MODIFICATION OF FALLOUT PATTERNS BY PRECIPITATION

by

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ABSTRACT

Radioactive particle trajectories were computed from models representing a 10 kiloton and 1 megaton thermonuclear explosion, and 12-hr ground patterns were established for several locations of the point of bomb detonation. Storms, both actual and idealized, were inserted in the paths of the particle trajcetories at different times and positions, and modifications of these 12-hr ground patterns by the rainout process were noted.

The percentage of total particles rained out was found to be highly dependent on the bomb yield, storm dimensions, and storm position. Increases and decreases of radioactive particle activity, because of the rainout process, however, seemed to be more uniform for the different bomb yields, less dependent on the vertical extent of a storm, but still highly dependent on the storm position and cross-sectional area.

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I. Introduction

The problem of radioactive fallout from a thermonuclear detonation has received a great deal of attention during the last fifteen years, since the distribution of radioactivity in the atmosphere and on the ground from an atomic blast can highly affect life on earth. The importance of a detailed analysis of this problem, from both a peacetime and wartime aspect, cannot be overemphasized.

In a surface burst ground debris, which is drawn up into the mushroom and stem of a bomb within a few minutes of the time of detonation, becomes radioactively contaminated and is represented, for purposes of calculation, by radioactive particles of various sizes. These particles fall slowly to earth, and in this process they are carried horizontally by the atmospheric winds and deposited at specific locations on the ground, forming ground patterns. The atmospheric distribution of radioactive particles can be broken down and analyzed on two different scales: 1) world-wide fallout, and 2) close-in fallout (1). World-wide fallout from a nuclear detonation is defined as that fraction of the total activity, usually confined to the smaller particles, that remains suspended in the atmosphere for several days, weeks, months, or even years, and that is dispersed on a world-wide basis by the atmospheric winds. By far the greatest percentage of radioactivity from a thermonuclear bomb, categorized as close-in fallout, reaches the ground within a radius of a few thousand miles from the point of detonation and within approximately twenty-four hours from the time of burst. Particle distributions associated with the latter classification are dealt with exclusively in this paper, although the transition between the two categories is sometimes difficult to define.

Radioactive particle trajectories and associated ground patterns may vary for different size bomb yields and different atmospheric conditions. The rainout process is a typical example of the latter. If radioactive particles falling freely through the atmosphere are blown into a storm by the upper-air winds, they would be caught and collected by rain droplets or snowflakes falling at different velocities from the particle itself. Both the droplet or snowflake and the collected particle are then brought to the ground at a time and place that could be different if the particle had followed its uninterrupted free-air trajectory. Hence these particle trajectories are clearly dependent on wind and weather patterns and may well be applied to the study of atmospheric motions. For calculation of fallout patterns, however, it was necessary to make use of assumed atmospheric motions by relying on standard wind reports, cloud physics studies, etc. This paper, then, primarily considers not the motions themselves but their effects on radioactive particle distributions. By the use of this type of analysis, additional information could be obtained on the extent to which particles from nuclear detonations would be useful in tracer studies. The modification of fallout patterns by precipitation thus assumes a high degree of significance on a synoptic as well as strategic basis.

II. Methods of Analysis

This paper deals primarily with the rainout effect on close-in fallout and leaves the highly detailed analysis of the thermonuclear model construction to various agencies working in this field (U. S. Weather Bureau, Ford Instrument Company, U. S. Naval Radiological Defense Laboratory, and others). Because of the security classification of data pertaining to initial particle distributions associated with a blast, such as vertical and horizontal dimensions of mushroom and stem and radioactive particle fall velocities, thermonuclear models were constructed from a rather limited source of material. As the project proceeded and new material became available, modifications to the models were introduced whenever possible, if it was felt that the change would have some significant bearing on future results.

An initial model, or radioactive particle distribution, was assumed which depended on the size of the detonation. Observed properties of fallout samples have led to the conclusion that the particle sizes in the mushroom are log-normally distributed for a surface burst (2). The particles in the model were then allowed to filter vertically through the atmosphere with appropriate fall velocities and move horizontally through a chosen wind field, until such a time as they reached the ground, where their positions were plotted and analysed. All fall velocities used were for particles with a density of 2.5 gms/cm3 (2)(3). Particles were initially allowed to fall along free-air trajectories uninterrupted by precipitation. These trajectories were then recomputed in given storm situations where rainout effects might change their original ground positions, and the pattern modifications were compared to the results obtained in the cases where no precipitation occurred.

In order to describe an initial radioactive particle distribution, the bomb was divided into sections called wafers, which were horizontal slices of a given thickness, whose cross-sectional area covered that of the physical bomb dimensions (2)(4). Radioactive material should be distributed throughout a wafer. However, for simplicity and ease of handling, all particles comprising this distribution were assumed to originate at the wafer's central point. A discrete particle position on the earth thus needed a dimensional interpretation. This was accomplished by relating the midpoint of the wafer from which the particle fell to the horizontal distribution it assumed in this wafer, which in turn reflected the cross-section area of the bomb itself. In the larger-yield detonations each wafer was further divided into subwafers for greater distributional detail(2).

The vast numbers of radioactive particles to be found in a nuclear explosion were grouped according to size, and these particle groups were the basic breakdown of radioactive material used in the fallout models. For the purposes of calculation the mean parameters of a particle group were reflected by a "representative particle." Representative particles will hereafter be referred to as radioactive particles, or simply particles, but it should be kept in mind that they are used solely for computation purposes and represent a group of actual radioactive particles whose size range (and hence the range of free-air fall velocities involved) is small but finite.

Particle trajectories were computed by means of the finite difference technique of dividing the atmosphere into layers and allowing the particles to fall through each layer for an appropriate amount of time---governed by particle fall velocities and layer thickness---until they reached the ground. The wind was assumed to be constant within each layer, and the horizontal motion of the particle was equated to the wind speed and direction.

The method of analysis of particles on the ground was determined by the number of particles selected to represent a given detonation and the yield of that detonation. If relatively few particles were widely dispersed by the winds, detailed ground patterns could not be drawn because of the discreteness of particle (or wafer) locations with respect to each other. It was assumed, however, that the ground activity would be continuously distributed if more particles had been used. With this in mind interpretations were restricted solely to broadly outlined activity areas. When a "very large" number of particles could be handled, final ground positions tended to overlap, resulting in more homogeneous distributions. For purposes of analysis the overlapping particles were grouped in small areas and then added. The area dimensions were chosen so that the resulting patterns would not significantly differ from the patterns established by the overlapping process.

Modifications by the rainout process took place when storms, both actual and idealized, were introduced, or inserted, in the three-dimensional fallout patterns. Idealized storms were allowed to move and develop in a realistic manner. All storms, nevertheless, were subject to dimension and position changes in discrete time steps, usually at intervals of ten minutes. The choice of storms was limited to situations involving wind and weather fields that would be fairly typical from a meteorological standpoint and yet would be detailed enough to permit the introduction into the fallout patterns of small-scale cellular structures as observed by weather radar.

It has been noted (2) that precipitation scavenging efficiencies are usually quite high. For simplicity and in the absence of any more accurate information, collection efficiencies of the rain drops and snowflakes were taken to be one-hundred percent. It was further assumed that the moisture patterns would uniformly fill each precipitation area so that any radioactive particle coming in contact (coinciding in time and space) with a storm would be caught and brought to the ground with the fall velocity of the precipitation. This assumption was introduced to eliminate the complications arising from mean free path trajectories of radioactive particles through a precipitation medium.

III. Hand Computed Fallout Patterns and Their Modification by Precipitation

In a preliminary computation a model was used which represented a 10 KT (kiloton) detonation. Since the number of radioactive particles selected had to be small enough for hand computation and large enough to adequately represent the distribution of atomic debris in the blast, the number 200 was chosen, each representative particle thereby containing 0.5% of the total fallout.

The mushroom was assumed to extend vertically from 17000-23000 ft, and the stem reached from the ground to the base of the mushroom (2). For simplicity the horizontal particle distribution in the mushroom was assumed to be uniform over a circle 1.8 mi in diameter (2). The representative particles which were selected, and their distributions, are given in Table I; particle fall velocities were obtained from Meteorology and Atomic Energy (5). The mushroom, containing 90% of the total radioactivity, was divided into seven wafers of 1000 ft thickness. Since the distribution of radioactive material in the initial cloud can be assumed to vary with atmospheric density (2), the ratio of particles in the 17000 ft wafer was taken to be about twice that of the 23000 ft wafer.

Fifteen percent of the radioactivity in the mushroom was attributed to small particles. Particles less than ten microns in radius were considered too small to be caught by precipitation, while those between 11 and 20 microns in radius were given no apparent fall velocities and hence could be collected by a storm at their initial height only. Since close-in fallout alone was being considered, the assumptions regarding the smaller particles, which would probably not reach the ground during a 12-hr period, were felt to be valid.

The remaining ten percent of the radioactive material was equally distributed in the stem at 5000 ft and 15000 ft.

The New England storm of 8-9 November 1957 was chosen for the preliminary computations because of the availability of not only adequate wind information from a number of northeastern radiosonde stations, but also a detailed radar analysis of the weather patterns within a radius of 120 mi of MIT. The storm provided a varied structure with a warm front and associated wide-spread weather for the general situation, followed by a line of convective showers along a cold front for a more detailed analysis.

The wind structure was averaged with respect to space and time from radiosonde data at Albany, New York; Portland, Maine; and Idlewild Airport, New York, over a 12-hr time interval (Table II). Trajectory vectors were plotted from each previously selected wafer height, starting at the point of detonation and continuing downward in 1000 ft layers. Vector directions were taken from the average wind directions in each layer, while vector lengths were calculated from the average wind speeds when particle fall velocities of 1000 ft/5, 10, 20, and 30 min were considered. Thus four discrete particle trajectories were plotted from each of nine initial levels (seven in the mushroom and two in the stem). The time that each of the 200 particles would take to reach the ground was then calculated, and final displacements on the ground, at or between the terminal points of the four discrete trajectories, were noted. Since an average wind in each 1000 ft layer was considered during the fallout period, the particle distribution at the ground from an individual wafer fell in a straight line with its origin at the point of detonation---though not necessarily the same straight line as that from any other wafer (Fig. 1). Hence, a horizontal ground dispersion of approximately fifty miles was observed perpendicular to the main axis.

Figure 2A, which illustrates this dispersion, shows the ground pattern, without rainout effects, for the 10 KT detonation in the selected wind field of 8-9 November 1957. Each dot represents 0.5% of the total radioactivity, and cumulative percentages of the total activity along the ground (in 5.0% intervals) are taken radially from the point of detonation. This type of ground distribution, as pointed out in the methods of analysis, is obviously associated with a model where an insufficient number of particles were chosen. The relative particle positions made it impossible to draw meaningful ground patterns, so only a general outline of areas affected by fallout was presented. The horizontal dimensions associated with particle positions at the ground were neglected in the outlining technique because of the large ratio difference between particle ground spread and wafer dimension.

Modifications by the rainout process were investigated by the use of 10 x 10 mi idealized storms of various heights: 15000 ft, 20000 ft, and 25000 ft. Fifty-mile space intervals, taken radially from the point of detonation, were selected for the particle grouping at the ground, and in order to obtain maximum effects from the rainout process, the time of insertion of idealized storms in these intervals (along the trajectory axis) was determined from the mean wind speed. It was realized, of course, that three-dimensional fallout patterns might not be affected by storms in the vicinity because of the similarity of storm and radioactive particle movements in a given wind field (6). Therefore, the average rainout effect of an idealized 10 x 10 mi storm on a given pattern was calculated by the use of probability techniques: the greater the particle spread over a 50 x 50 mi area, the more probable a particle comprising this spread would be caught by a storm. Rainout effects were then attributed to an idealized storm of a 10 x 10 mi area which appeared at the time when maximum particle activity would be available for collection and which could be located anywhere within a given 50 mi interval (taken radially from the point of detonation) and within 25 miles on either side of the main fallout axis. In a calculation of this type, the inserted storms will sometimes be referred to as "average" storms.

Figure 3 shows the original fallout pattern in the absence of rainout and the patterns as modified by the average effects of 10 x 10 mi storms associated with given 50 x 50 mi intervals. It is of interest to note the high percentage of rainout activity associated with the interval immediately downstream from the one where an average storm appeared. This is explained by the fact that storms located in the first few intervals with respect to the point of detonation rained out a rather large percentage of the total activity because the radioactive particles were collected before a great deal of atmospheric dispersion took place. Now, if collections occurred at relatively high levels, the particles were subjected to the winds for long periods of time and thus were carried across chosen boundaries and deposited at the ground in an interval other than the one where the particles were originally collected. As rainout occurred at greater times and distances from the point of detonation, and hence at lower levels, the rained-out particle trajectories usually terminated within the same interval.

