the distance downwind that the particle travels, a change in nominal particle diameter of 20% makes only a slight change in the wind-weighting factors (24).

CRITICAL ANALYSES OF RADIOACTIVE PARTICLE DATA

Data from Airborne Samplers

A large number of radioactive cloud samples have been obtained over the years by use of various devices carried by drones, rockets, and manned aircraft. The reliability of such data depends on (a) sufficiency of cloud sampling, (b) degree of particle size bias introduced by nonisokinetic[7] flow of the sample to the collecting device, and (c) the percentage filter penetration by particles as a function of particles diameter, filtering speed, and air density.

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6 The DELFIC model makes use of the Freiling model for distribution of radioactivity with particle size, taking into account radionuclide fractionation (23).

7 When the sampling rate is subisokinetic, some air initially in the projected area upstream of the filter collector will be deflected around the collector. A nonrepresentative number of larger particles will be collected (26).

For a given filter and given conditions there is a specific particle diameter for maximal percentage filter penetration; lesser percentages of smaller and larger particles penetrate the filter. The particle diameter for maximal penetration decreases with increasing filtering speed (8 and 25). Both aerial and fallout nuclear debris samples are probably subjected to artificial agglomeration by the presently used collection devices (18).

Russell (20) studied the radionuclide composition of the particles retained by a sheet of IPC 1478 carried on aircraft during traversal of a nuclear cloud. IPC 1478 is a cellulose paper developed to retain essentially all 0.02-micron diameter particles when sampling a megaton-weapon cloud (27). However, when sampling at lower altitudes, significant percentages of this diameter and larger particles will penetrate this material (28 and 29). This is due to the reduced effect of diffusion. Based in part on a study of the portion of the airborne material retained by this filter, Russell concluded that the radioactivity associated with small particles far exceeded that generally assumed. Russell's conclusion might be too conservative because of the likelihood that part of the airborne radioactivity had passed through the filter, the percentage penetration being a function of altitude, particle size, and filtering speed. Lockhart and his coworkers (28) use a filter pack consisting of three or four sheets of filter material. The first sheet is IPC 1478. Figures 3 and 4 show that the particle retentivity by IPC 1478, as used by

