A FALLOUT FORECASTING TECHNIQUE WITH RESULTS OBTAINED AT THE ENWETOK PROVING GROUND

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by

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ABSTRACT

A generalized fallout forecasting technique is presented with detailed computations of input parameters which were used at the Eniwetok Proving Ground.

Results obtained at a recent weapons test are briefly discussed by comparison of forecast fallout with preliminary measured data.

SUMMARY

The Problem

A fallout forecasting technique is needed to qualitatively describe the fallout hazard resulting from nuclear detonations. This technique should have such flexibility that its employment is valid for field use.

Findings

A summary of the latest experimental and theoretical considerations has resulted in the development of a technique whose complexity is dependent on the required accuracy of the results desired. Such a technique has been satisfactorily tested at the Eniwetok Proving Grounds for land surface and water surface bursts.
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**ADMINISTRATIVE INFORMATION**

This work was done under Bureau of Ships Project No. NS 011.021, Subtask 1, Technical Objective AW-7, as described in U.S. Naval Radiological Defense Laboratory Annual Progress Report (DD Form 612) to the Bureau of Ships, July 1956.

The fallout studies were made at Operation REDWIND, Project 2.6.3, as described in DD Form 613, NS 788-001, Subtask 4B, Em3 (1) to CO USNRDL Secr No 3-920-335 Ser 004173 of 16 March 1956.

The work also is part of the technical program for the Department of the Army established between Department of the Army, Office, Chief of Research and Development, and Bureau of Ships (Joint Agreement, 23 November 1955).

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INTRODUCTION

Fallout research continues to seek a theoretical working model that will describe in detail the mechanism of fallout. Aside from this long-range problem, consideration must be given to making available a working tool that will meet the needs of the military for solving fallout problems in the field. Such consideration requires a simplified rapid system capable of producing qualitative if not quantitative results.

Within a program studying fallout as a recent weapons test operation there was a fallout forecasting assignment that had many aspects of the practical field problem yet, at the same time, required quantitative results for use in reducing other data. This program needed position data such that three ships could be located properly in the fallout to obtain data on its parameters. Also, aerial and oceanographic survey projects required knowledge of the fallout to instigate their navigational procedures properly.

To meet these requirements a technique for rapid fallout forecasting was developed which not only satisfied the needs of the fallout program but also was accurate enough to allow comparison between the meteorological aspects of model work and the results obtained from surface measurements. This technique was restricted to describing quantitatively the perimeter of the fallout, the axis of the "hot line," and to determining the time of arrival of fallout throughout the pattern. No attempt was made to quantitate the expected levels of gamma activity or to develop radiation contour lines.

At this operation the Task Force employed a fallout prediction unit for determining the safe time to detonate the test devices. Although many of their techniques for forecasting were similar to those described in this report, their problem was of a different nature than that of the fallout program. Several of their methods were unique in that portable analog computers were tested as field instruments. These computers permitted consideration of complex parameters. One, in particular, obtained essentially an instantaneous solution to the problem once the meteorological data were available.
The fallout program and the Task Force prediction unit functioned independently. It was not feasible for the two to employ the same technique because the post shot variability of the winds aloft were especially critical in fire location problems of the fallout program. This problem will be discussed in detail later.

1.1 Objective

This report describes a technique for forecasting fallout employed at a recent weapons test operation. The results obtained in the field are discussed as examples of the reliability of the technique. Although the technique was designed for analysis of land surface detonations where the fallout is particulate, its application to water surface detonations is considered.

2 FORECASTING TECHNIQUE

The forecasting technique uses many ideas from fallout model work. Several simplifications, as well as a plotting device, have been developed to the end that the time involved has been reduced greatly without sacrificing accuracy. In general, an initial source of activity is defined in describing the “stabilized” nuclear cloud by appropriate spatial and size distributions of radioactive particles. These particles are tracked to the earth’s surface by considering their falling speeds and effects of the winds existing aloft.

2.1 Basic Considerations

In some cases the input parameters for the forecasting technique were obtained from weapons test measurements. In others, where data were lacking, the parameters were derived from theory.