The actual precipitation patterns which occurred on 8-9 November 1957 were analyzed using signal intensity contours on the SCR-615-B radar at MIT and scope photographs of the echoes on the AN/CPS-9 radars at both MIT and the Air Force installation at Blue Hill, Massachusetts. The observed actual storms were then introduced in the original fallout trajectories, and ground patterns showing rainout effects were calculated by the previously described methods for two points of detonation located less than twenty miles apart. (The positions of bomb detonations were not arbitrarily chosen, but specifically placed in time and space where particle trajectories and actual storms could come together.)

Figures 2B and 2C show the rainout effects on the pattern of Fig. 2A. It is of interest to note the comparatively different areas outlined and the radial percentage changes associated with the same general storms, even for detonation points as close together as those chosen. The explanation again may be given that the storms penetrated the fallout pattern fairly close to the initial burst, and because of the lack of atmospheric dispersion a high percentage of activity could be rained out by any single storm. Thus a small difference in storm locations, with respect to the point of detonation, could greatly affect the final ground distributions. Comparisons between the patterns for no precipitation and those patterns affected by rainout showed that in original patterns, approximately three-fourths of the radioactive particles fell within a radius of 400 miles from the point of detonation, whereas with the introduction of storm cells, the radius was decreased to half that size. It is also interesting to note the "gaps" in the distribution of activity at the ground due to the rainout process.

A comparison of the actual and average rainout percentage distributions was then made to determine the degree of uncertainty introduced by the averaging process. This was done as follows: Each interval where actual storms appeared was noted, and percentage distributions were then recomputed using the averaged storm technique in those intervals. The comparison, as shown in Fig. 4, indicated that only a small amount of detail was lost in the storm-averaging process when the three 50-mi intervals containing the majority of particles were considered.

In the storm of 8-9 November 1957 the winds were relatively strong, and fallout patterns extended long distances. A second hand computation was made using the more moderate wind field of 22-23 July 1959, as given in

Table III, and some refinements were introduced in the previous techniques. It was felt that accuracy limits should be assigned to the entire computation wherever possible, in order to provide a more solid basis for the evaluation of the final data. The error limits, for this second model, were taken to be 10%. Particles in a 10 KT detonation that originate from heights of 17000 ft to 23000 ft are subject to an error of 5%/1000 ft of initial vertical displacement; thus the selection of 2000 ft wafers would keep within the specified limits.

The error due to particle grouping by size was calculated as follows:

$t - t'/[(t + t')/2] = 0.1$

$t' = 0.905t$

or

$W_{(\mu+\Delta\mu)} = 1.105 W_{\mu}$

t = time that it takes a particle of radius μ to fall to the ground from a given wafer

t' = time that it takes a particle of radius $\mu + \Delta\mu$ to fall to the ground from the same wafer

W = fall velocity

and particles were grouped accordingly.

A more precise method was used to determine the mushroom particle distribution. The ratio of the air density between the 2000 ft wafers centered at 18000, 20000, and 22000 ft, which now divided the mushroom into three sections, was 1.15/1.07/1.00 respectively (7).

If the assigned error limits were assumed to hold, and the original idea of 200 particles was maintained, the distribution of representative particles over the three mushroom wafers was standardized to remain as close to 4/3/3/ (5% of the total activity) as possible. Although most of the particles in the mushroom fell within the assigned 10% limits, the particles in the stem greatly exceeded these limits because of wafer selection (centered at 2000 ft, 6000 ft, 11000 ft, and 15000 ft) and particle grouping. The 10% of the total radioactivity attributed to the stem was, however, composed of larger particles, and the majority of these particles tended to reach the ground near the point of detonation. Therefore, the absolute error in their ground position was not extremely great as compared with a 10% error at a point several times as far away from the origin.

Two major changes in the wind pattern were introduced. First, since the use of the average winds at any given level from the three reporting stations left no possibility for particle dispersion due to atmospheric convergence and divergence, it was decided to use the average wind only if the three reports agreed within the following limits:

Height (ft)	Wind Speed (MPH)	Wind Direction (deg)
0-10000	10	50
10000-20000	15	40
20000-25000	20	30

If the differences in wind speed or direction were greater than the selected limits, the winds were handled on an individual basis so that a spread might occur in a group of particles originating from any given wafer (differing from the straight line ground distribution of the first model).

Secondly, winds were allowed to change every three hours, which is, of course, a more realistic picture from a meteorological standpoint.

The ground fallout pattern associated with the second model, neglecting rainout effects, is shown in Fig. 4. Of primary interest in this pattern is the particle dispersion due to the use of non-averaged winds, as depicted by the straight lines. If average winds for each level were used, the particles would have fallen in the positions indicated by the dots. It must be re-emphasized that most of the blank area between representative particles in distributions where precipitation is absent may have radioactivity associated with them. These areas occur because of the small number of particles chosen to represent the true distribution. It is for this reason then that a detailed study of the horizontal particle dispersion in this model was not attempted.

The particle percentage distributions at the ground after approximately twelve hours, with no precipitation and with the average effects of idealized storms, were hand calculated; Fig. 6 shows these distributions. The 12-hr ground pattern distances depicted in this figure were now considerably shorter due to the more moderate atmospheric wind speeds. For purposes of comparison, 10 mi radial distances were chosen to replace the 50-mi intervals used in the previous case. Since the probabilities associated with radioactive particle collection were meaningless when the interpretation of horizontal particle spreads was limited, the average 10 x 10 mi storm technique was used in only the first few intervals. The percentage of particles crossing chosen boundaries after having been rained out was less noticeable in these distributions because of the moderate winds.

No comparisons of the average effects of idealized storms to those of actual weather occurrences were attempted, since it was assumed from the last model that the distributions near the point of detonation from averaged and actual storms were quite similar. Despite the different areas covered by the ground patterns in the first model, the particle spread in the second model, and the relative distances between the ground patterns of the first and second models, fallout percentages corresponded very closely in the various radial intervals. The differences that did occur seem to be largely the result of boundary effects.

In any event the total amount of particles rained out and the particle percentage changes in the 12-hr ground pattern of a 10 KT detonation can certainly be highly significant, as evidenced from both the models presented.

IV. Machine Computed Fallout Patterns and Their Modification by Precipitation

In order to work with a more detailed particle distribution as well as weapons of higher yield, it was apparent that the use of a high speed electronic computor would be required. With the availability of the IBM-704 electronic computor at the MIT Computation Center, the entire problem of radioactive fallout was reanalysed for machine computation.

A. Initial Distribution of Radioactive Particles

A detonation of 1 megaton was considered. The mushroom, centered at 60000 ft with a vertical extent of 28000 ft, was assumed to be approximately 100000 ft in diameter. [These dimensions are a general compromise between two references.

$T = 3320(1000\ KT)^{0.3} \cong 26000$ ft (2)

$T \cong$ graphically 28000 ft (3)

where T = mushroom thickness

$D = 3360(1000\ KT)^{0.46} \cong 80000$ ft (2)

$D \cong$ graphically 115000 ft (3)

where D = mushroom diameter]

The stem, extending from the ground to the base of the mushroom, was assumed to have a diameter of 20000 ft, or 1/5 that of the mushroom (2). The 1 megaton model dimensions are depicted in Fig. 7A.

Greater horizontal and vertical distances were now involved because of the higher bomb yield, and an attempt was thus made to keep the particle distribution error to 5%. The error introduced by the spread of particle sizes within a single group was computed as follows: For any given initial height Z_j (in thousands of ft), the time for a particle with radius μ_i to reach the ground is t_{ij}. The 5% error limit specifies that

$$t_{ij} - t_{i+1,j}/[(t_{ij} + t_{i+1,j})/2] = 0.05$$
$$t_{i+1,j} = 0.951 t_{ij}$$

Since $t_{ij} = 1000Z_j/W_i$ where W_i is the fall velocity of the particle with radius μ_i (ft/sec), substitution from the above yields

$$1000Z_j/W_{i+1} = 0.951(1000)Z_j/W_i$$
$$W_{i+1} = 1.05W_i \qquad \text{Eq 1}$$

Similarly, if the height intervals are to remain within a 5% error limit, they should satisfy

$$Z_{j+1} = 1.05Z_j \qquad \text{Eq 2}$$

The mushroom was therefore divided into fourteen 2000 ft wafers (Eq 2), whose centers ranged from 47000-73000 ft. Each wafer was subsequently divided into twelve 10 x 10 mi subwafers, arranged in such a manner as to best represent the horizontal mushroom dimensions (Fig. 7B). Five wafers, each of approximately 9000 ft in height, were selected to represent the distribution of particles in the stem, and in the case of a 1 megaton detonation, a subwafer division was unnecessary. A log-normal distribution of particle sizes with the following characteristics was assumed (2).

Cloud location	Radius (microns)	Mean	Standard deviation	% of total activity
Mushroom	0- 500	3.7	0.8	90
Stem	80-1500	4.4	1.2	10

The size range in each particle group was determined according to Eq 1, and by use of tables of normal distributions [$Z = (\ln\mu - m')/\sigma$], a given percentage of activity was assigned to each group (Table IV, Columns 1, 2, and 3).

As stated earlier, the particle density distribution among the wafers of the mushroom was taken to be proportional to the air density. The NACA Standard Atmospheric ratio of the air density at 73000 ft to various other levels corresponding to the mushroom wafers is as follows (7):

Height (thousands of feet)	Air density ratio	Height (thousands of feet)	Air density ratio
73	1.00	59	1.80
71	1.06	57	1.99
69	1.16	55	2.16
67	1.25	53	2.40
65	1.36	51	2.62
63	1.49	49	2.90
61	1.64	47	3.22

Nine thousand representative particles were distributed throughout each "column" (group of vertically adjacent subwafers extending from the base to the top of the mushroom) according to the air density ratio, with each subwafer of the column containing all of the particle groupings. Thus the total amount of particle activity attributed to the mushroom was 9000 representative particles per column x 12 columns, or 108000 representative particles---each containing 1/108000 of the total activity.

The 10% of the activity assigned to the stem was distributed according to the ratio $(Z_{j+1})^2 - (Z_j)^2$, and again, all particle groupings were considered in each individual wafer.

With the great vertical distances involved, significant changes in the fall-rate of a particle occurred as it descended from its original position in the bomb to the ground. These changes were discretely considered between the 0-20000, 20000-40000, and 40000-75000 ft layers (Fig. 7). A total summary of the 1 megaton computational model can be found by referring to Table IV.

B. Weather Patterns

The 0000Z wind reports for 23 July 1959 taken from the radiosonde stations in northeastern U.S., were plotted and analyzed at twenty-six reporting levels from the surface to 75000 ft (1000 ft intervals from 0-10000 ft, 2000 ft intervals from 10000-20000 ft, and 5000 ft intervals from 20000-75000 ft). A 600 x 600 mi area with sixteen grid points spaced 200 miles apart was superimposed at each of the twenty-six levels, and the representative winds were plotted at the 416 grid points.

Figure 8 depicts the weather pattern for 0000Z, 23 July 1959 (the same date and approximate time as that used in the second model) and other information pertaining to the fallout model. It may be noted that individual cellular structures in thunderstorms (as observed by the MIT weather radar in western Massachusetts) and larger scale precipitation patterns associated with overcast skies in the lower portions of the fallout grid, afforded excellent opportunities for the study of both detailed and general precipitation effects on fallout patterns.

C. Machine Method for Computing Fallout

The machine computation of a particle trajectory in the atmosphere required that discrete time steps be used in order to locate the position of each individual particle in time and space. If this time step was taken to be too large, certain errors occurred which significantly changed final results and gave erroneous solutions to the problem at hand, whereas the choice of a minutely small time interval would provide unnecessary detail and consume a great deal of machine time. A 12-hr ground pattern broken into 10-min time steps was ultimately decided upon. Ten-minute intervals would fulfil the requirement of time consumption from a computational standpoint, since a 12-hr ground pattern would be composed of 72 time steps for each particle, and the entire problem could be run in 10-15 minutes. When a group of cells was then considered to cover a 5 x 5 mi area, a 10-min time interval would also allow the storms to move as fast as 30 MPH before a "gap" between leading and trailing edges would take place.

Many programs have been previously written dealing with close-in fallout from a nuclear detonation, but few, if any, have been developed to deal directly with the problem of rainout. Although precipitation probability factors have entered into some computations, the actual insertion of storms into weather patterns has not been given a great deal of consideration. The reason may be that the atmospheric trajectory of a particle uninterrupted by weather factors is considerably easier to handle than one of a particle that may or may not be subject to accelerations or decelerations in the vertical and horizontal because of the rainout process.