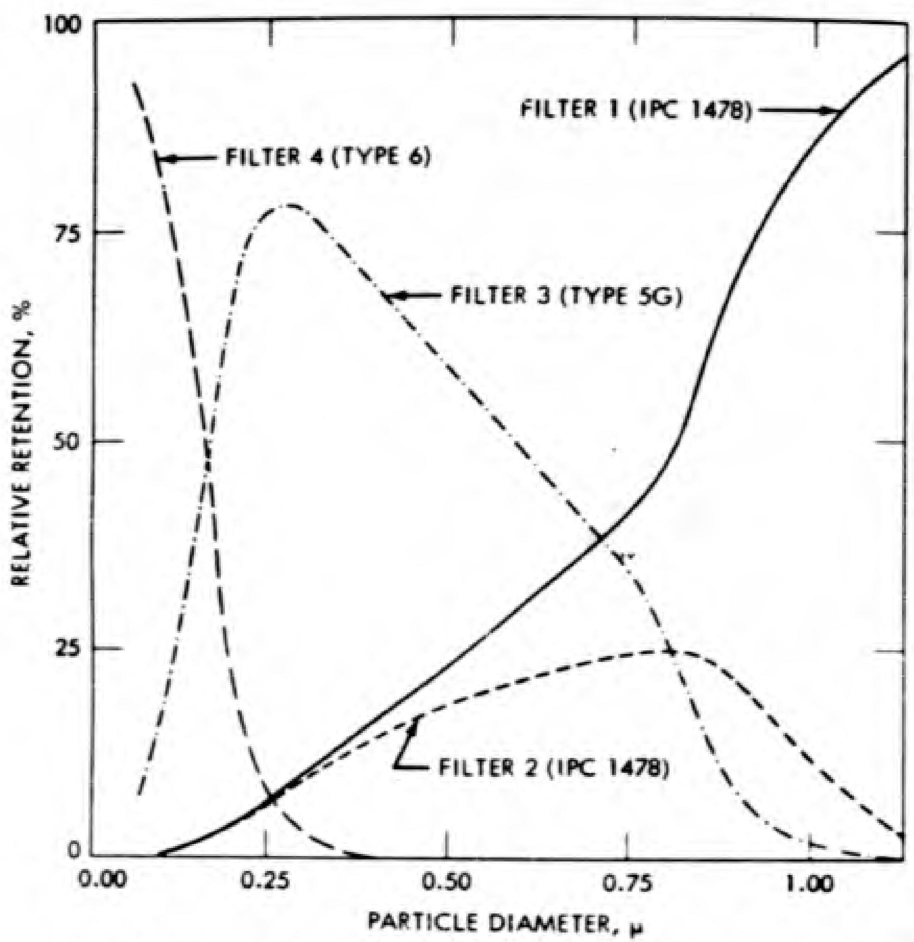

Fig 3. - Effect of size on the distribution of particles among filters in a four-filter pack (air velocity, 145 cm/sec).

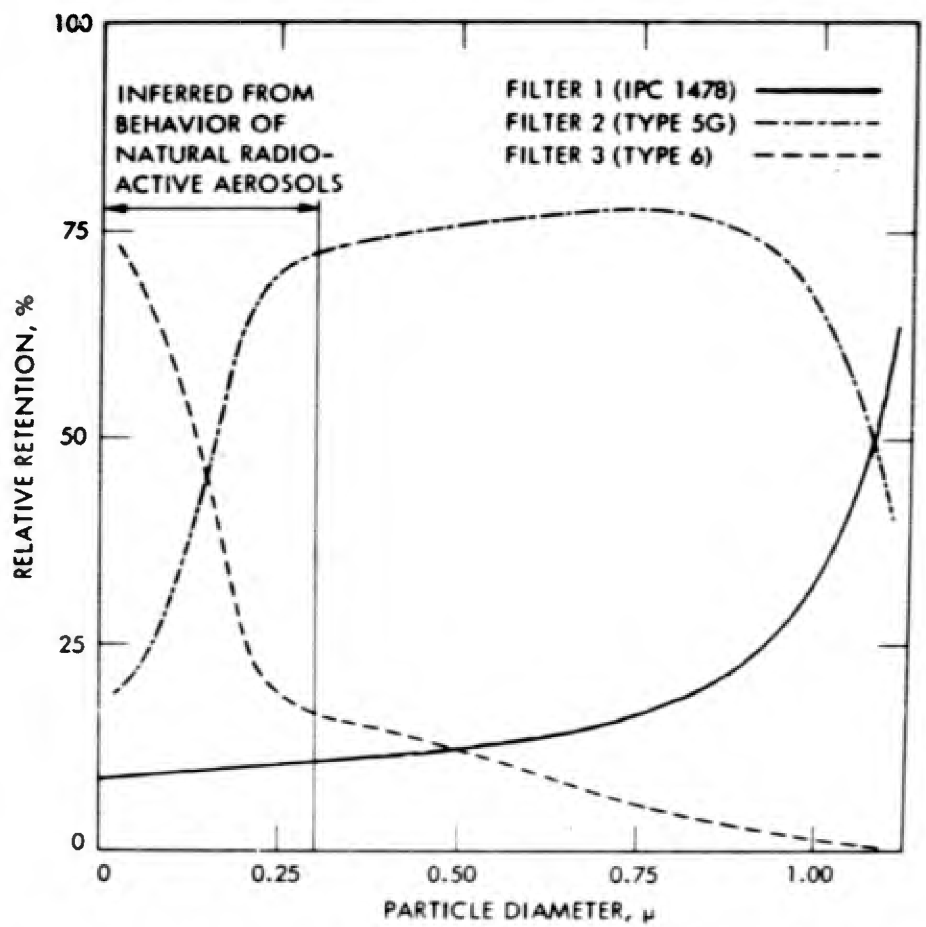

Fig 4 - Effect of size on the distribution of particles among filters in a three-filter pack (air velocity, 61 cm/sec).

Lockhart, is poor for particles having diameters less than one micron. They use cellulose-glass fiber filter material, Type 5G, to remove part of the particles passing through IPC 1478. Cellulose-asbestos fiber filter material, Type 6, which offers appreciable resistance to air flow, is used to remove essentially all particles which have passed through the preceding filters. In Figures 3 and 4, for any given particle diameter, the percentage retention by the filter pack is the sum of the percentages of retention for each filter. Lockhart and his co-workers use the filter pack to determine the particle size distribution.