2.1.1 Source Model

The optical or visible dimensions of the initial cloud from a nuclear detonation have been documented in past weapons tests. Available data describe such parameters as height to top of mushroom, height to top of mushroom, and mushroom diameter as functions of time. Vertical rise stabilizes in approximately 6 min post detonation. This time is independent of yield however, the expansion of the mushroom diameter, particularly for the megaton devices, continues for perhaps 30 min. Available diameter measurements have not been made in excess of Ht10 min, however fairly reliable data are known for the optical cloud dimensions as functions of yield to Ht10 min. The ultimate cloud diameter can be extrapolated from low yield curves and some qualitative data. Figures 1 and 2 present values of the cloud dimensions from past tests. The source model was assumed cylindrical having, for a given yield, these dimensions. Its stem diameter was taken as 10 percent of mushroom diameter.

2.1.2 Activity Distribution in Source Model

The greater part of the activity was assumed to be concentrated in the lower two-thirds of the mushroom. The lower two-thirds of the stem was ignored; the remainder of the stem and upper two-thirds of the cloud were weighted lightly. This description (Fig. 3) of the activity distribution within the cloud appeared most reasonable in the light of available data and logical theoretical considerations. The activity was concentrated nearer the axis of symmetry of the cloud than at its outer edges.

2.1.3 Particle Size Distribution in Source Model

All particle sizes were assumed at all elevations within the cloud except the lower two-thirds of the stem. However, to obtain agreement with past fallout measurements and with the optical diameter of the mushroom, it was necessary to fractionate the particle size distribution radially within the cloud. Otherwise the computed fallout area about ground zero would be too large. The fractionation was specified as follows: particles of 1000 microns in diameter and larger were restricted to the inner 10 percent of the mushroom radius; those from 500 to 1000 microns in diameter were limited to the inner 50 percent of the cloud radius. Since the relation of activity to particle sizes is some direct function of the particle diameter, this fractionation tends to concentrate the activity about the axis of symmetry of the cloud.

2.1.4 Particle Falling Speeds or Settling Rates

Computations of the terminal velocities of the particles were based on aerodynamic considerations for a still atmosphere having temperature and density distributions typical of the Marshall Islands atmosphere in the spring months.

Experimental data from past tests at Eniwetok Atoll indicated that the particles were irregular in shape and had a mean density of 3.16 g/cc.

* Unpublished data from a recent weapons test.
It can be shown that particles falling at their terminal speed experience three types of flow in a fluid: streamline or laminar flow where viscous forces predominate ($10^{-5} \leq R_e \leq 2.0$); intermediate flow where inertia forces predominate ($2 \leq R_e \leq 500$); and turbulent flow where inertia forces predominate ($500 \leq R_e \leq 10^5$). Below a Reynolds number of $10^{-4}$ certain corrections must be applied to the equations because the particle diameter approaches the mean free path of the fluid medium; the region above a Reynolds number of $10^4$ is important only in ballistics. These limiting cases will not be discussed here.

The parameters actively affecting a particle's falling speed are: its weight, its drag coefficient, its density, as well as the fluid density and fluid viscosity.

Most empirical equations developed in past experimental work have been for spheres dropped in various liquids. Some work has been done on irregular-shaped particles and some done in wind tunnels. The equations used to determine the falling rates for particles in a fluid medium follow.

For streamline motion, $10^{-4} \leq R_e \leq 2.0$

$$v_t = K_t \left( \frac{\rho_0}{\rho} \right) \left( \frac{d}{\rho} \right)^{1/2}$$

where

- $v_t =$ terminal velocity in cm/sec
- $\rho =$ particle density in gm/cm$^3$
- $\rho_0 =$ fluid density in gm/cm$^3$
- $d =$ particle diameter in cm
- $a =$ absolute viscosity of fluid in poises
- $K_t =$ constant incorporating gravity
  - = 54.5 for spheres
  - = 36.0 for irregular-shaped particles.

