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UNITED STATES ATOMIC ENERGY COMMISSION

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RADIOACTIVE DEBRIS FROM OPERATIONS

TUMBLER AND SNAPPER

Observations Beyond 200 Miles from the Test Site

Part II

By

Robert J. List

February 25, 1953

Weather Bureau

This document is
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ABSTRACT

The results of the fallout monitoring program at fixed stations more than 200 miles from the test site following the series of atomic tests in Nevada during the spring of 1952 are shown in a series of maps. Trajectories of debris from the individual bursts are given, together with a discussion of meteorological phenomena associated with the transport of atomic debris.

It was found that significantly greater amounts of radioactive debris were associated with tower bursts than with air drops and that significant fallout continued to be observed for longer periods following tower bursts. The important role of precipitation in bringing debris to the ground was again evident. At practically all stations, the highest activity observed on the gummed paper was associated with precipitation and with a tower burst. The maximum observed gummed paper activity was 7,900,000 d/m/ft²/day at Salt Lake City; the maximum observed air filter activity was 130,000 d/m/meter³ at Elko, Nevada.

Debris from the second burst of the series which had been predicted to move eastward, actually moved around a small, newly-formed cyclonic center in southwestern Utah and then westward over California. Although the presence of this cyclone may have been suggested by the wind field, the existence of a cloud circulation could be confirmed only by the radiological data.

Activity from this series of tests was detected in Europe and South America, and in the case of the third burst significant concentrations were detected by the monitoring network in the United States after the debris had been carried completely around the world.

CHAPTER 1

CHARACTERISTICS OF ATOMIC CLOUDS

The detonation of an atomic weapon in the atmosphere results in a tremendous heat source. This heat in turn expands the air around it and creates a bubble of intensely hot gases, which is lighter than the surrounding air. As this buoyant bubble rises, it cools both by radiation and by the entrainment of cooler surrounding air. These processes produce a violent inrush of air and serve to carry aloft not only the debris resulting directly from the fission and subsequent disintegration of the bomb casing and auxiliary equipment, but also suck up great amounts of soil and dust from the earth below. The ascending column of air and debris continues to rise until the bubble of buoyant gases has cooled to equilibrium with its environment, usually in about fifteen minutes. The height to which the cloud rises is governed primarily by the characteristics the burst and the stability of the atmosphere.

The cloud of debris which evolves after the ascent has stabilized consists initially of a long, slender "stem" capped by a broader "mushroom top." Although appreciable amounts of debris are contained in the stem, the great bulk of the material is in the mushroom cap. The subsequent configuration of the cloud is determined by such factors as the size distribution of the particles and the rate at which they fall out and the nature of the wind field which moves and diffuses the cloud.

The movement of the cloud is governed by the wind field. At any given level the trajectory of the primary cloud, that portion of the initial cloud which moves approximately horizontally and is unaffected by diffusion or fallout, can be computed by conventional meteorological techniques from upper air wind and pressure data. The determination of the movement of all the debris is, however, a much more complex problem.

It is, of course, apparent that all of the particles will descend relative to the air around them. The larger particles will fall to the ground soon after the burst, while the smaller particles will remain airborne for long periods--some for many weeks. Knowledge of the size distribution and fall velocities of the particles is so incomplete that only qualitative estimates can be used.

Similarly, the phenomenon of diffusion is difficult to treat in a quantitative manner. It is evident that the ever-present turbulent elements of the atmosphere will diffuse the debris both horizontally and vertically, at a rate many orders of magnitude greater than

ordinary molecular diffusion. The extent of the diffusion depends not only on the characteristics of the turbulent eddies of the atmosphere but also on the time and space scale under consideration. As the cloud grows, larger and larger eddies become diffusing elements, so that the rate of growth increases.

Horizontal and vertical wind shears coupled with fallout and diffusion result in a very rapid spreading of the cloud, both in width and, even more markedly, in length. In fact, after a few days of cloud growth the ordinary cyclones and anticyclones of the weather map can act as diffusing elements. Although primary cloud movement and the effects of shear can be determined quantitatively, the complications introduced by fallout and diffusion make it necessary to use empirical techniques derived from studies of these and other atomic clouds in order to determine the areas affected by debris from the tests.