Data From Fallout Trays (Local Fallout)

Russell (20) reported on a series of particle size distribution measurements made on radioactive fallout deposited in trays. The distance from the radioactive cloud to the trays was too short to permit the deposition in the trays of radioactive particles with diameters less than 50 microns. The size distribution of the radioactive particles was approximately log-normal in form, with a geometric mean particle diameter of 112 microns.

For local fallout, the NRDL Dynamic Model by the U. S. Naval Radiological Defense Laboratory (30) uses a straight line relationship between the logarithm of particle diameter and the cumulative percent residual activity. It is based on half of the activity being associated with particles having diameters larger than the 112 microns cited by Russell[8]; about two percent of the activity associated with particles larger than about 3500 microns.

Particle Diameter vs. Total Radioactivity

For ground surface bursts the radioactivity is concentrated on a relatively small proportion of the particles, mainly those that appear to have been partially melted (31). The WSEG fallout model (3) uses the simplifying assumption that the radioactivity is uniformly distributed throughout the mass of the radioactive fallout. This also ignores radionuclide fractionation[9] during radioactive fallout particle formation (20 and 21). Tetsuo Mamuro et al (32), studied samples from Chinese and Russian nuclear tests. The difference in fractionation behavior was ascribed to the fact that the former was a small-scale land-surface burst, while the latter was a large-scale airburst.

Russell (20) has shown that fallout models which ignore the effects of fractionation do not give realistic estimates of radioactive fallout deposition areas. The current state-of-the-art[10] does not

8 The WSEG model is based on a median diameter of 90 microns; other models, also not reflecting Russell's recent work, use values of 85 to 160 microns. There are NRDL-D models for bursts on coral and Nevada soil, as well as on water (33).

9 Freiling (cited in reference 32) defines fractionation as any alteration of radionuclide composition occurring between the time of detonation and the time of radiochemical analysis which causes the debris sample to be nonrepresentative of the detonation products as a whole.

10 According to Rapp (34), a complete theoretical calculation of the activity-size distribution from a complete knowledge of the conditions of the detonation does not appear feasible.

permit the translation of fractionation research data into a specific quantitative mathematical relationship suitable for use in a fallout model. Some assumptions, compatible with the pertinent physical principles, must be used. The validity of data from samples of fallout material while airborne, and later after deposition on the ground, must be checked to evaluate the effects of possible bias due to the sampling equipment and techniques being used under varying sampling speed and altitude.

ESTIMATION OF NOMINAL PARTICLE DIAMETER

Calculations presented in this report are based on a modification of the log-normal relationship of the NRDL Dynamic Model for particle diameter vs. total radioactivity. The recent work on radionuclide fractionation has shown that a very large part of the total radioactivity is associated with small particles. Estimating the effect, quantitatively, of this work, the log-normal relationship was redrawn showing half of the total radioactivity associated with particles having diameters greater than 20 microns, two percent with particle diameters greater than 1000 microns.

The fraction, F, of the total radioactivity associated with particles in a specified range of diameters can be read from a graph or calculated by use of the following equation:

$$F = \left[1/\sqrt{2\pi\sigma^2} \right] \int_{\phi_1}^{\phi_2} e^{-(\phi - \bar{\phi})^2/2\sigma^2} \, d\phi \qquad (13)$$