The limiting diameter to which Eq (1) holds is:

$$d^* = \left( \frac{36 \mu}{g \rho_0 \rho} \right)^{1/2}$$

for spheres and

$$d^* = \left( \frac{36.4 \mu}{g \rho_0 \rho} \right)^{1/2}$$

for irregular-shaped particles.

For intermediate motion, $2.0 \leq R_e \leq 500$

$$v_t = K_1 \left( \frac{\rho_0}{\rho} \right) \left( \frac{d}{\rho} \right)^{1/4}$$

where

- $d_0 = d - 0.7 d^*$
- $\bar{f} = 0.4$ for spheres
- $\bar{f} = 0.279$ for irregular shapes
- $d^* =$ limiting diameter to which streamline motion applies
- $K_1 =$ 30.6 for spheres
  - = 19.0 for irregular-shaped particles.

The limiting diameter to which the Eq (2) holds is:

$$d^* = 43.5 \left( \frac{\rho_0}{\rho} \right)^{1/2}$$

for spheres

$$d^* = 51 \left( \frac{\rho_0}{\rho} \right)^{1/4}$$

for irregular-shaped particles.

For turbulent motion, $500 \leq R_e \leq 10^4$

$$v_{\infty} = K_T \left( \frac{\rho_0}{\rho} \right)^{1/2}$$

where

- $K_T =$ 54.0 for spheres
  - = 50.0 for irregular-shaped particles.

These equations were taken from Ref 1, however, certain constants have been re-evaluated.
The average falling rate for a group of irregular-shaped particles of a given size will be given by the equations. However, individual particles of the group may deviate from this average.

2.1.5 Marshall Islands Atmosphere

Marshall Islands atmospheric conditions determined the values for the density and viscosity parameters used in computing particle falling rates. Available data on the temperature, pressure, density and viscosity as functions of altitude for the atmosphere common to the Marshall Islands area in the spring months follow.

It was not possible to use a "standard atmosphere" in this problem because such use introduced a large error in the particle falling rate at high altitudes. This error originates primarily because an isothermal layer is assumed above the tropopause in the standard atmosphere—an unrealistic assumption.

Temperature Distribution. From the weather data published by Task Force Weather Central (Operation CASTLE), four published radiosonde runs obtained temperature measurements to high altitudes:

1 March 1954 0600 M Bikini
27 March 1954 0600 M Bikini
7 April 1954 0620 M Bikini
26 April 1954 0610 M Bikini

No data were available above 67,000 ft. Fortunately two of these runs penetrated the tropopause which was located at approximately 55,000 ft. To extend the measured data beyond 67,000 ft, climatological averaged for latitude 12°N were employed. Agreement with measured data was satisfactory except for the range from 50,000 to 55,000 ft where the climatological data indicated a well-defined isothermal layer. The most significant finding from the measured data was the complete lack of an isothermal layer above the tropopause. Instead, a distinct and rapid inversion was observed which, when extrapolated as a straight line, agreed with the climatological data above 70,000 ft. Since the atmosphere was to be defined to 120,000 ft, further extrapolation was necessary. Temperature data available at these higher altitudes were taken by rockets over White Sands, New Mexico. A plot of three points from the rocket data justified to some extent a continued extrapolation of the curve to 120,000 ft.

Therefore the profile of the vertical temperature gradient (Fig. 4) was based on measured data to 67,000 ft and extrapolated to 120,000 ft on the basis of supporting climatological data and temperature measurements made at high altitudes with rockets.

Pressure Distribution. Published high altitude measurements of the pressure distribution were obtained on two occasions at Operation CASTLE. These measurements made at Bikini on 7 April 1954 and on 26 April 1954, were not taken above 67,000 ft. Below this altitude the pressure was extrapolated as a straight line on semi-log paper to 120,000 ft. Agreement with published rocket data from White Sands, New Mexico was good to 50,000 ft (Fig. 5).