CHAPTER 2

METEOROLOGICAL TRAJECTORIES

The movement and distortion of the primary cloud, which can be thought of initially as the vertical line representing the core of the cloud after it stabilizes, can be computed from routine upper-air meteorological observations. In the continental United States, there are about 140 stations which report the direction and speed of the winds aloft every six hours. In addition, about 45 stations take vertical soundings of the pressure, temperature and moisture content of the air to very high elevations (about 60,000 feet on the average) every 12 hours. The results of these observations are normally entered on maps representing surfaces of constant pressure. For most purposes, including this report, these surfaces may be considered as levels of constant height above sea level. The standard pressure surfaces for which meteorological charts are usually drawn and the heights above sea level which they approximate are given in Table 2.1.

TABLE 2.1

Standard Meteorological Surfaces

<u>Pressure</u>	<u>Approximate Height Above Sea Level</u>
850 millibars	5,000 feet
700 "	10,000 "
500 "	18,000 "
400 "	24,000 "
300 "	30,000 "
200 "	40,000 "

Since the 850 mb level is near to, or even below, the surface of the earth in the vicinity of the Nevada Proving Ground, no attempt was made to trace the primary cloud at this level, although some debris certainly is carried at levels below 10,000 feet. Therefore, trajectories of the primary cloud were computed for each burst at all standard meteorological levels from 700 mb to the top of the

mushroom. Where the top of the mushroom reached an elevation between two standard levels and it was felt that movements computed from the nearest standard surface would be unrepresentative, additional maps were drawn for the intermediate level. Since the bulk of the radioactive debris is contained in the mushroom top, it was considered particularly important to attempt to track the cloud at that level.

All trajectories were computed by assuming that the flow patterns indicated on a given map were representative of the six-hour period centered at the time of the observations. As far as possible, actual wind observations were used to determine the flow patterns. On occasion, however, due to the paucity of wind observations it became necessary to use the geostrophic wind, which is based on the relation of the pressure pattern to the wind field.

Meteorological trajectories are, of course, subject to error, particularly at levels or over regions of sparse data. In general, over the United States for trajectories of the order of a thousand miles, it has been found that the errors average ten to twenty percent of the length of the trajectory.

CHAPTER 3

FALLOUT MONITORING

3.1 SAMPLING TECHNIQUES

As described in Part I of the report, the two types of equipment used in collecting debris at the ground by the fixed stations were gummed paper and high-volume air filters, the former at 97 stations in the United States, Canada and Bermuda and at 13 other foreign stations; the latter at 51 stations within 1,000 miles of the test site. Twenty-two stations made both types of observations. The location of the stations in the United States, Canada and Bermuda and the type of observations made at each is shown in Figure 3.1.

There is a fundamental difference between the two types of observation. The gummed paper collects debris actually deposited on a horizontal surface, while the air filter collects particles suspended in, or falling through the air.

Studies of previous tests, which have also been verified in the present tests, have shown that the gummed paper collects significantly greater amounts of debris during periods of precipitation, as compared to periods of no precipitation. No such large bias was found with the air filter samples.

A comparison of gummed paper and air filter results for the five stations furthest from the test site making both types of observations is shown in Figure 3.2. The stations, Williston, North Dakota; Bismarck, North Dakota; Huron, South Dakota; Norfolk, Nebraska; and Concordia, Kansas, are all about 1,000 miles from the site. The activity indicated by the air filter is plotted against the activity on the gummed paper for every case in which at least one of the measurements indicated significant amounts of debris were present on the sampling date (0.1 d/m/meter^3 for the air filter or $100 \text{ d/m/ft}^2/\text{day}$ for the gummed paper). The open circles indicate that no precipitation had fallen during the period, the solid circles indicate the occurrence of precipitation. It is evident there is a positive correlation between the two types of observation. An estimated regression line is shown. However, the tendency for precipitation to bring higher values to the gummed paper relative to the air filter readings is indicated by the tendency for the solid circles to lie below the regression line, as well as by the increasing proportion of solid circles to be found with increasing gummed paper activity. The latter tendency is not found with the air filter observations.

FIGURE 3.1 LOCATION OF FALLOUT MONITORING STATIONS IN THE UNITED STATES AND CANADA

It should be emphasized that the characteristics of the gummed paper are not fully known. For example, the effect of temperature and humidity on the stickiness of the paper has not been investigated. A snow cover would undoubtedly affect the collection characteristics. The amount of debris carried away in rain which runs or spatters off the surface is not known, nor is the effect of the vigor with which the observer shakes off surplus water when removing a rain-soaked paper from the frame. However, the increase of reported activity in precipitation indicated that debris is carried down in the precipitation, and that the gummed paper does retain much of this debris.