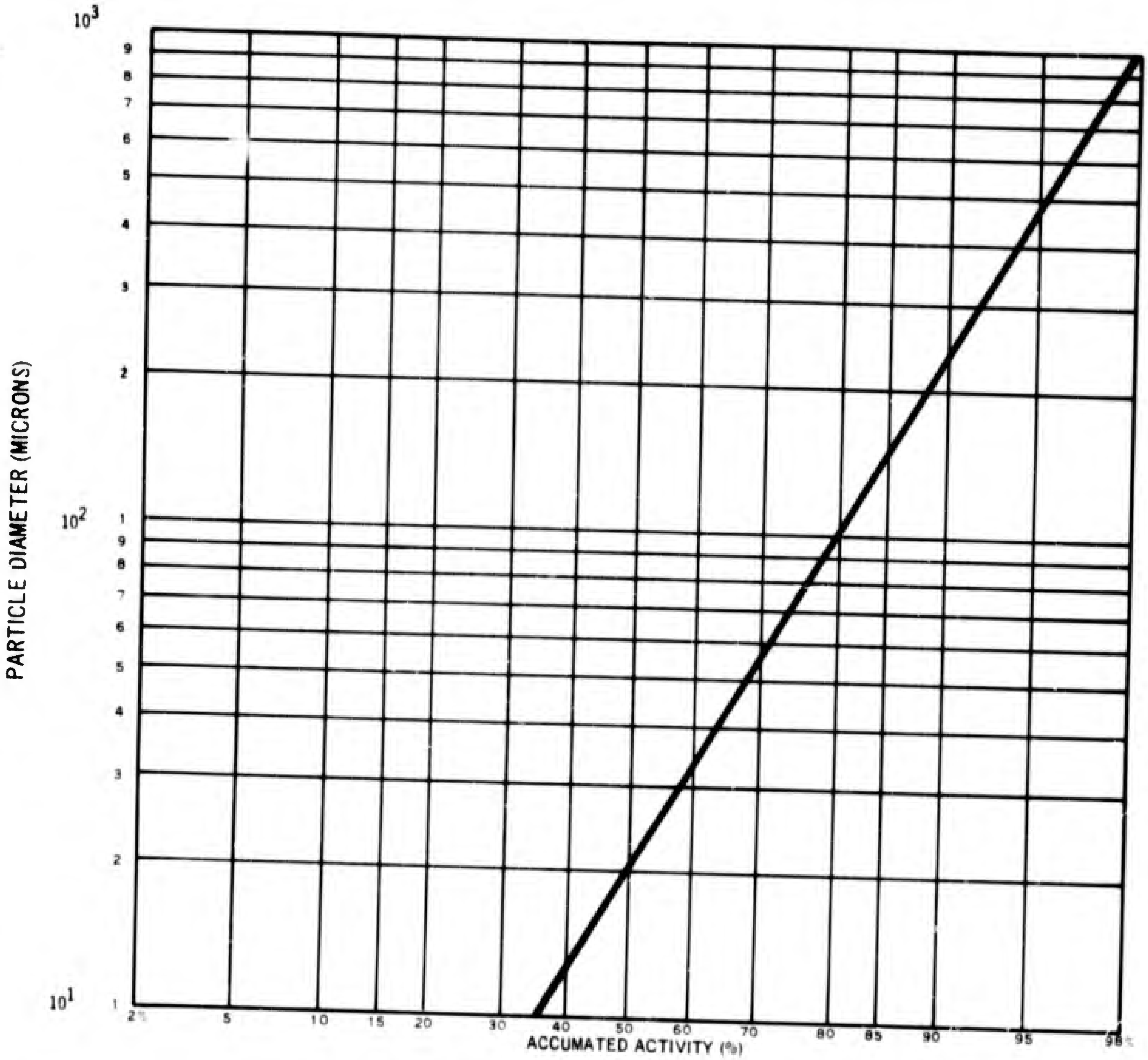

FIGURE 5. ACTIVITY DISTRIBUTION

where

ϕ = common logarithm of particle diameter

$\bar{\phi}$ = common logarithm of 20 = 1.30103

σ = standard deviation

The above equation can be evaluated by use of Hasting's approximation (from reference 35). Setting $\phi = 3$ (the logarithm of 1000) and F = .48, the value of $\sigma = 1.02662$.

By use of this approximation, the increment of total radioactivity for each 20-micron increment of particle diameter was obtained for the diameter range of 20 to 1000 microns. The corresponding nominal particle diameter is 137 microns A diameter of 149 microns was similarily obtained for the diameter range of 25 to 1000 microns. Calculations by field army units are based on a nominal particle diameter of 143 microns (3). Wind-weighting factors based on any of these three diameters would not differ significantly, because within this particle size range the slope of the curve for rate of fall versus altitude is almost independent of particle diameter (24).