The program in this study, however, was written to handle both the rainout and non-rainout situations so that comparisons could easily be made between the various results obtained. It is shown in diagram form in Appendix C (references 1,2,3,8,9,10 were used in the program construction). The basic equations that appear in the program may be found in Appendix D.

D. Patterns Without Rainout Effects

A particle height at D + 12 hrs (Detonation + 12 hours) was computed (Z*) according to the vertical displacement formulae. This height, either above, at, or below the ground, was stored in core memory. The particle, beginning at its initial position in the mushroom (Z) at time D + 0 hrs, descended unobstructed by precipitation effects through each of the various wind levels where its component horizontal displacements were calculated from one level to the next, until such a time as the particle either hit the ground, or the 12-hr trajectory was completed. The 12-hr ground positions were plotted, without the loss of particle resolution, on a 10 x 10 mi grid, i.e.: all particles whose 12-hr positions fell within a given 10 x 10 mi square were added, with the results appearing at the center of the square. Lines of equal particle percentage were then drawn, and a ground pattern was established for any given detonation point.

A conversion from percentage of total particles to deposit rates and deposit doses when dealing with the radioactivity in a thermonuclear detonation was not used because of the necessity of working with individual particles.

Detonation points were chosen from meteorological standpoints alone so as to give synoptic realism to the storms that were inserted and allow a majority of particles to fall within the 600 x 600 mi limit. It should be emphasized that absolutely no strategic considerations were given to the location of ground zero.

Because of the machine time limitations, it was not possible to operate on all the column distributions of the mushroom or on the stem itself. To compensate for this computational deficiency, the ground pattern for one mushroom column was established and expanded in accordance with both its original position in relation to the other mushroom columns and the 10 x 10 mi surface grid. Each computed particle position was multiplied by that fraction of the particles in the adjacent sub-wafers that would be expected to land within the same 10 x 10 mi square. This process was then continued, operating on the four adjacent 10 mi squares along the main axis of the original square until such a time as the entire wafer was taken into account. Thus the resultant pattern was attributed to the entire mushroom and not mainly to one of its columns. The patterns of radioactive particle activity due to the stem have not yet been calculated, so that all results are in terms of the mushroom fallout alone.

Figures 10 and 17 show the 12-hr ground patterns, unaffected by the rainout process, for two differently located one megaton detonations. The patterns close to the point of detonation are realistically in error, since the stem particles, many of which could be expected to fall in this area, were omitted from the computations.

E. Patterns Modified by Rainout

In the computations where rainout effects were included, a particle height and horizontal position were calculated by the non-rainout techniques until such a time as precipitation activity appeared on the map. Each position was then tested to determine a coincidence between particle and storm. If no coincidence occurred, a new 10-min position was calculated by the previous technique and the test reapplied, assuming a discrete 10-min storm movement. When a particle was caught (coincident with a storm in time and space), it assumed the fall velocity of the rain or snow associated with the storm, depending on the position of the melting level, and appropriate velocity changes were introduced in the basic equations. After being caught, the particle moved horizontally with the storm speed and direction until it reached the ground or until the storm subsided, in which case the particle continued to move in a free-air trajectory.

During any 10-min interval, a radioactive particle could get caught by 1) being located directly in a storm, 2) being blown into the side of a storm, 3) falling into the top of a storm, 4) entering the storm through the process of entrainment. The last category was not considered because of the meteorological and computational problems involved. Category one was handled by considering the particle to be caught and proceeding accordingly. The main problems that arose were to be found in categories two and three, which related to the particle entry into a storm. Particles blowing into the side of a storm were subjected to a horizontal position error because of the use of a discrete 10-min interval. This error could be magnified to the extent that a particle, moving in a sufficiently strong wind field, would blow "through" a storm, since particle-storm relative positions were tested only at the beginning of each time interval. In actuality, however, a storm and nearby radioactive particles usually move at about the same speed and direction throughout middle levels; for this reason, changes in the basic computational procedures, which would have been difficult to introduce, were not considered.

Category three presented the problem of small-scale vertical motions in the atmosphere. A particle falling into the top of a storm in its building stages would most likely be caught in an updraft and remain near the top of the cloud. This category, unlike the previous one, could be handled more realistically with a fairly simple change in the computational procedure. If a particle, initially above a storm, entered through the top during a given time interval, its free-air trajectory was calculated for a second 10-min interval, and if the particle was still within the storm limits, its position was shifted to the storm height for that interval. This method distributed certain particles discretely at the top of the storm and realistically permitted a storm to move from under a falling particle.

Actual and idealized storms were inserted into the radioactive particle trajectories. For more realistic representations of a convective-type cloud, the idealized storms were now taken to be 5 x 5 miles in area. These storms built up and dissipated at standard rates (11) (10000-20000 ft/10 min for building and 2000-5000 ft/10 min for dissipating) and were of standard durations (approximately 30-120 min). Idealized warm frontal type precipitation, which was also considered, maintained a constant height and lasted for longer periods.

Four 5 x 5 mi storms were chosen to be inserted into the pattern of Fig. 10. Initially, a storm of 1:40 min duration beginning at D + 3 hrs (maximum height 40000 ft) was arbitrarily placed in a position where it was felt the rainout process would take place. It was realized, however, that additional information was necessary in order to insert storms in more critical locations. Thus a detailed analysis of the three-dimensional fallout distribution at D + 6 hrs was obtained by considering each of ten 5000 ft layers extending from the ground to 50000 ft. An example of a typical pattern in the 20000-25000 ft layer is shown in Fig. 15. From the above analysis the total particle distribution from the ground to 40000 ft was determined and is shown in Fig. 16. With the use of these patterns it was now possible to place two storms, beginning at D + 5:50 hrs, in optimum rainout locations. Each of these idealized storms lasted for one hour (maximum height 40000 ft). The fourth storm of one hour duration (maximum height 35000 ft), beginning at D + 9 hrs, was an actual 5 x 5 mi echo observed on the MIT weather radar.

Because of the effect of computationally considering only one column of the mushroom distribution, it was necessary to extend the horizontal dimensions of any storm, in the machine computation, to those of the mushroom itself (20 x 20 mi), thus enabling the proper bomb-storm area relationship to catch a realistic amount of particles. Compensations were then made for the "extended" storms in the final ground pattern analysis.

F. Pattern Interpretations

The most significant particle percentage changes were found, as might be expected, near the storms themselves, while the patterns further downstream remained relatively unaltered. The unexpected lack of changes in these downstream areas may be attributed to the fact that particles, rained out in the upper portions of the storms, would most likely have been widely dispersed by the winds, if they had been allowed to continue along their uninterrupted trajectories. Thus, no single area downstream was greatly affected. The changes in all of the cases observed followed the same general pattern---increased activity in the direct vicinity of the storm tracks, decreased activity slightly downstream, with generally insignificant particle percentage changes over the remaining portions of the 12-hr ground pattern. All of these changes were observed through a detailed analysis of values associated with individual 10 x 10 mi areas as computed by the IBM-704. Figures 11-14 show the overall rainout effects on a large-scale basis.

The patterns calculated from the bomb detonation at X = 100, Y = 200 on the fallout grid were to be used, primarily, to test the generality of the results obtained above by the insertion into the fallout pattern of a different type of weather situation---one involving the precipitation usually associated with non-cellular low-lying stratus.

It should be re-emphasized that the location of the point of detonation was originally chosen so that fallout patterns would be in a region where this type of situation was more likely to take place. A warm frontal precipitation area 15000 ft in height and covering 100 x 100 miles was inserted into the fallout computation model on the basis of the three-dimensional fallout distribution which was computed, as before, at D + 6 hrs for ten 5000 ft layers. The four most important patterns from the standpoint of a 15000 ft precipitation area are shown in Figs. 19-22. Movement of the area, which was inserted at D + 4:30 hrs for a 3-hr duration, was not taken into consideration because it would not appreciably affect the number of particles the storm would rain out. Figure 18 shows the modifications by this type of weather pattern on the 12-hr ground distribution of Fig. 17. The "extended" storm technique used with 5 x 5 mi convective-type storms was not needed in this analysis, since the precipitation area was greater than that of the initial mushroom dimensions.

Fallout percentage changes near the upstream section of the vast weather area were considerably greater than those associated with convective-type storms, as can be seen by comparing Figs. 23 and 24. With the exception of an overall broadening effect, however, the pattern closely resembled the previous modifications of increased and decreased activity upstream and insignificant changes downstream, even under the storm area itself. Another outstanding feature in Fig. 17 is the southerly shift in the ground pattern, which can be attributed to the location of the large number of particles that were rained out in the 0-15000 ft layer (see Fig. 22).

V. Conclusions

It is most difficult to compare the results obtained in this study to the fallout ground patterns of actual thermonuclear detonations. First of all, few detailed measurements of close-in fallout from bomb yields in the megaton range have been made, and much of the material that is available remains classified for security purposes. Secondly, most detonations, of all sizes, are carefully controlled to keep the rainout effect at a minimum. Thus, these results must rely solely on the assumed realism of the two idealized models.

The most striking difference between 12-hr ground patterns of the 10 kiloton and 1 megaton bomb yield was the total particle activity associated with the rainout process. This may be seen most readily from a comparison of the percentages from a convective-type storm, grouped in radial intervals, for the 1 megaton blast as depicted in Fig. 23 with those of the 10 KT blast in Figs. 3 and 6. These differences may be explained as follows. A storm whose horizontal dimensions correspond closely to those of a nuclear detonation and whose vertical extent is as great or greater than the height of the mushroom would most likely rain out a large percentage of the total particles. If the storm location is close to the point of bomb detonation where radioactive particles were relatively undispersed before being caught, the percentage would be even greater. This was fairly typical of the hand calculated patterns obtained for the 10 KT blasts. However, if a storm of approximately the same dimensions is now compared to a bomb of a much higher yield, the cross-sectional area of the storm would be very small compared to that of the mushroom, and vertical storm development would rarely exceed the height of the stem. The percentage of rained-out particles in this situation, associated with the 1 megaton blasts, will therefore be smaller, especially if the rainout occurs at greater distances from the point of detonation.

An examination of the fallout patterns from both models makes it quite clear that the rainout process can be extremely important. Particle collections throughout most of the models have been maximized to fully illustrate this point. Although the modifications in some of the 1 megaton patterns are not as obvious from a visual standpoint, percentage changes at the ground were similar to, or even exceeded, those changes that altered the patterns of Fig. 2. Activity increases and decreases of 100-200% were not at all uncommon near convective-type storm tracks in the machine computed patterns, and some increases as high as 800% were noted in the pattern in which warm frontal precipitation was inserted. A second comparison between Fig. 23 and Figs. 3 and 6, with emphasis on percentage changes, shows the importance of the storm position in time and space.

It is now of interest to compare pattern modifications associated with storms of different dimensions. Percentage increases and decreases, as previously mentioned, were both considerably greater in the vast low-lying weather situation, since more particles were collected and rained out. Precipitation inserted into the 10 KT detonations also produced changes that were highly dependent on horizontal storm dimensions, as evidenced from Figs. 3 and 6 (the idealized 10 x 10 mi storm in Fig. 6 completely covered the fallout trajectories, which was not the case in Fig. 3). In addition it can be observed that modifications by the rainout process in these figures depended on the vertical storm extent only to a certain point. From that point on, an increase in storm height failed to alter the patterns significantly.

It can thus be stated that the percentage of the total particles rained out in a thermonuclear explosion was inversely proportional to the bomb yield, directly proportional to the storm dimensions (for the storm height less than the mushroom height), and highly dependent on the positions of these storms, relative to the close-in fallout patterns, in both time and space. Particle percentage changes at the ground because of the rainout process, however, seem to have been more uniform for the different bomb yields, less dependent on the vertical extent of a storm, but still highly dependent on the storm position and cross-sectional area. These changes were greatest in the direct vicinity of storm tracks, or slightly downstream, and, in the case of a larger detonation, became insignificent over the remainder of the 12-hr ground pattern.