The air filter, on the other hand, was sheltered from the rain and debris contained in the precipitation elements is not collected. Occasionally, in heavy rain, the water did get to the filter, in which case the filter frequently burst and the sample was lost.

3.2 EXTRAPOLATION TO SAMPLING DATE

All activity reported for the United States and Canadian stations has been extrapolated to the sampling date. This has been done by ascribing the measured activity to a particular burst and assuming that the decay has been proportional to $t^{-1.2}$, where t is the time since the burst. No attempt has been made to extrapolate the samples from Mexico, Central or South America, Europe, or Africa because of the difficulty of ascribing the observed activity to a particular burst.

Even for the domestic stations, there is considerable uncertainty in determining which burst is responsible for the activity at a given station, although the bursts were separated by several days in these tests. In addition to considering the computed meteorological trajectories and estimates of low-level trajectories made from the flow patterns near the ground, it is also necessary to note the arrival of increased activity at the various stations. This is not always easily done; for example, the onset of precipitation can result in increased activity on the gummed paper which may erroneously be ascribed to the arrival of debris from a more recent burst. Changing wind speeds or directions may also cause increases of activity not associated with a new burst; this is especially true in the dry areas of the Southwest. Since the samples are not measured until quite a few days, and in some cases weeks, after the date of observation, the extrapolation factors can be quite large, as much as two orders of magnitude, if the collection was made within a day of the assigned burst. Another source of difficulty is that minor contamination of the sample in the counting process could result in very high extrapolated values, a possible example of this is pointed out below in the discussion of the first burst. Also, mixed debris from two bursts would in general be all ascribed to the latest burst.

These factors, coupled with the tendency to ascribe debris to the latest burst when there is some doubt as to its origin, make for a definite bias toward reporting higher activities than actually existed.

CHAPTER 4

RESULTS OF THE TUMBLER-SNAPPER FALLOUT MONITORING PROGRAM

4.1 BURST DATA

Table 4.1 lists the bursts of the Tumbler-Snapper series, the type of burst and the reported heights of the mushroom tops.

TABLE 4.1

Tumbler-Snapper Tests

<u>Burst</u>	<u>Date</u>	<u>Time*</u> <u>(GCT)</u>	<u>Type</u> <u>of Burst</u>	<u>Height of</u> <u>Detonation</u> <u>Above Ground</u> <u>(feet)</u>	<u>Height of Top</u> <u>of Cloud (MSL)</u> <u>(feet)</u>
1	1 Apr 52	1700	Air Drop	800	16,000
2	15 Apr 52	1730	Air Drop	1,050	15,500
3	22 Apr 52	1730	Air Drop	3,450	42,000
4	1 May 52	1630	Air Drop	1,050	43,500
5	7 May 52	1215	Tower	300	34,000
6	25 May 52	1200	Tower	300	41,000
7	1 Jun 52	1155	Tower	300	37,000
8	5 Jun 52	1155	Tower	300	41,500

*To nearest five minutes.

Since the heights of the cloud tops were estimated from aircraft or ground observations, it must be assumed that some uncertainty exists as to the exact heights, particularly for the higher clouds.

4.2 PRE-TEST BACKGROUND IN THE UNITED STATES

The level of activity found on the gummed papers prior to this series of tests is shown in Figure 4.1. The figures indicate the average activity ($d/m/ft^2/day$) found on all papers exposed at the various stations during the week preceeding the burst. It is evident

FIGURE 4 1 PRE-TEST BACKGROUND VALUES ON THE GUMMED PAPERS ($d/m/ft^3/day$)

that the background activity deposited on the gummed papers was negligible. The highest average activity at any of the stations was $10 \text{ d/m/ft}^2/\text{day}$ and the highest activity found on any individual paper was $45 \text{ d/m/ft}^2/\text{day}$.

Unfortunately, air filter measurements were not started at most stations until the day of the first burst, so that no similar series of background observation is available. However, at those stations which were obviously unaffected by the first burst on observations started at 1830 GCT 1 Apr, the activity was less than 0.05 d/m/meter^3 , and in many cases no activity was found.