NEW WIND-WEIGHTING FACTORS

These wind-weighting factors are based on the altitude increment (wind layer) corresponding to each of the five wind levels shown in Table 2, under standard atmospheric conditions (5). The WWF determined by use of summer or winter atmospheric conditions do not differ significantly from a determination based on the standard atmosphere because of the slight difference in particle fall rates (see Table 1).

The wind weighting-factors (WWF) shown in Table 3 are based on the rate of fall of a 137-micron diameter particle having an aerodynamic density of 2.35 gm/cc.

Appendix B gives the WWF used by field army units (3) and the National Military Command System Support Center (36).

TABLE 3

New Wind-Weighting Factors

Initial Altitude	WWF				
	700 mb	500 mb	300 mb	200 mb	100 mb
Ft.					
60,293	.288	.183	.167	.169	.193
45,873	.357	.227	.206	.210	0.0
34,364	.451	.288	.261	0.0	0.0
24,177	.611	.389	0.0	0.0	0.0
14,086	1.0	0.0	0.0	0.0	0.0

MODIFICATION OF CURRENT COMPUTER PROGRAM

Equations 14 to 18 show the use of the new WWF. Specific wind data, such as the 36-hour-forecast wind velocity, at each wind level is resolved into east-west (V_x) and north-south (V_y) components. For a nominal particle starting at 60,000 ft., equation 14 is first used with the V_x values of the winds to obtain the effective east-west component, $\bar{V}_x$; equation 14 with north-south components give $\bar{V}_y$. Equations 15-18 are used similarly for particles starting at lower altitudes. The initial height of the particle, h_o, in thousands of feet, is obtained by using equation 12 for a series of specified weapon yields.

For $h_o = 60$,

$$\bar{V}_x = .289V_{x,700} + .184V_{x,500} + .167V_{x,300} + .170V_{x,200} + .190V_{x,100} \quad (14)$$

For $h_o = 40$,

$$\bar{V}_x = .398V_{x,700} + .254V_{x,500} + .231V_{x,300} + .117V_{x,200} \quad (15)$$

For $h_o = 30$,

$$\bar{V}_x = .506V_{x,700} + .323V_{x,500} + .171V_{x,300} \quad (16)$$

For $h_o = 20$,

$$\bar{V}_x = .724V_{x,700} + .276V_{x,500} \quad (17)$$

For $h_o = 10$,

$$\bar{V}_x = 1.000V_{x,700} \quad (18)$$

In these equations $V_{x,700}$, $V_{x,500}$, $V_{x,300}$, $V_{x,200}$, and $V_{x,100}$ are the east-west components of the wind velocities at 700-mb, 500-mb, 300-mb, 200-mb, and 100-mb levels, respectively, when determining $\bar{V}_x$. The corresponding north-south components are used when determining $\bar{V}_y$.

The effective wind, $\bar{V}$, for use in the WSEG fallout model is given by

$$\bar{V} = (\bar{V}_x^{\,2} + \bar{V}_y^{\,2})^{\frac{1}{2}} \quad (19)$$

The direction, θ, in degrees, of $\bar{V}$ is given by

$$\theta = \arcsin\,(\bar{V}_x/\bar{V}) \quad (20)$$

Large-scale nuclear attack vulnerability analyses were made under an arbitrarily chosen set of realistic conditions, using equations 14 to 18. The results were compared with analyses made under the same conditions, using the currently accepted WWF shown in Appendix B. The Resource Status Evaluation System (REST) model, as used by the National Military Command System Support Center, showed differences in the geographical distribution of fallout casualties. Using the new WWF resulted in an indicated 3% increase in population at risk, but a 7% decrease in casualties. These differences are not significant when considering the continental United States as a whole. Use of either set of WWF showed casualties at locations not shown when using the other set. In many cases, for a given population cell, there was a sizeable difference in the indicated number of casualties. Consequently, casualty estimates for sub-divisions of the United States might differ significantly when changing from one to the other set of WWF.

SUMMARY

Particle rate of fall, available actual wind data, and total fallout radioactivity as a function of particle size have been critically reviewed as a basis for determining wind-weighting factors (WWF). A set of WWF for calculating mean effective wind vectors has been determined for use with 700-mb, 500-mb, 300-mb, 200-mb, and 100-mb level actual wind data in predicting the location and military significance of radioactive fallout deposition, based on the calculated diameter of the typical or nominal radioactive fallout particle.