APPENDIX A

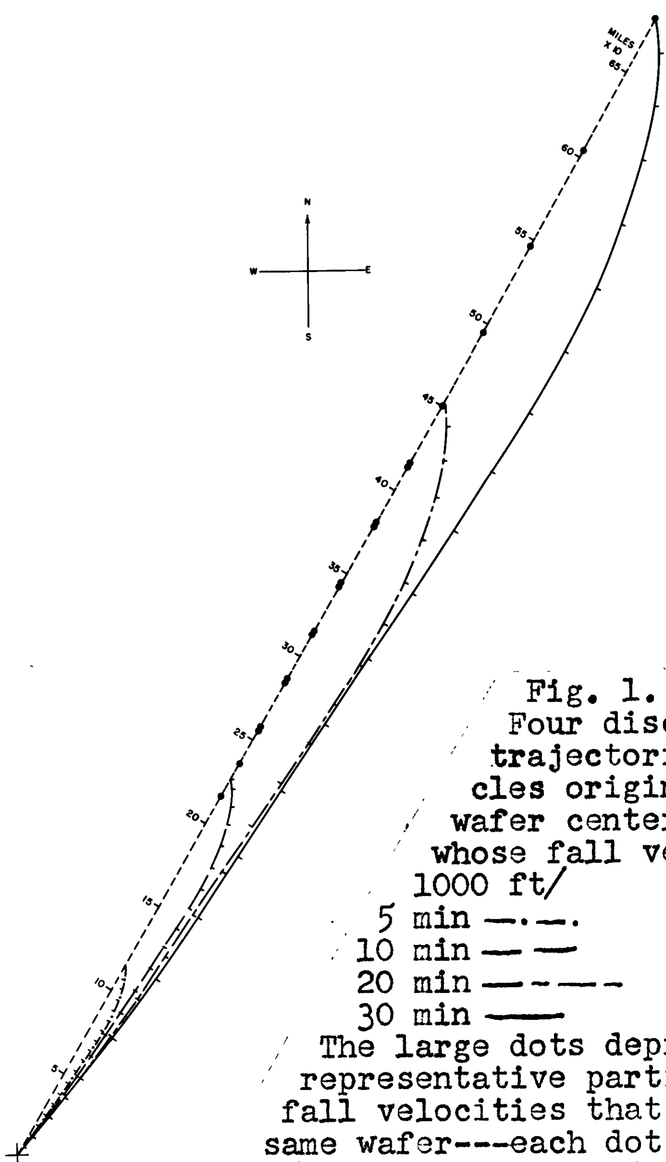


Fig. 1.
Four discrete particle trajectories for particles originating in a wafer centered at 19000 ft whose fall velocities are 1000 ft/
5 min —·—·
10 min — —
20 min — - — -
30 min ——
The large dots depict all the representative particles of various fall velocities that fell from the same wafer---each dot representing 0.5% of the total radioactivity associated with a 10 KT detonation during the storm of 8-9 November 1957.

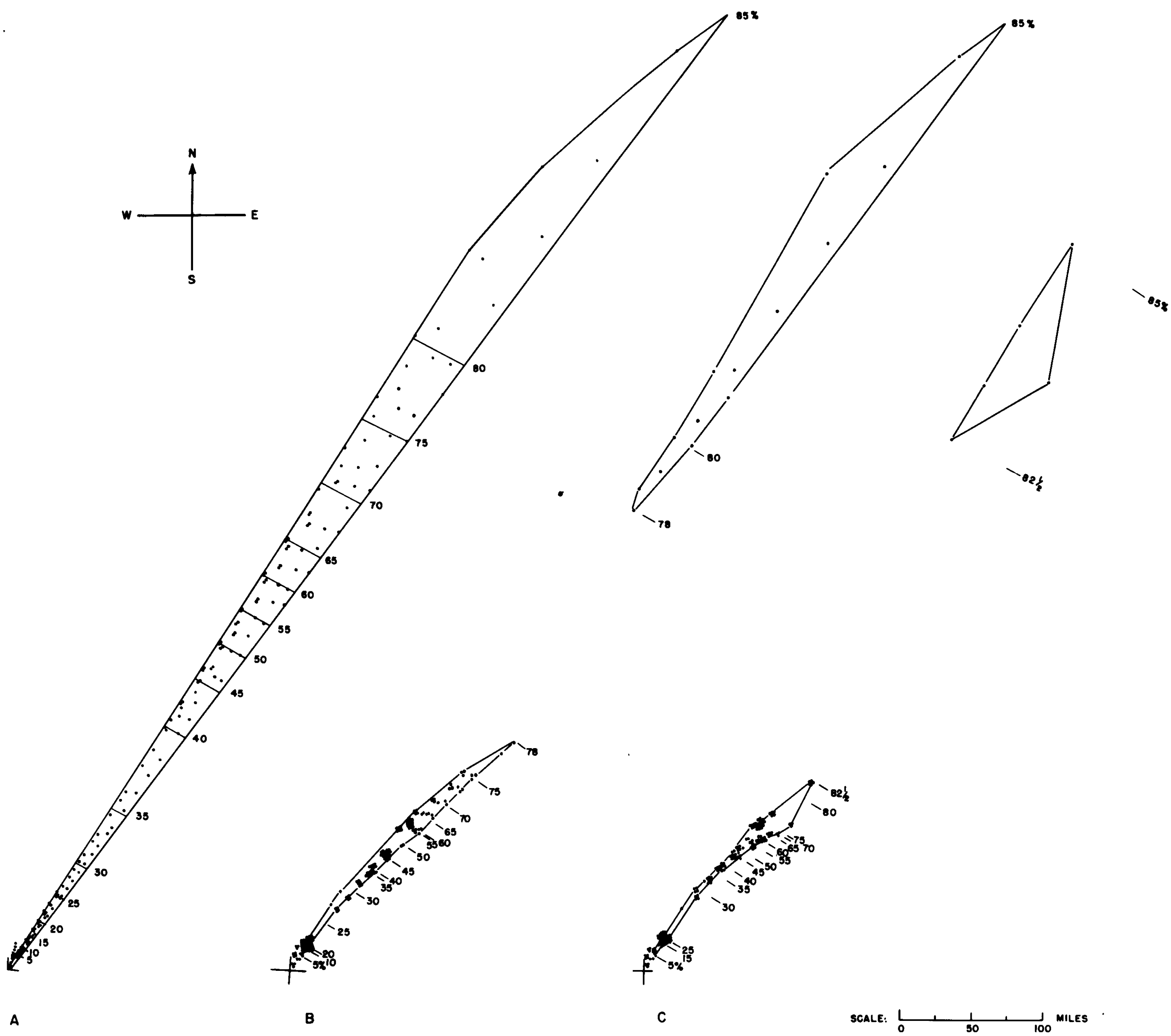
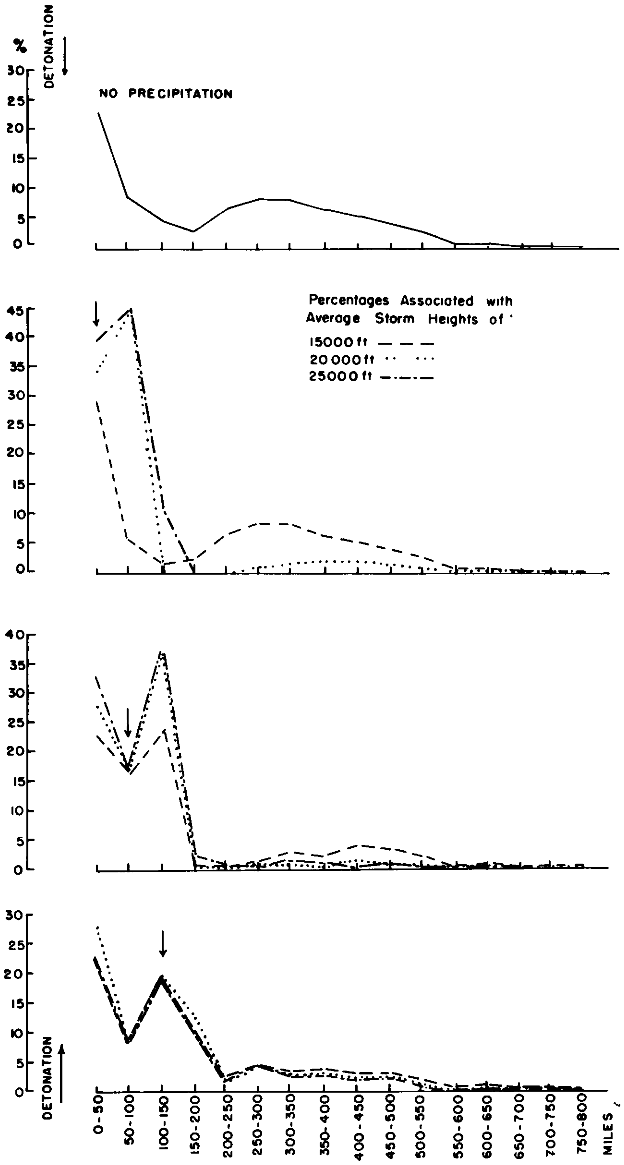


Fig. 2. Computed distribution on the ground for particles each containing 0.5% of the total radioactivity for a 10 KT detonation during the storm of 8-9 November 1957. A) Pattern for the average wind field during the storm but with no rain. B) and C) Patterns for two particular assumed positions and times of detonation for the same average wind field and the actual rain distribution observed by the radar.



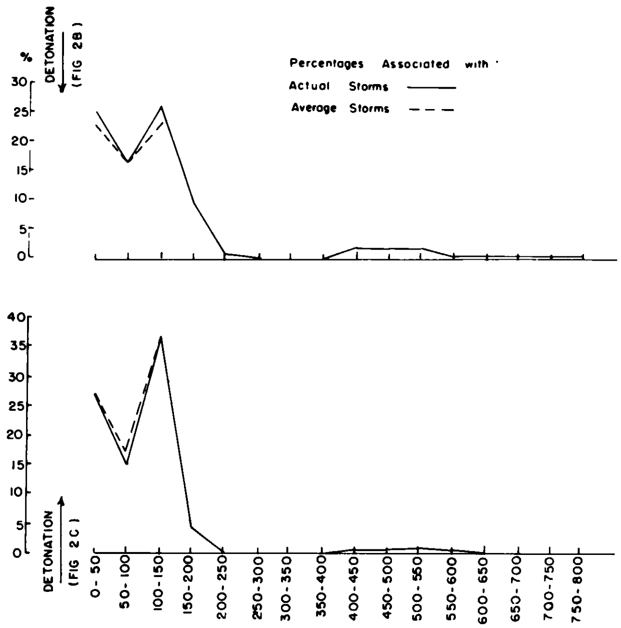


Fig. 4 (above). Comparison of the effects of actual storms (modifications shown in Figs. 2B and 2C) with the average effect of 10 x 10 mi storms (in the same 50 x 50 mi areas) on the fallout pattern depicted in Fig. 2A.

Fig. 3. Percentages of radioactive fallout from a 10 KT detonation during the storm of 8-9 November 1957 taken radially at 50 mi intervals from the point of detonation for situations involving A) No precipitation. B) Average effects of 10 x 10 mi storms of varying heights located in different 50 x 50 mi areas. Initial storm locations are depicted by the short arrows.

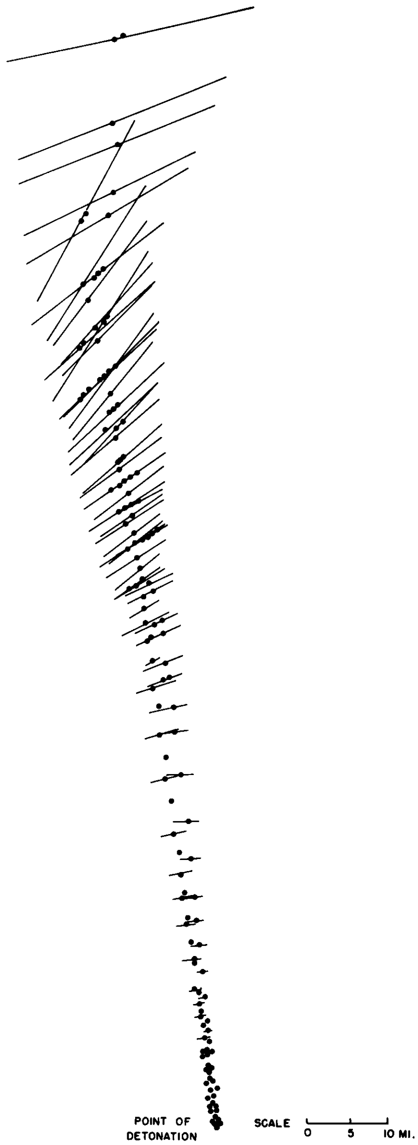


Fig. 5. Computed distribution on the ground, in the absence of rainout effects, of particles each containing 0.5% of the total radioactivity for a 10 KT detonation during the storm of 22-23 July 1959. The lines indicate possible horizontal dispersion of particles due to the use of non-averaged winds.