Density Distribution. The density distribution of the atmosphere (Fig. 6) was calculated from the perfect gas law using the above pressure and temperature distributions,

\[ \rho = \frac{P}{RT} \]

where the gas constant was taken for dry air. The assumption of no moisture in the mixture introduces an error of several percent in the lower layers of the atmosphere where the relative humidity is high. However, this assumption can be safely neglected. Also, the latest theories on the composition of the atmosphere indicate it to be constant to altitudes above 150,000 ft which justified the assumption of a non-varying gas constant.

Viscosity Distribution. The variation of absolute viscosity with altitude was computed from the observed temperature distribution using Sutherland's formula,

\[ \mu = \frac{\mu_0}{\left( \frac{T_0 + 114}{T + 114} \right)^{\frac{T}{T_0}}} \]

\[ \mu = 0.00769 \frac{387.17}{(T_0 + 114)^{\frac{T}{273.17}}} \]

where \( T \) = temperature in degrees Kelvin and \( \mu \) is viscosity in centipoises. These data are plotted in Fig. 7.

\[ \text{Fig. 7. U.-13 Operations Memo No. 14, 30 April 1954.} \]
The data on pressure, temperature, density, and viscosity in 1000-ft intervals to 120,000 ft are summarized in Table 1.

2.1.6 Terminal Velocity Computations

The average falling speed through 5000-ft layers was computed for four particle sizes over an altitude range from 0 to 120,000 ft. In these computations, all in-flight transition of the particles from streamline to intermediate flow had to be considered through use of the plot shown in Fig. 8.

Four particle sizes (75, 100, 200, and 350 µ diameter) were employed since there was evidence from past tests that the 75-µ particle defined the limiting distance of fallout of interest and the larger sizes best described the pattern within this limit. Table 2 presents the falling speeds computed for the four sizes. Tables 3, 4, 5, and 6 display the cumulative distance of fallout from a given altitude for these particle diameters.

2.1.7 Meteorological Procedures

It is necessary to have available the best possible description of the winds aloft in order to determine the arrival points of particles of various sizes originating at various altitudes. Such data are usually available from the normal upper air soundings routinely taken by Weather Bureau and Military Meteorological stations. Although wind velocity at a function of height varies continuously, it can be described by an average speed and direction in discrete layers. Such averaging can best be obtained from the WIND-20 Form where the original data are recorded. The technique employed in this report was to divide the atmosphere into layers 5000 ft thick and determine an average speed and direction for each layer. When the average falling speed of particles through these 5000-ft layers and the speed and direction of the wind are known, horizontal displacement can be computed. Thus, for each particle size a vector may be drawn for the average particle displacement in a particular 5000-ft layer. Addition of such vectors from all layers described the trajectory projection of a particle of given size. Similar plotting for all particle sizes originating at all elevations within the cloud source will map the fallout on the earth’s surface.

This technique is invalid for any atmosphere that has negligible vertical motion and is in a steady state condition with respect to the horizontal winds during the time needed for the slowest particle to fall from the highest altitude to the ground. Such an assumption is not realistic for situations arising from many of the megaton devices because 15 to 20 hr are necessary to establish the fallout area. Consequently, when computing particle trajectories, an attempt should be made to consider how the wind varies with time and how it varies with distance from ground zero; what effect vertical motions have on particle falling speeds and how they vary with space and time. Such considerations complicate computation of trajectories extremely. In most cases valid input data describing these variables are not available. This phase of the problem is discussed below.

2.2 Plotting Technique

The use of “particle-sizes” and “height” lines in mapping fallout is a standard technique employed by most analytical methods. This technique simply describes a grid (Fig. 9) on the earth’s surface indicating where fallout particles of certain sizes will arrive and from what altitude they came. These parameters are the basic data for describing the fallout pattern.

Assuming steady state meteorological conditions without vertical motion or space variation of the winds, it is very easy to construct a grid describing arrival points on the earth’s surface for particles of various sizes originating at different altitudes. This grid is constructed by ignoring the horizontal distribution of particles in the cloud model and by plotting those trajectories that originate along the line source describing the vertical axis of the cloud.