According to Army TM 3-210, dated May 1962, fallout estimates by field army units are based on a particle diameter of 143 microns. There is no indication of how this diameter was determined. Much pertinent data have become available since that particle diameter determination. Based on recently published analyses of fallout particle data, the recalculated typical (or nominal) diameter of radioactive local-fallout particles is 137 microns (no significant change).

Although the distance that particles travel downwind is sensitive to changes in particle diameters, a 20% change in nominal particle diameter does not significantly change the WWF. The WWF being presented are based on a credible assignment of altitude range for each wind level. By means of these WWF, multi-level wind data are combined to give the speed and direction of the effective fallout wind needed for the WSEG Fallout Model.

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GLOSSARY OF SYMBOLS

B_s	Stokes constant for particles of unit density (1 gm/cc)
C	Drag coefficient
D	Particle diameter
D_p	Particle diameter in microns
D_r	Relative particle diameter (See equation 7)
D_s	Particle diameter in microns when Re = 0.3 and $\rho_p = 1$
F	Fraction of the total radioactivity associated with particles in a specified range of diameters
G	Gravitational attraction
L	Mean free path of molecules in microns
Re	Reynolds number, dimensionless
T	Particle descent time in hours
U	Particle rate of fall
V	Wind velocity
$\bar{V}$	Effective wind velocity
V_x	Wind speed in east-west direction
$V_{x,700}$	Wind speed in east-west direction at 700-mb level
V_y	Wind speed in north-south direction
x	Function based on the Re-C relationship (See equation 7)
Z	Geometric altitude in thousands of feet
μ	Micron (10^{-6} meter)
μ_a	Coefficient of air viscosity[2]

2 See page 2 of text.

ρ_a	Density of air in gm/cc, unless specified[11]
ρ_p	Density of particle in gm/cc, unless specified
ϕ	Common logarithm of particle diameter
$\bar{\phi}$	Common logarithm of 20 = 1.30103
σ	Standard deviation
θ	Direction, in degrees, of effective wind velocity

11 In this study, milliliters (ml) and cubic centimeters (cc) may be used interchangeably.

APPENDIX A

Cumulative Fall-time of Nominal Particles

The data in Table A1 are based on the free-fall of spheres, having a diameter of 137 microns and a density of 2.35 gm/cc, falling through the standard atmosphere.

The following set of empirical equations is based on the data in Table A1 and gives time (T) as functions of altitude (Z):

$$T = 10.337 \; (Z/100) - 4.395 \; (Z/100)^2 \quad \text{for } 0 < Z \le 35 \qquad \text{(A1)}$$

$$T = 0.157 + 9.40 \; (Z/100) - 3.0 \; (Z/100)^2 \quad \text{for } 35 < Z \le 48 \qquad \text{(A2)}$$

$$T = 0.305 + 8.71 \; (Z/100) - 2.2 \; (Z/100)^2 \quad \text{for } 48 < Z < 65 \qquad \text{(A3)}$$

$$T = 0.756 + 7.31 \; (Z/100) - 1.11 \; (Z/100)^2 \quad \text{for } 65 \le Z \le 89 \qquad \text{(A4)}$$

$$T = -0.389 + 9.74 \; (Z/100) - 2.396 \; (Z/100)^2 \quad \text{for } 89 < Z < 101 \qquad \text{(A5)}$$

$$T = 1.714 + 5.519 \; (Z/100) - 0.278 \; (Z/100)^2 \quad \text{for } 101 \le Z \le 120 \qquad \text{(A6)}$$