4.3 MAXIMUM OBSERVED ACTIVITY IN THE UNITED STATES AND CANADA

Table 4.2 shows the highest activity reported at each of the domestic stations on both the gummed paper and the air filter during periods of no precipitation and during periods with a trace of precipitation or more (see Appendix A for precipitation code). The stations are grouped in accordance with distance from the test site. The efficacy of precipitation in depositing high activity on the gummed paper is clearly evident for stations at some distance from the test site. Only two stations* more than 1,000 miles from the site had over $20,000 \text{ d/m/ft}^2/\text{day}$ without precipitation, while many experienced over $100,000 \text{ d/m/ft}^2/\text{day}$ in precipitation. It should be pointed out that for stations close to the site, a considerable bias exists for high counts to occur in days without precipitation because of the fact that no tests were detonated when there was rain in the area. Also, in the southwest, the dry climate means there is a preponderance of days without rain; no such strong preponderance of days without precipitation exists at stations over 1,000 miles from the site.

Figure 4.2 shows the highest activity encountered on the gummed papers in each of the groups of Table 4.2, plotted as a function of the distance of the outer boundary of that group from the test site. The solid circles represent the cases with precipitation, the open circles the cases of no precipitation. Some idea of the maximum activity to be expected at various distances from the test site can be obtained from this figure. However, great caution must be exercised in drawing any general conclusions, since the data represent a very limited sample, and presumably a combination of circumstances not encountered in these tests could produce much higher concentrations of radioactivity, particularly at those stations closest to the test site. In any case, these figures would only apply to the types of bombs and techniques of detonation used in the Tumbler-Snapper series.

*These observations, incidentally, each showed high counts on only one of the three simultaneously exposed papers; the other two had negligible activity.

TABLE 4.2

Maximum Observed Activity at North American Stations

Station	<u>Gummed Paper</u>						<u>Air Filter</u>					
	<u>No Rain</u>			<u>Rain</u>			<u>No Rain</u>			<u>Rain</u>		
	Activity d/m/ft ² /day	Burst		Activity d/m/ft ² /day	Precip.	Burst	Activity d/m/meter ³	Burst		Activity d/m/meter ³	Precip.	Burst
A: Stations 200-400 naut. miles from the test site												
51 Santa Catalina, Calif.	54,000	3		23,000	2	2						
Los Angeles, Calif.							38	5		2.1	2	7
Bakersfield, Calif.							51	2		0.2	4	3
Fresno, Calif.	23,000	7		18,000	2	7	50	8		130	2	7
Sacramento, Calif.							18	8		5.4	3	8
Reno, Nev.	60,000	7		47,000	2	7	150	7		130	4	8
Winnemucca, Nev.							2400	7		5700	4	8
Elko, Nev.	710,000	7		400,000	4	8	93,000	7		130,000	4	8
Salt Lake City, Utah	3,300,000	5		7,900,000	4	5	1200	8		160	3	8
Flagstaff, Ariz.	5500	4		62,000	2	6						
Phoenix, Ariz.							230	6		46	3	7
Yuma, Ariz.	2200	6		19,000	2	7	16	8		11	2	7
San Diego, Calif.							4.1	8		2.6	5	7
B: Stations 400-600 naut. miles from the test site												
Eureka, Calif.	25,000	3		27,000	3	7	5.4	6		5.1	3	7
Red Bluff, Calif.							22	7		45	4	8
Mt. Shasta, Calif.							14	6		46	2	8

TABLE 4.2 (Cont'd)

Station	<u>Gummed Paper</u>					<u>Air Filter</u>				
	<u>No Rain</u>		<u>Rain</u>			<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst	Act.	Burst	Act.	Prec.	Burst
Medford, Oregon	6300	3	61,000	5	7					
Roseburg, Oreg.						6.5	7	1.5	2	5
Burns, Oreg.						46	8	77	2	7
Pendleton, Oreg.						8.4	7	44	3	8
Baker, Oreg.						24	8	440	4	8
Boise, Idaho	24,000	8	5,900,000	2	8	730	8	6800	2	8
Pocatello, Idaho	140,000	8	1,400,000	2	7	2200	8	1400	2	7
Lander, Wyo.						300	7	510	2	5
Rock Springs, Wyo.	10,000	7	460,000	2	5	210	7	1200	2	5
Denver, Col.						230	7	220	4	6
Grand Junction, Col.	7400	7	350,000	2	6	370	8	180	2	6
Colorado Springs, Col.						290	7	140	3	6
Pueblo, Col.						330	7	290	3	6
Alamosa, N. M.						190	7	520	4	6
Raton, N. M.						150	6	210	2	7
Albuquerque, N. M.	11,000	6	68,000	6	7	340	7	92	5	6
Tucson, Ariz.	8900	6	160,000	3	7	260	6	88	3	7