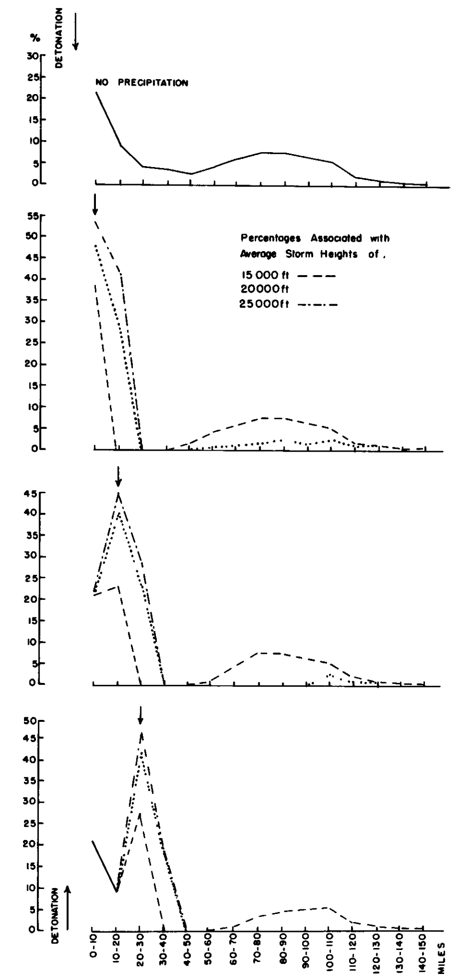


Fig. 6. Percentages of radioactive fallout, from the 10 KT detonation of 22-23 July 1959 taken radially at 10-mi intervals from the point of detonation, for situations involving:

A. No precipitation.

B. Average effects of 10 x 10 mi storms of varying heights located in different 10 x 10 mi areas. Initial storm locations are depicted by the short arrows.

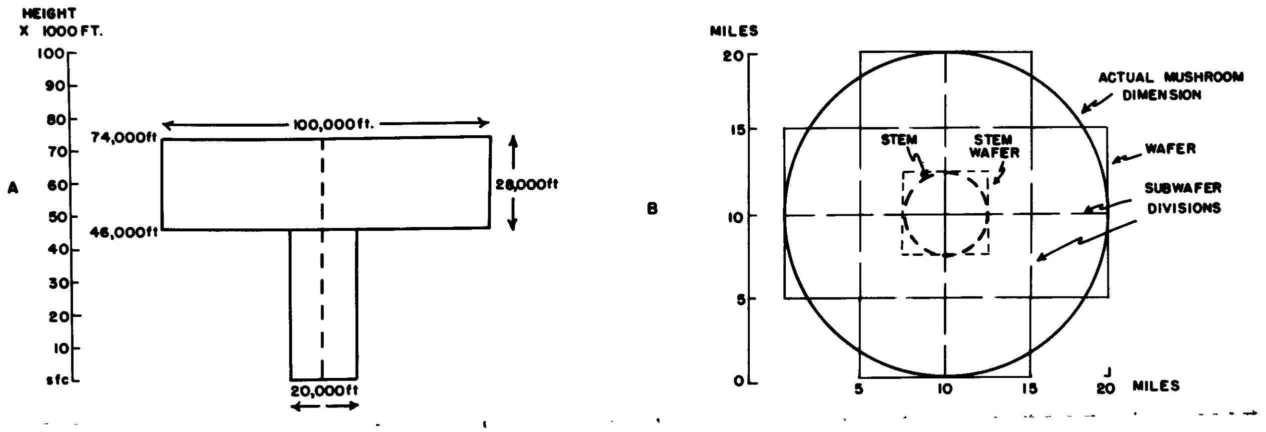


Fig. 7. A) Vertical bomb dimensions of the 1 megaton blast used in conjunction with the machine computation method. B) Top view of the 1 megaton detonation, showing a single mushroom wafer and its division into subwafers. The corresponding stem and its wafer representation is also depicted.

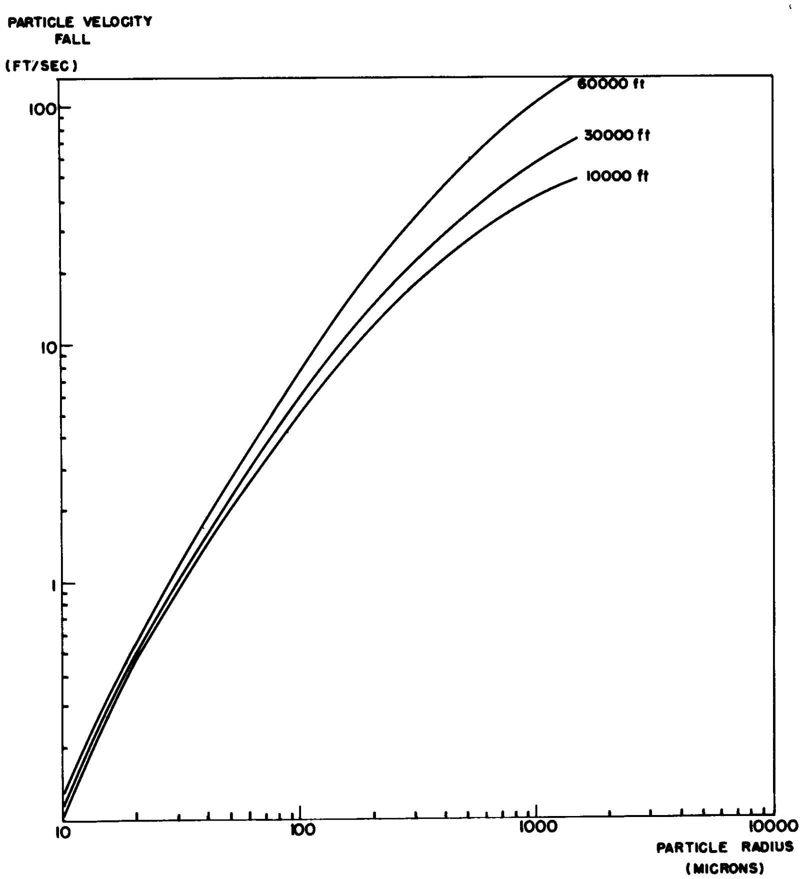


Fig. 8. Particle fall velocities for various size particles of 2.5 gms/cm^3 density at three levels in the atmosphere.

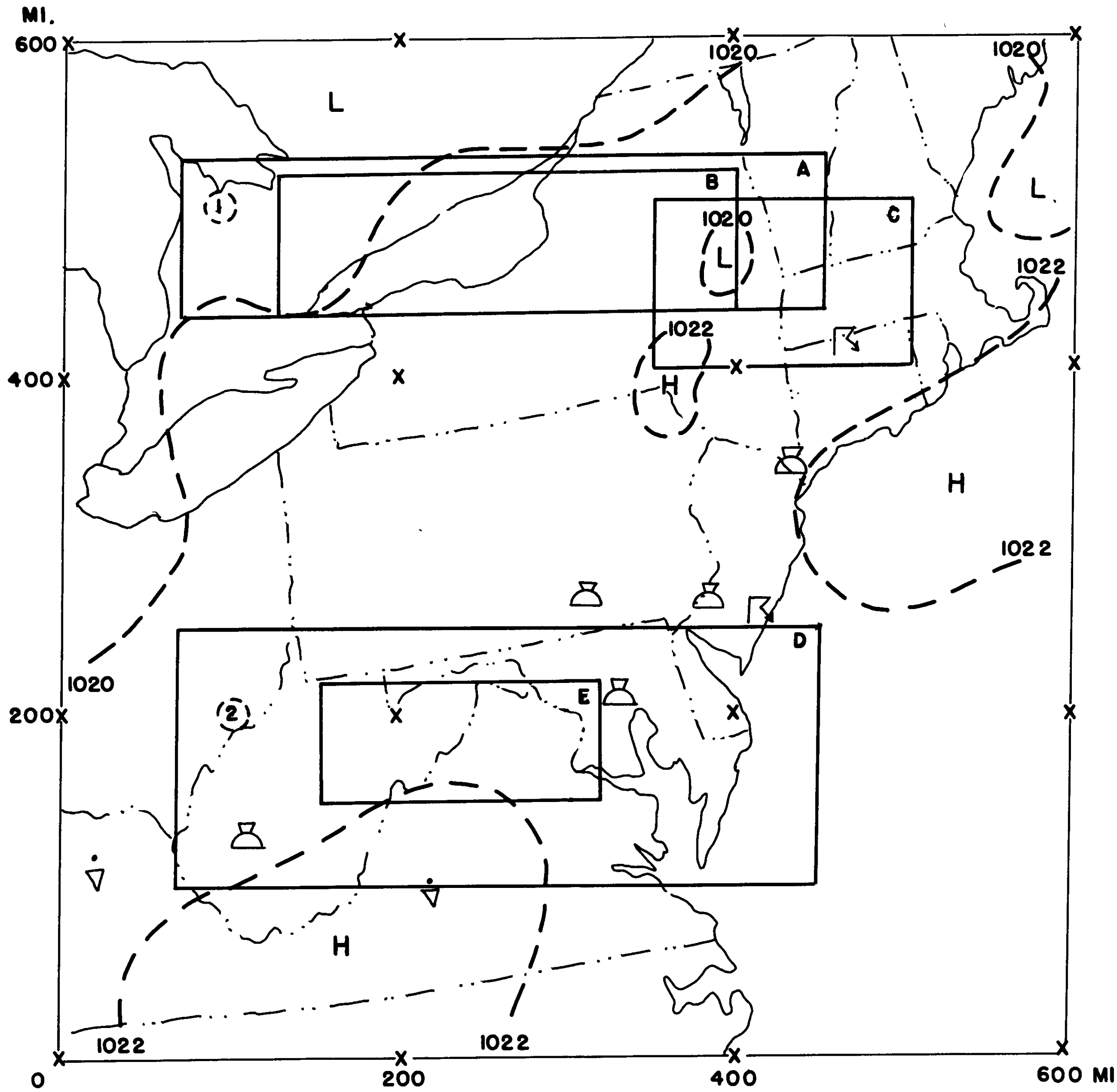


Fig. 9. The 23 July 1959, 0000Z surface weather pattern in the 600 x 600 mi fallout grid at the time of the two assumed 1 megaton detonations. Bomb dimensions and detonation points are indicated by the circled numbers. #1 is located at X = 95, Y = 505, on the fallout grid. #2 is located at X = 100, Y = 200. The rectangles labeled A, B, C, D, and E, identify areas in which specific fallout patterns in Fig. 10 through Fig. 22 took place. Each cross represents the position of a grid wind.

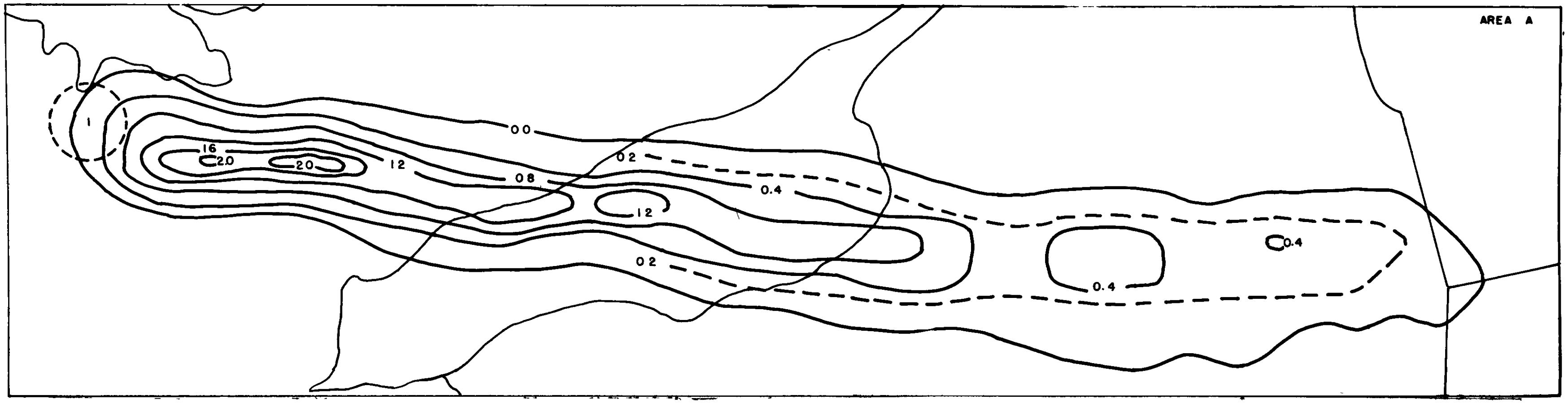


Fig. 10. The 12-hr fallout ground pattern in the absence of precipitation from a 1 megaton blast during the storm of 22-23 July 1959, with point of detonation at X = 95, Y = 505, on the fallout grid. Isolines and the numbers associated with them indicate percentages of the total representative particles from the mushroom. The entire pattern contains 54% of these particles.