Plotting trajectories for each particle size at every starting elevation is the first step in determining the resultant fallout pattern; however, the drafting involved is tedious and time-consuming. This effort can be reduced greatly by plotting from the ground up, as is done in the construction of a wind hodograph. Such a plot is made by starting at ground zero and working up through the altitude increments to the desired elevation. Although this technique does not plot the trajectory of the particle, it does define the arrival points on the surface of the earth of particles starting at each altitude increment (Fig. 10). To plot these size-lines one must make the preliminary computations of particle-falling times through each altitude increment to obtain the displacement for various wind velocities as described earlier in the Section on Terminal Velocity Computations (p 8).

A plotting device (Fig. 11), described elsewhere, facilitates the computations required for the size-lines of the fallout pattern. Such devices were constructed for four particle sizes: 75, 150, 200, and 350 µ in diameter. With these plotters, trajectories or size-lines can be plotted from an elevation up to 120,000 ft for the four particle sizes. The plotters automatically account for the variable particle falling speed. They also eliminate the need for drafting equipment. After establishing the particle arrival points by either the use of size-lines or trajectories, height lines can be constructed. These lines, joining
surface zero with the arrival points of all particles from the same elevation, are most descriptive for they define the path along which all particle sizes will deposit from that originating altitude.

The height lines describing the fallout from the lower portion of the mushroom immediately establish the "hot line." The "hot line" is best defined as that portion of the fallout area wherein the highest levels of activity are found relative to the adjacent areas. Under most meteorological conditions this area is described by a line from surface zero that coincides with the height lines from the altitude layers that include the base of the mushroom for the source model it was so defined to concentrate the activity in this volume.

Since the plotted grid of size-lines and height-lines was based on a source of activity, each particle path must be expanded to the appropriate cloud or stem diameter from which it originated. The expansion, after taking into consideration the radial particle size fractionation in the source model, defines the perimeter of the area. One then has a map indicating the fallout area and the path of expected highest activity.

Curves of time of arrival of fallout through the pattern are established by simply assigning the appropriate value of falling time to each expanded circle about the arrival points and by constructing from this network of value iso-time contours that indicate the earliest time at which fallout will arrive at a given distance from the shot point. Similarly, the determination of the time of cessation of fallout at any location may be plotted. However, one is faced with the question of how to define cessation. Very small particles that do not contribute significantly to the radiation field continue to arrive for days after zero. Consequently, a plot which describes time-to-peak activity seems more meaningful. During the field operation time-to-peak activity was defined as the time of arrival of fallout particles originating in the lower third of the mushroom.

This method determines the fallout plot under conditions that do not include all important meteorological variables. In this sense it is most valid for a fallout of short duration and over a relatively small area, for example, a 1-KT surface detonation. Megaton devices and large KT yields deposit primary fallout over long periods and to great distances. To map such extensive deposition of fallout necessitates inclusion of complex meteorological variables and consideration of the fact that clouds from these large detonations extend to great heights in the atmosphere.

* A recent study of available data indicates that the time-to-peak activity can be excellently defined as twice the time of arrival.
from surface zero, the ideal situation would be to take winds-aloft measurements throughout the volume traversed by the particles. Correction for space variation of the winds is then necessary, however in most cases not as significant as time variation. Most weather networks are not refined enough to allow quantitative correction for these errors.

2.2.3 Vertical Motions

In applying particle falling speeds to the forecasting technique, it is assumed that the atmosphere has no vertical velocity. Computations made at the Eniwetok Proving Ground* to 50,000 ft indicated that large cellular vertical motions in the atmosphere sometimes attained speeds equal to and greater than the settling speed of a 75-p particle. A time-space correction should be made for the falling speeds of the particles to compensate for this parameter. However, in the work at the test site it was not possible to include this effect in the fallout forecasts. Certain anomalies discussed below may be due to such an effect and could be analyzed to see whether they are resolved when the vertical motions have been taken into account.