C: Stations 600-800 naut. miles from the test site

Northhead, Wash.	370	4	2100	5	6					
Spokane, Wash.	13,000	8	36,000	3	7	3.1	6	17	3	7
Kalispell, Mont.						210	8	51	5	8
Missoula, Mont.						110	7	220	8	8

TABLE 4.2 (Cont'd)

Station	<u>Gummed Paper</u>					<u>Air Filter</u>				
	<u>No Rain</u>		<u>Rain</u>			<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst	Act.	Burst	Act.	Prec.	Burst
Butte, Montana						220	7	990	5	8
Helena, Mont.						380	7	900	5	8
Great Falls, Mont.	190,000	8	3,600,000	4	8					
Havre, Mont.						280	8	780	5	8
Billings, Mont.	35,000	7	69,000	2	8	810	7	390	2	8
Sheridan, Wyo.						420	7	390	2	8
Casper, Wyo.						280	7	500	2	8
Rapid City, S. D.	46,000	7	55,000	6	7	90	7	90	3	7
Scottsbluff, Nebr.	7800	7	160,000	4	5	190	7	320	2	7
Cheyenne, Wyo.						700	7	270	4	7
North Platte, Nebr.						130	7	150	3	8
Goodland, Kans.	4100	7	180,000	5	6	180	8	140	4	7
Dodge City, Kans.						150	7	17	5	6
Amarillo, Tex.	7600	6	7900	2	5					
Roswell, N. M.	31,000	7	190,000	3	7					
D: Stations 800-1000 naut. miles from the test site										
Williston, N. D.	12,000	7	16,000	4	8	74	7	230	4	8
Bismarck, N. D.	7600	8	21,000	3	7	52	8	190	2	8
Huron, S. D.	45,000	7	98,000	6	7	10	8	42	6	7
Valentine, Nebr.						120	7	120	6	8
Norfolk, Nebr.	13,000	7	260,000	3	7	75	7	88	2	7

TABLE 4.2 (Cont'd)

Station	<u>Gummed Paper</u>					<u>Air Filter</u>				
	<u>No Rain</u>		<u>Rain</u>			<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst	Act.	Burst	Act.	Prec.	Burst
Concordia, Kans.	280,000	7	170,000	3	1	270	7	200	3	7
Wichita, Kans.	85,000	8	130,000	7	7					
Wichita Falls, Tex.	14,000	1	23,000	5	7					
Abilene, Tex.	4100	6	17,000	4	7					
Del Rio, Tex.	3400	6	730	4	5					

16 E: Stations 1000-1200 naut. miles from the test site

Fargo, N. D.	6300	7	14,000	3	6
St. Cloud, Minn.	8400	7	76,000	6	6
Rochester, Minn.	3000	7	140,000	4	7
Des Moines, Iowa	6000	7	240,000	5	7
Columbia, Mo.	18,000	7	35,000	2	1
Ft. Smith, Ark.	2800	7	110,000	6	7
Texarkana, Ark.	52,000	7	19,000	6	7
Port Arthur, Tex.	7600	5	2000	4	1
Corpus Christi, Tex.	3000	6	6000	2	7

F: Stations 1200-1400 naut. miles from the test site

Green Bay, Wis.	6800	7	14,000	4	7
Milwaukee, Wis.	5500	7	290,000	5	7
Terre Haute, Ind.	13,000	7	460,000	5	7

TABLE 4.2 (Cont'd)

Gummed Paper

Station	<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst
Memphis, Tenn.	4100	7	10,000	4	7
Jackson, Miss.	6000	5	6800	6	1
New Orleans, La.	4400	6	5400	5	8
Peoria, Ill.	6400	7	260,000	5	7

G: Stations 1400-1600 naut. miles from the test site

17	Marquette, Mich.	2800	7	8100	5	8
	Saulte Ste Marie, Mich.	67,000	8	12,000	6	8
	Escanaba, Mich.	2500	7	13,000	3	7
	Alpena, Mich.	5900	7	29,000	4	7
	Grand Rapids, Mich.	11,000	7	400,000	6	7
	Toledo, Ohio	17,000	7	20,000	2	7
	Fort Wayne, Ind.	6700	7	99,000	3	7
	Dayton, Ohio	10,000	7	18,000	6	7
	Louisville, Ky.	4600	7	34,000	4	7
	Nashville, Tenn.	15,000	7	31,000	5	7
	Knoxville, Tenn.	6900	7	22,000	3	7
	Atlanta, Ga.	2400	4	6500	2	5
	Birmingham, Ala.	3900	5	7900	2	5
	Montgomery, Ala.	3600	5	42,000	4	3
	Mobile, Ala.	1800	2	6300	4	7