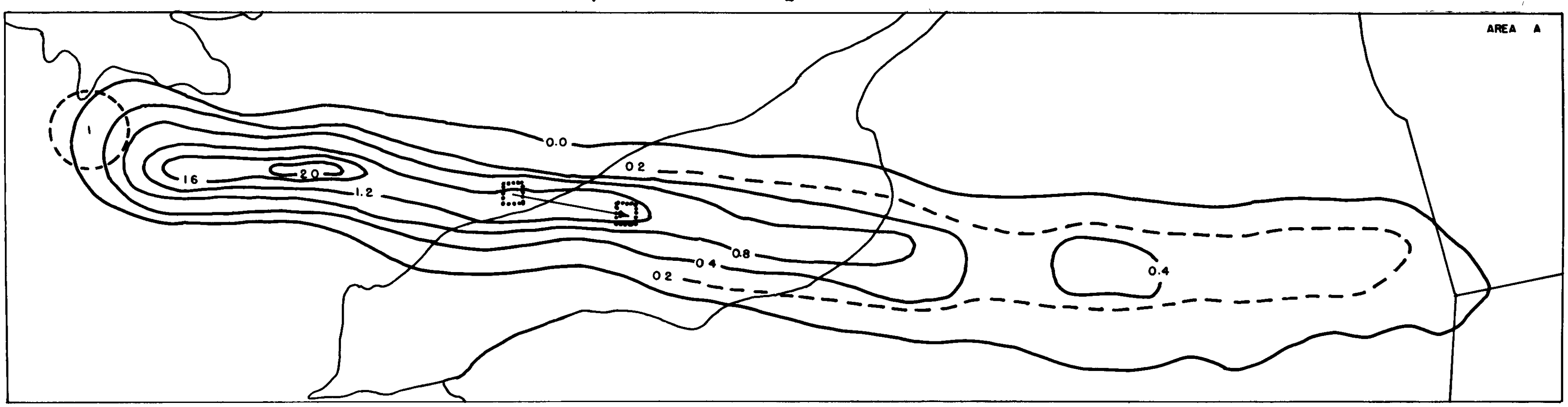


Fig. 11. Same as Fig. 10. However, the pattern is modified by the rainout effect from an idealized 5 x 5 mi storm (dotted square) of 1 hr 40 min duration beginning at D + 3 hrs with movement as indicated by the arrow.

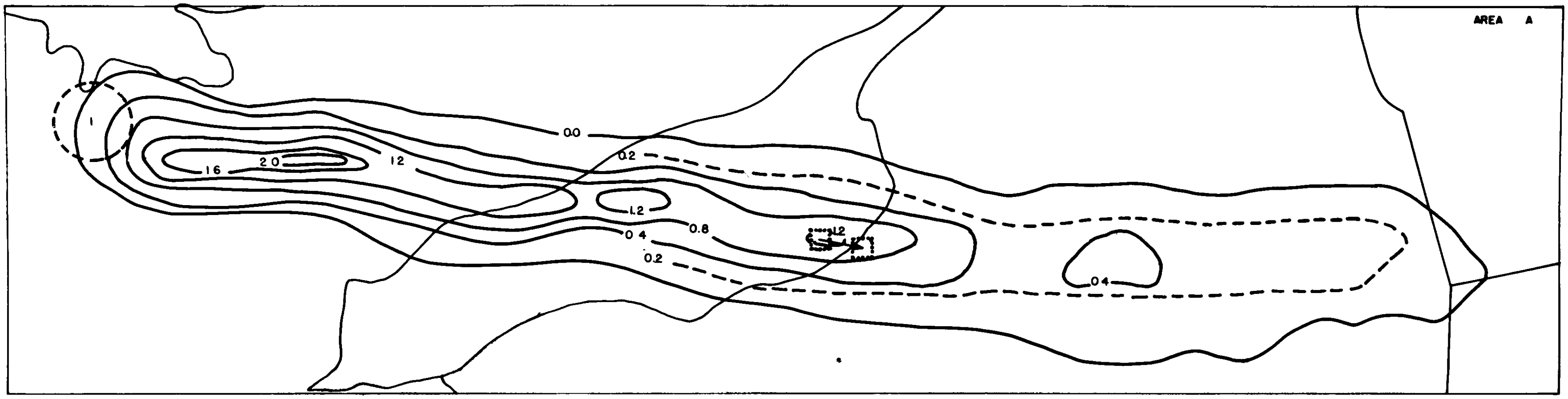


Fig. 12. Same as Fig. 10, except for the modification by the rainout effect from an idealized storm of 1 hr duration beginning at D + 5:50 hrs.

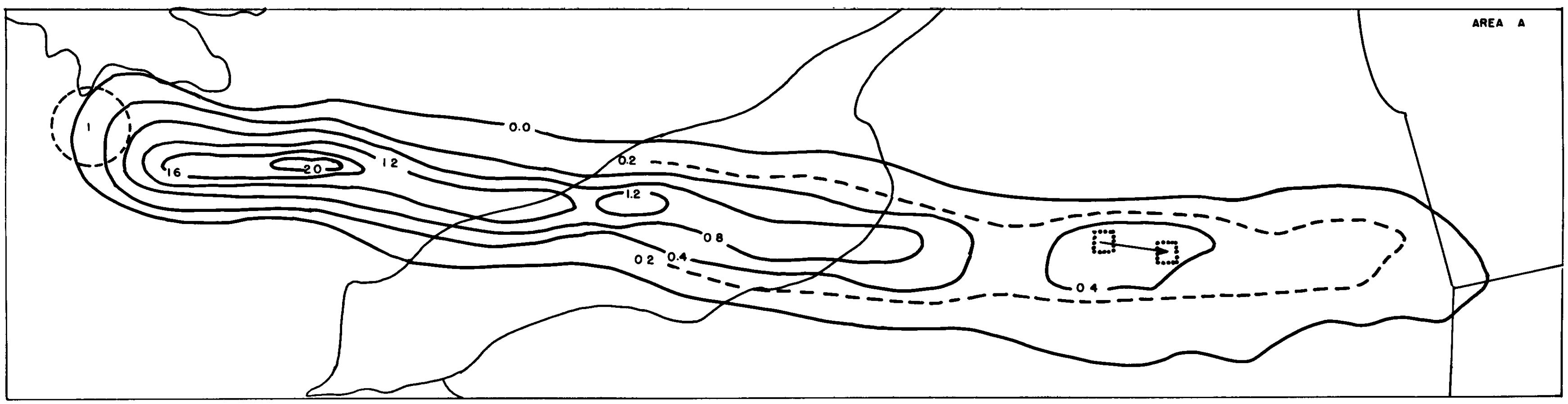


Fig. 13. Same as Fig. 10 except for the modification by the rainout effect from an idealized storm of 1 hr duration beginning at D + 5:50 hrs. The storm differs from that of Fig. 12 only in its location with respect to the point of detonation.

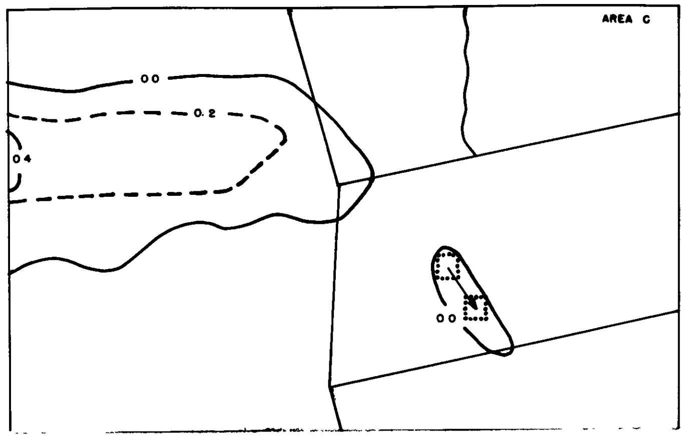


Fig. 14. Same pattern as Fig. 10 except for an area in western Mass. where rainout occurred due to an actual storm of 1 hr duration, as observed by weather radar, beginning at D+9 hrs.

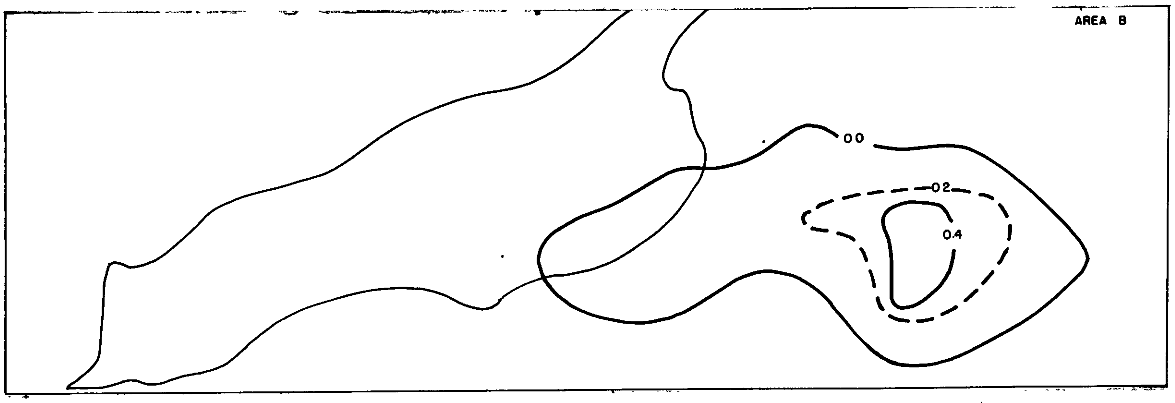


Fig. 15. Particle distribution at **D+6 hrs** in 25000-30000 ft layer from a 1 megaton detonation (storm of 22-23 July 1959) at X=95, Y=505---containing 4% of the mushroom particles.

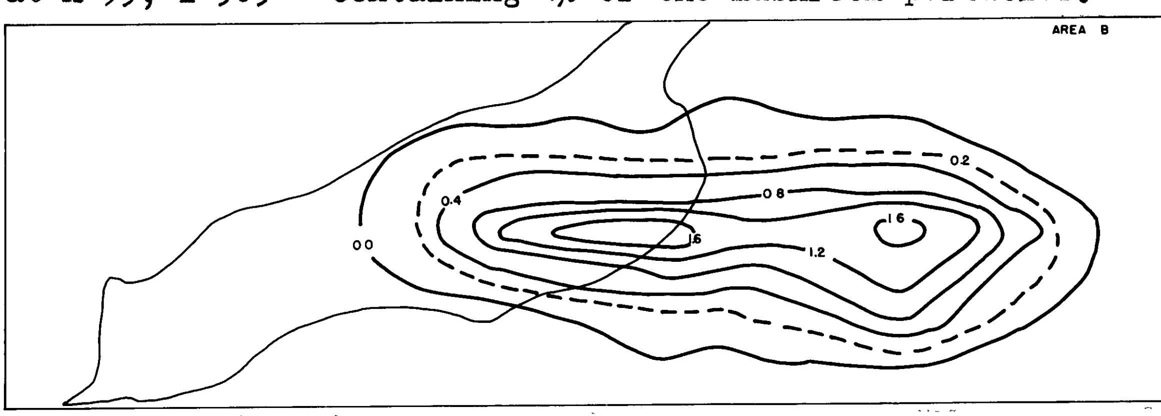


Fig. 16. Same as Fig. 15: 0-40000 ft layer, containing 40% of the mushroom particles.

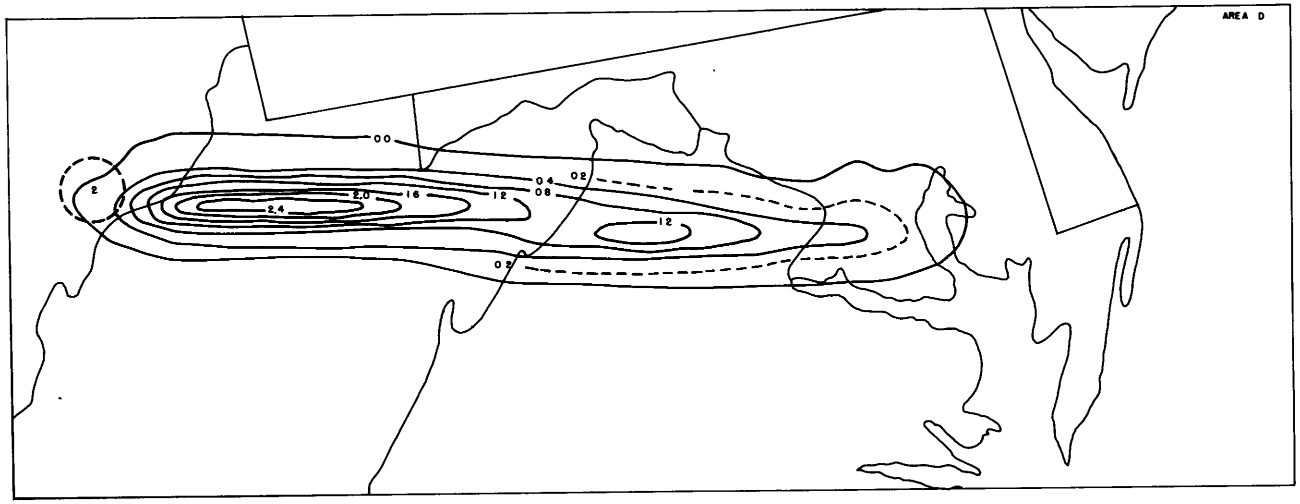


Fig. 17. The 12-hr fallout ground pattern in the absence of precipitation from a 1 megaton blast during the storm of 22-23 July 1959 with point of detonation at X=100, Y=200 on the fallout grid. Entire pattern contains 54% of the mushroom particles.