TABLE A1

Cumulative Fall-Time vs. Altitude

Altitude 10^3 Ft.	Time Hrs.	Altitude 10^3 Ft.	Time Hrs.	Altitude 10^3 Ft.	Time Hrs.
1	0.103	41	3.506	81	5.949
2	0.205	42	3.576	82	6.004
3	0.307	43	3.644	83	6.058
4	0.407	44	3.712	84	6.113
5	0.506	45	3.780	85	6.167
6	0.605	46	3.847	86	6.222
7	0.703	47	3.913	87	6.276
8	0.799	48	3.980	88	6.329
9	0.895	49	4.045	89	6.383
10	0.990	50	4.110	90	6.437
11	1.084	51	4.175	91	6.490
12	1.178	52	4.239	92	6.543
13	1.270	53	4.303	93	6.596
14	1.361	54	4.367	94	6.649
15	1.452	55	4.430	95	6.702
16	1.541	56	4.493	96	6.754
17	1.630	57	4.555	97	6.805
18	1.718	58	4.617	98	6.855
19	1.805	59	4.678	99	6.905
20	1.891	60	4.739	100	6.955
21	1.976	61	4.800	101	7.005
22	2.061	62	4.860	102	7.054
23	2.144	63	4.920	103	7.104
24	2.227	64	4.979	104	7.153
25	2.309	65	5.038	105	7.203
26	2.390	66	5.097	106	7.252
27	2.470	67	5.155	107	7.301
28	2.549	68	5.213	108	7.351
29	2.628	69	5.272	109	7.400
30	2.705	70	5.329	110	7.449
31	2.782	71	5.387	111	7.498
32	2.858	72	5.444	112	7.547
33	2.933	73	5.501	113	7.596
34	3.007	74	5.558	114	7.645
35	3.080	75	5.614	115	7.694
36	3.153	76	5.671	116	7.743
37	3.225	77	5.727	117	7.792
38	3.296	78	5.783	118	7.840
39	3.367	79	5.838	119	7.889
40	3.437	80	5.894	120	7.937

APPENDIX B

Currently Used Wind-Weighting Factors

Field army units (3) use the wind-weighting factors* shown in Table B1. These are based on a nominal radioactive fallout particle with a diameter of 143μ which falls to the ground from 11,000 meters in three hours. For a spherical particle with an aerodynamic density of 2.35 gm/cc, equations 7, 8 and 9 give substantially this rate of fall in the standard atmosphere. Equations 10 and 11 are applicable. Tables 2 and B1 show a significant difference in the altitude increment (wind layer) arbitrarily assigned to each wind level.

TABLE B1

Wind Layers and WWF Used by Field Army

Wind Level	Wind Layer	Time in Layer	WWF**
mb	10^3 Ft.	Hrs.	
850	0-5	.51	.125
700	5-10	.46	.113
500	10-18	.68	.167
300	18-30	.92	.227
100	30-53	1.51	.370

* Due to a difference in definition, the wind-weighting factors in Table B1 correspond to, but are not numerically equal to, those found in reference 3.

** Use these WWF for a nominal particle starting at 53,000 ft.

Use of equation 12 with five representative nuclear weapon yields gives five corresponding initial heights of nominal diameter particle.

Table B2 gives the five sets of WWF, a set for use with each initial height given by equation 12, as used by the National Military Command System Support Center. This table was included in a 1962 publication (36) without indicated source or method of determination. However, the WWF in this case are in agreement with the following assumptions:

a. The effective wind acting on particles falling through the lowest 10,000 ft. wind layer has approximately three-fourths of the velocity of wind at the 700-mb level.

b. Particles starting above the tropopause (about 40,000 ft) fall very rapidly, then fall at a much reduced rate (about a third as fast) between 40,000 ft. and 30,000 ft. This is based on an early nuclear effects supposition, later disproved by fallout deposition data.

TABLE B2

Wind Layers and WWF Used By NMCSSC

Initial Height of Particle	Wind Weighting Factors for 5 Wind Levels				
	700mb	500mb	300mb	200mb	100mb
10^3 Ft.	(0-10)*	(10-20)	(20-30)	(30-40)	(40-60)
60	.265	.180	.160	.205	.130
40	.359	.245	.215	.100	----
30	.454	.305	.140	----	----
20	.627	.235	----	----	----
10	.740	----	----	----	----

* Wind layer in thousands of feet corresponding to each wind level

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13. ABSTRACT

Particle rate of fall, available actual wind data, and total fallout radioactivity as a function of particle size have been critically reviewed as a basis for determining wind-weighting factors (WWF). Based on recently published analyses of fallout particle data, the recalculated typical (or nominal) diameter of radioactive local-fallout particles is 137 microns. A set of WWF for calculating mean effective wind vectors has been determined for use with actual wind data in predicting the location and military significance of radioactive fallout deposition. The WWF are used with fallout models such as the Weapons Systems Evaluation Group (WSEG) model.

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