3 DISCUSSION OF FIELD TEST RESULTS

The forecasting technique described was employed by the fallout program at the Eniwetok Proving Ground to satisfy certain project requirements. One project had three ships equipped to collect fallout and their positions had to be determined for efficient collection. Another sampled the ocean for fallout; while another made an aerial survey of the contaminated area. The navigational schedules for these latter projects were based on the forecast fallout pattern. Operations were controlled through the Program Control Center aboard the Task Force Command Ship where the forecasts were prepared.

The meteorological data were received from the weather ship at Bikini as well as from weather stations at Rongerik and Eniwetok atolls. Furthermore, all forecasts made by the Task Force Weather Center at Eniwetok atoll were usually available aboard the command ship by facsimile through the ships Weather Station.

* Under the direction of CMD Daniel F. Res, Joint Task Force Seven, Meteorological Center, Pearl Harbor, T.H.,

Upper air measurements were made at Bikini, Rongerik, and Eniwetok atolls every 3 hr starting at H-24 hr and continuing until H+24 hr for any given detonation. The frequency of observations was increased during the period from H-6 to H-2 hr. The altitudes reached on the wind runs were remarkably high and gave perhaps the best set of winds-aloft measurements to date. The average termination altitude was approximately 50,000 ft with many runs over 100,000 ft. Such excellent coverage of the winds prior to and during the fallout forecasting.

Fallout forecasts were made every 3 hr starting at H-24 hr. using the measured winds available at the time. This process was continued up to shot time and from then, on the technique of correcting for time variation, was employed every 3 hr until the fallout event was completed. It was not feasible to correct for space variation and vertical motions during this period because of the lack of time and data.

3.1 Fallout Plots

The fallout forecasts determined at the weapons test operation were based entirely on measured data and quantitatively considered time variation of the wind. On space variation corrections or computed values of vertical motions were employed in their construction.

The area of measured fallout from shot A is compared with the forecast fallout plot in Fig. 12. Figures 13, 14, and 15 are similar comparisons for shots B, C, and D. Although C and D were water surface shots, it is evident that the forecasting technique succeeded in representing the measured fallout area as well as it did for the land surface detonations, A and B.

The comparison is excellent for all shots except B and as yet the discrepancy between the forecast fallout area and that which was measured is unknown. There is some indication that consideration of vertical motions will have to be made for shot B during the time of fallout and computed vertical motions were significant in magnitude. Such analysis including space variation is being carried out at this time for all four detonations and the refined data will be published later.

4 SUMMARY

The fallout forecasting technique described in this report was successfully employed for both land surface and water surface detonations.
at the Eniwetok Proving Ground. With known meteorological data such a technique will successfully quantify the area of fallout and indicate qualitatively the relative intensity of radiation.

Precise determination of the fallout area requires consideration of many complex meteorological parameters. However, from the above analysis a practical field tool can be developed that in most cases will satisfactorily define the area of interest.

Approved by:

E.R. TOMPKINS

HEAD, CHEMICAL TECHNOLOGY DIVISION

For the Scientific Director

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Fig. 1: Mushroom Diameter As a Function of Yield
Fig. 4 Temperature as a Function of Altitude for a Marshall Islands Atmosphere

Fig. 5 Pressure as a Function of Altitude for a Marshall Islands Atmosphere
Fig. 6  Density as a Function of Altitude for a Marshall Islands Atmosphere

Fig. 7  Absolute Viscosity as a Function of Altitude for a Marshall Islands Atmosphere
Fig. 9. Falling Speed Transition Zones for the Marshall Islands as a Function of Particle Size and Altitude.
Fig. 13 Comparison of Fallout Forecast With Test Results - Shot B

Fig. 14 Comparison of Fallout Forecast With Test Results - Shot C
### Table 1 (Continued)

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- (Continued) -
### Table 1 (Continued)

Temperature, Pressure, Density, and Viscosity of the Atmosphere Over the Marshall Islands During the Spring

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### Table 3
Cumulative Time of Fall for the 75-μm Particles (hr)

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### TABLE 5
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</tr>
</tbody>
</table>

**Table 6 (Continued)**

Cumulative Time of Fall for 150 μm Particles (hr)
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OVERSIZE COLLECTION
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