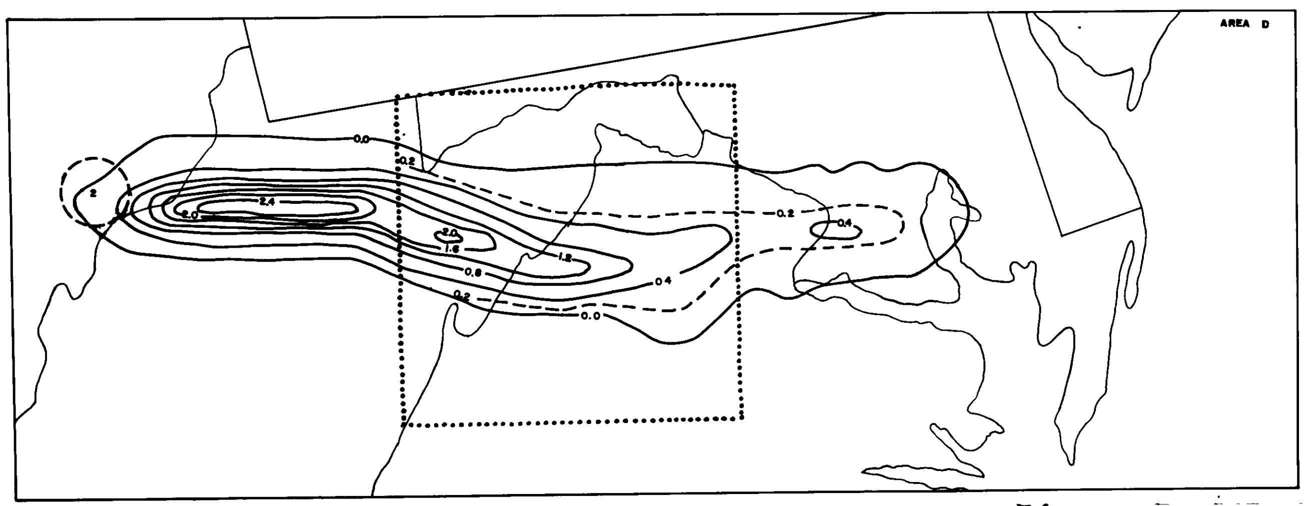


Fig. 18. Same as Fig. 21 except for the modification **by the rainout effect from a 100 x 100 mi area of warm frontal precipitation of 3 hrs duration beginning at D + 4:30 hrs.**

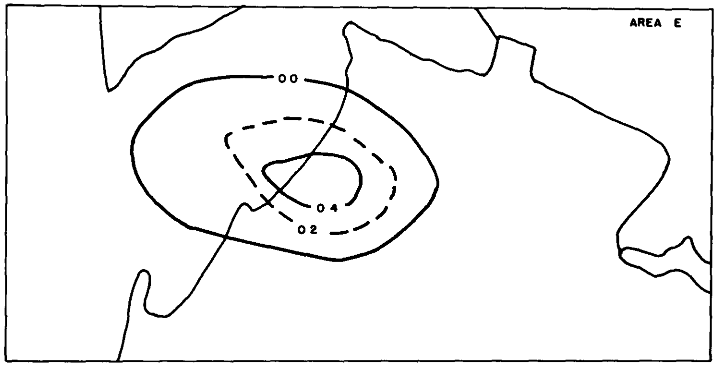


Fig. 19. Particle distribution at D+6 hrs in the 0-5000 ft layer from a 1 megaton detonation during the storm of 22-23 July 1959 at X=100, Y=200, on the fallout grid containing 3% of the mushroom particles.

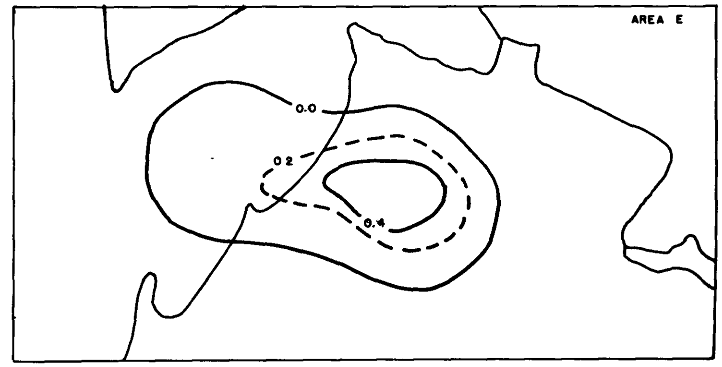


Fig. 20. Same as Fig. 23. 5000-10000 ft layer containing 4% of the mushroom particles.

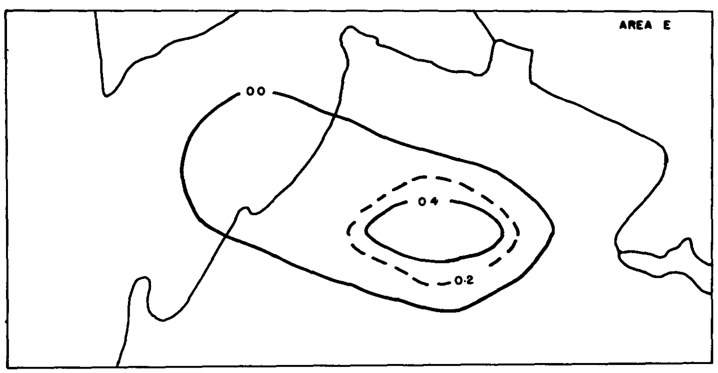


Fig. 21. Same as Fig. 23. 10000-15000 ft layer containing 4% of the mushroom particles.

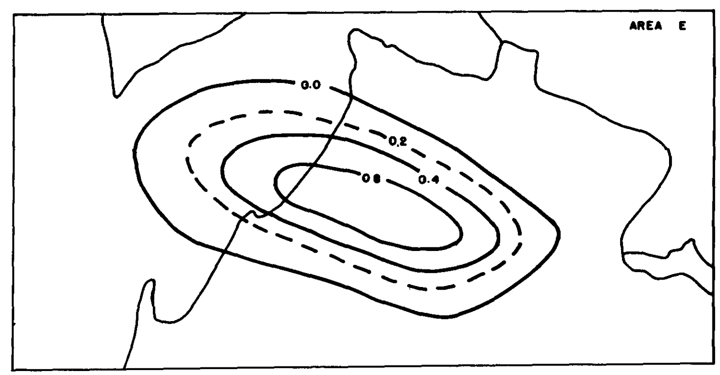
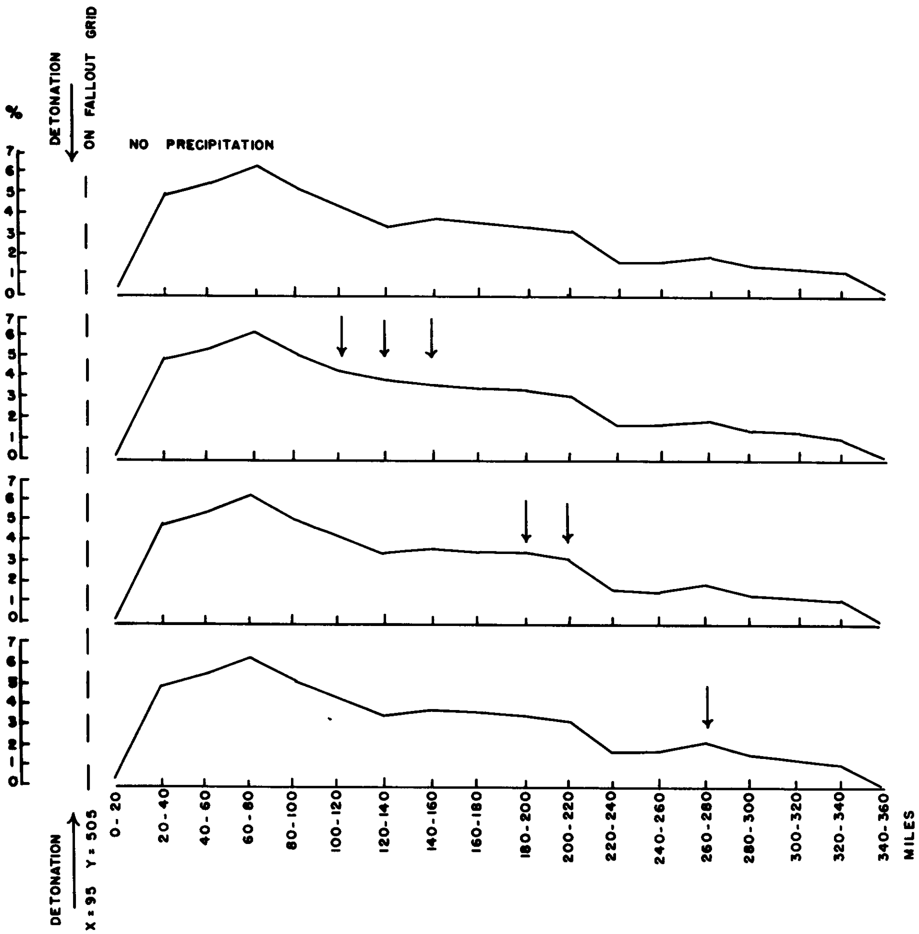


Fig. 22. Same as Fig. 23. 0-15000 ft layer containing 11% of the mushroom particles.



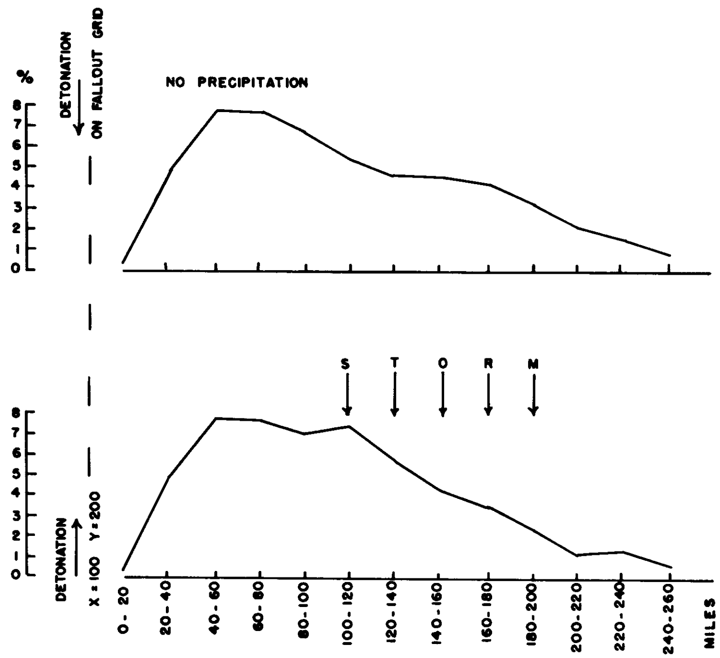


Fig. 24(above). Same as Fig. 23; warm frontal precipitation was inserted at D + 4:30 hrs.

Fig. 23. Percentage of radioactive particles from the mushroom of a 1 megaton blast taken radially from the point of detonation for the 12-hr ground patterns unaffected by precipitation and those where idealized storms (small arrows) were inserted at D + 3, D + 5:50, D + 5:50 hrs, respectively.

APPENDIX B

Table I. Representative radioactive particle distribution used in a thermonuclear detonation during the storm of 8-9 November 1957.

Mushroom Radius (microns)	Mushroom %	Stem Radius (microns)	Stem %
21 - 24	5	89	1
25 - 27	5	103	1
29	5	118	1
31	5	136	1
33	5	154	1
35	5	184	1
38	5	224	1
40	5	276	1
42 - 45	5	368	1
48 - 60	5	462	1
64 - 84	5		10
90 - 123	5		
134 - 180	5		
195 - 320	5		
347 - 491	5		
	75*		

* Particles smaller than 21 microns have been omitted.

Table II. Winds, averaged with respect to space and time over a 12 hr time interval from Albany, N.Y.; Portland, Maine; and Idlewild, N.Y., used to calculate particle trajectories for a 10 KT detonation during the storm of 8-9 November 1957.

Height (thousands of feet)	Wind Direction and Speed (deg/mi per hr)	Height (thousands of feet)	Wind Direction and Speed (deg/mi per hr)
0 - 1	175 / 35	12 - 13	215 / 83
1 - 2	187 / 54	13 - 14	215 / 81
2 - 3	194 / 58	14 - 15	215 / 78
3 - 4	199 / 69	15 - 16	216 / 76
4 - 5	203 / 72	16 - 17	218 / 76
5 - 6	208 / 74	17 - 18	219 / 78
6 - 7	212 / 74	18 - 19	222 / 80
7 - 8	214 / 74	19 - 20	225 / 83
8 - 9	215 / 74	20 - 21	227 / 83
9 - 10	215 / 78	21 - 22	227 / 83
10 - 11	215 / 83	22 - 23	227 / 83
11 - 12	215 / 83		

Table III. Winds, averaged with respect to space and time over 3 hr time intervals from Albany, N.Y.; Portland, Maine; and Idlewild, N.Y., used to calculate particle trajectories for a 10 KT detonation during the storm of 22-23 July 1959.

Height (thousands of feet)	Wind Direction and Speed (deg/mi per hr) 1800-2100Z	2100-0000Z	0000-0300Z	0300-0600Z
0 - 1	160-360/ 6	230/ 7	170-260/ 9	180-290/ 8
1 - 2	200-330/ 8	240/ 8	180-270/ 9	230-300/10
2 - 3	260/ 8	240/ 8	180-270/ 9	220-300/10
3 - 4	260/10	220-280/ 9	180-280/ 7	220-310/ 9
4 - 5	270/13	180-290/ 9	280-110/ 7	180-300/ 7
5 - 6	280/15	300/11	280-020/ 7	300/ 7
6 - 7	270/16	290/12	280-340/ 9	290/ 9
7 - 8	270/16	280/13	300/11	-
8 - 9	270/15	270/13	280/11	-
9 - 10	260/16	260/14	230-300/13	-
10 - 12	260/17	260/16	240-290/15	-
12 - 14	260/19	260/18	280/18	-
14 - 16	260/22	270/20	260-310/18	-
16 - 18	260/21	260/21	270/19	-
18 - 20	260/22	260/22	270/22	-
20 - 25	260/24	260/27	270/30	-

Table IV. Particle fallout model for a 1 megaton detonation.

Radius[1] (microns)	% in Mush	% in Stem	Distribution Code[6] Mush	Distribution Code[6] Stem	Fall Velocity (ft/sec) 73000-40000ft	Fall Velocity (ft/sec) 40000-20000ft	Fall Velocity (ft/sec) 20000-0.0ft
10- 19	12.8	-	I-L	-	0.1- 0.5	0.1- 0.4	0.1- 0.4
20- 29	15.0	-	L-M	-	0.5- 1.0	0.5- 0.9	0.5- 0.8
30- 39	12.9	-	L-J	-	1.0- 1.6	1.0- 1.4	0.9- 1.3
40- 49	10.1	-	H-J	-	1.7- 2.4	1.5- 2.0	1.4- 1.8
50- 59	7.6	-	F-H	-	2.4- 3.2	2.1- 2.7	1.9- 2.4
60- 71	7.0	-	F-I	-	3.3- 4.4	2.8- 3.7	2.5- 3.1
73- 93	8.1	0.8[5]	F-I	B-G	4.6- 6.6	3.8- 5.3	3.3- 4.4
96- 128	6.7	2.6	E-G	A-B	6.9-10.3	5.5- 7.8	4.6- 6.4
132- 174	3.5	2.2	C-D	B-C	10.8-16.2	8.1-11.6	6.7- 9.4
179- 249	1.8	1.8	A-C	C-D	16.9-25.6	12.0-17.2	9.7-14.2
260- 380	0.9	1.3	A-C	D-E	26.8-41.1	17.9-26.1	14.8-21.1
397- 620	0.1[3]	0.8	-	F	43.4-66.9	27.2-39.3	21.8-30.5
660-1440[2]	-	0.5	-	G-H	70.4-128.	41.1-70.0	31.7-48.0
	86.5[4]	10.0					

1 Each category contains 10 representative particles.
2 13 representative particles.
3 6 representative particles ending at 495 microns.
4 Particles smaller than 10 microns have been omitted.
5 6 representative particles starting at 81 microns.
6 See next page.

Table IV (cont.)

Particle Density Distribution

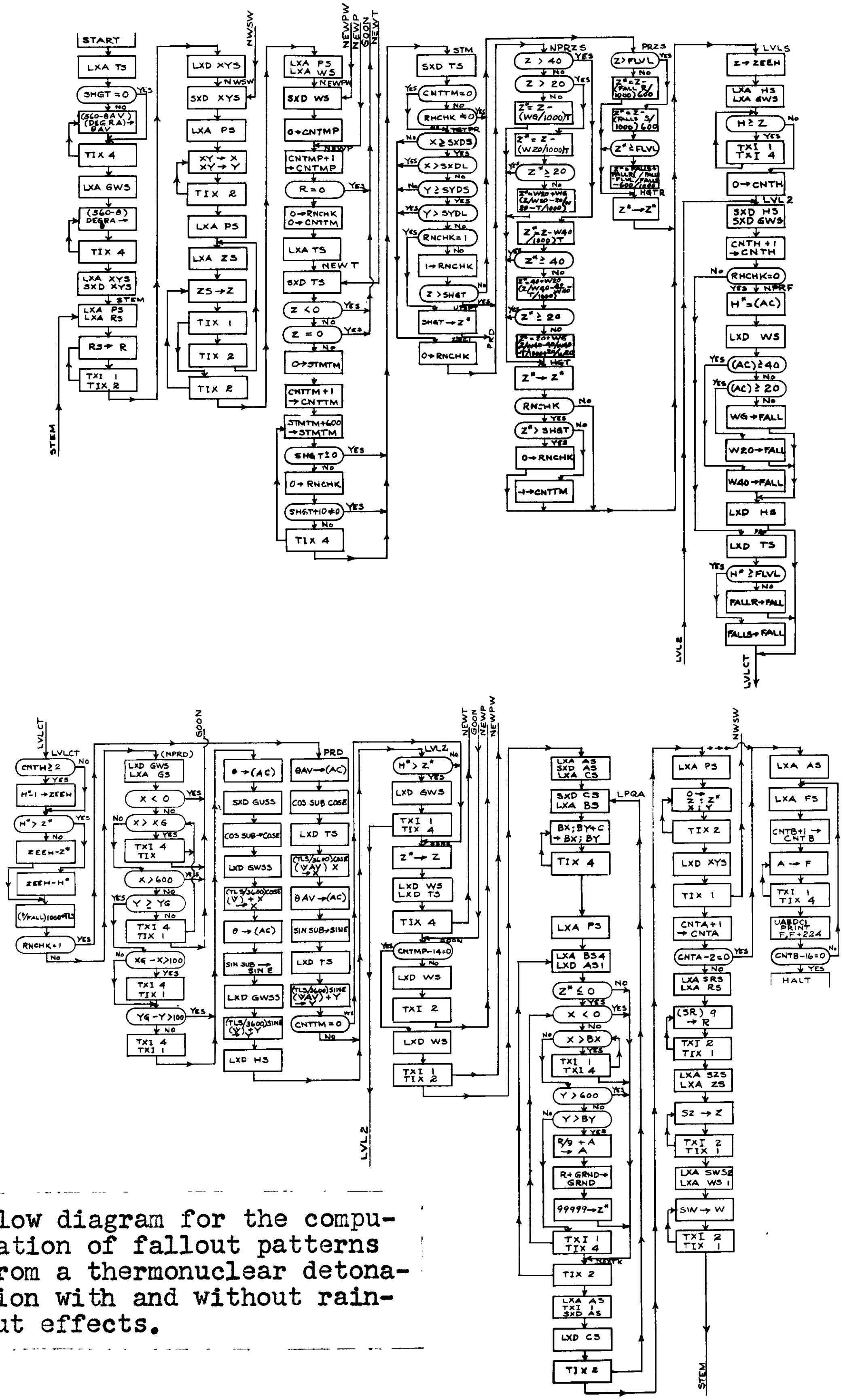
Mushroom

Height (thous of feet)	A	B	C	D	E	F	G	H	I	J	K	L	M
73	0	1	1	2	2	3	3	4	4	5	5	6	6
71	1	1	1	2	2	3	3	4	4	5	5	6	6
69	0	1	1	2	2	3	3	4	5	5	6	6	7
67	0	1	1	2	2	3	4	4	5	6	6	7	7
65	1	1	1	2	3	4	4	5	5	6	7	7	8
63	0	1	1	2	3	4	4	5	6	7	7	8	9
61	0	1	2	2	3	4	5	6	7	7	8	9	10
59	1	1	2	3	4	5	5	6	7	8	9	10	11
57	0	1	2	3	4	5	6	7	8	9	10	11	12
55	1	1	2	3	4	5	7	8	9	10	11	12	13
53	1	1	2	4	5	6	7	8	10	11	12	13	14
51	1	1	3	4	5	7	8	9	10	12	13	14	16
49	1	1	3	4	6	7	9	10	12	13	14	16	17
47	1	2	3	5	6	8	10	11	13	15	16	18	19
	8	15	25	40	51	67	78	91	105	119	129	143	155

Stem

Height (thous of feet)	A	B	C	D	E	F	G	H
41	9	8	7	6	5	4	3	2
32	8	7	6	5	4	3	2	1
23	6	5	4	3	2	2	0	0
14	5	4	3	2	1	1	0	0
5	3	2	1	0	0	0	0	0
	31	26	21	16	12	8	5	3

APPENDIX C



Flow diagram for the computation of fallout patterns from a thermonuclear detonation with and without rainout effects.

APPENDIX D

Basic Equations.

1. Vertical displacement.

The time it takes a particle, starting at height Z (thousands of feet), to reach height Z* (thousands of feet) is given by

$$T = (1000/W40)(Z - Z^*) \;,\; Z^* \geq 40$$

$$T = (1000/W40)(Z - 40) + (1000/W20)(40 - Z^*) \;,\; 40 > Z^* \geq 20$$

$$T = (1000/W40)(Z - 40)+(1000/W20)20+(1000/WG)(20 - Z^*), \; 20 > Z^*$$

where $Z > 40$

$$T = (1000/W20)(Z - Z^*) \;,\; Z^* \geq 20$$

$$T = (1000/W20)(Z - 20) + (1000/WG)(20 - Z^*) \;,\; 20 > Z^*$$

where $40 > Z > 20$

$$T = (1000/WG)(Z - Z^*) \;,\; 20 \geq Z^*$$

where $20 > Z > 0$

W40 = particle fall velocity from 73000-40000ft

W20 = " " " " 40000-20000ft

WG = " " " " 20000ft-surface.

Solving for Z* and simplifying

$$Z^* = Z - W40(T/1000)\ ,\ Z^* \geq 40$$

$$Z^* = 40 + W20[(Z - 40)/W40 - T/1000]\ ,\ 40 > Z^* \geq 20$$

$$Z^* = 20 + WG[(Z - 40/W40 + 20/W20 - T/1000]\ ,\ 20 > Z^*$$

where $Z > 40$

$$Z^* = Z - W20(T/1000)\ ,\ Z^* \geq 20$$

$$Z^* = 20 + WG[(Z - 20/W20 - T/1000]\ ,\ 20 > Z^*$$

where $40 > Z \geq 20$

$$Z^* = Z - WG(T/1000)\ ,\ 20 \geq Z^*$$

where $20 > Z > 0$.

2. Horizontal displacement.

The component horizontal displacement (miles) of a particle falling through a wind layer (layer where a particular trajectory encounters a constant wind speed and direction) is given by

$$X = V\,SIN\theta(TLS/3600)$$

$$Y = V\,COS\theta(TLS/3600)$$

V = wind speed

θ = wind direction[1]

TLS = time it takes a particle to fall through a given wind layer (sec)

[1]See next page.

[1]It should be recognized that a conversion must take place between the meteorological and mathematical coordinate systems— the former using North to represent 0° and moving clockwise, and the latter using East to represent 0° and moving counterclockwise. Since the meteorological wind direction describes the direction from which the wind is blowing, 360 − θ(meteorological) will be an accurate conversion to the mathematical coordinate system. The more familiar formulae

$X = V\cos\theta(\text{time factor})$

$Y = V\sin\theta(\text{time factor})$

are now suitable for machine computation.

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