H: Stations 1600-1800 naut. miles from the test site

	North Bay, Ont.	1000	8	5200	3	8
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TABLE 4.2 (Cont'd)

Gummed Paper

Station	<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst
Rochester, N. Y.	4100	6	93,000	3	7
Buffalo, N. Y.	6000	7	64,000	3	7
Dansville, N. Y.	2800	7	68,000	6	7
Dunkirk, N. Y.	4500	8	55,000	3	7
Youngstown, Ohio	2400	7	20,000	3	7
Charlestown, W. Va.	4200	7	8400	2	7
Lynchburg, Va.	3300	5	17,000	2	7
Greenville, S. C.	1500	7	42,000	3	5
Florence, S. C.	24,000	7	34,000	4	3
Savannah, Ga.	960	7	51,000	6	3
Jacksonville, Fla.	7800	8	3,000	6	3
Tallahassee, Fla.	18,000	3	3300	2	5

I: Stations 1800-2000 naut. miles from the test site

Moosonee, Ont.	1700	8	56(u)	5	8
Watertown, N. Y.	1900	7	170,000	5	7
Oswego, N. Y.	1400	7	140,000	4	7
Syracuse, N. Y.	2100	7	34,000	3	7
Albany, N. Y.	940	7	55,000	4	7
Binghampton, N. Y.	590	5	8100	2	7
La Guardia, N. Y.	5500	7	60,000	6	7

TABLE 4.2 (Cont'd)

Gummed Paper

Station	<u>No Rain</u>		<u>Rain</u>		
	Act.	Burst	Act.	Prec.	Burst
Harrisburg, Penn.	4600	7	13,000	5	3
Wilmington, Del.	3700	7	17,000	4	7
Baltimore, Md.	13,000	7	16,000	7	3
Richmond, Va.	3200	7	17,000	7	3

J:Stations 2000-2200 naut. miles from the test site

Caribou, Me.	17,000	7	14,000	6	7
Mt. Washington	2700	5	26,000	2	7
East Boston	2100	8	43,000	3	7
Providence, R. I.	2100	7	57,000	4	7

K:Stations 2200-2400 naut. miles from the test site

Moncton	90(u)	8	22,000	5	7
East Port, Me.	920	6	22,000	4	7

L:Stations 2400-2600 naut. miles from the test site

Goose Bay, Lab.	390	6	2600	2	6
Stephensville	720	8	20,000	5	7
Bermuda	1800	5	380	3	2

FIGURE 4.2 HIGHEST ACTIVITY OBSERVED ON THE GUMMED PAPERS AT VARIOUS DISTANCES FROM THE TEST SITE

In certain zones (e.g., stations from 1000-1200 nautical miles from the test site) none of the stations experienced as much activity as would have been expected on the basis of the results from stations farther from the test site. For this reason, lines representing the outer envelope of the points in Figure 4.2 at stations over 600 nautical miles from the proving ground have been drawn for the cases with precipitation (solid line) and without precipitation (dashed line). The lines have not been extended to the area close to the test site because of the greater probability that much higher activity occurred, in this area, at other than the fixed stations.

It is interesting to note in Table 4.2 that at virtually all of the stations, the highest activity is attributable to debris from the tower bursts, which create and carry aloft more debris than would result from an air drop. In general, more activity was observed in the monitoring network following a tower burst as compared with an air drop. However, other factors such as the intensity of the explosion, the height attained by the debris, and, of course, the meteorological conditions associated with the cloud may have also contributed to this difference.

4.4 FALLOUT IN THE UNITED STATES AND CANADA

4.4.1 Description of Maps

The results of the fallout monitoring program at the fixed stations in the United States, Canada, and Bermuda are in Appendix A. Figures A.1-A.79. Each map shows the results of all gummed paper and air filter observations started on a given day. All significant activities are extrapolated to the sampling date, the burst to which the debris is ascribed is also indicated, as are the precipitation amounts at each station, in accordance with the key printed on each map.

No measured gummed paper activities of less than 100 d/m/ft²/day or measured air filter concentrations less than 0.05 d/m/meter³ were extrapolated to the sampling date. For low gummed paper activities the actual unextrapolated value is given, for the air filters low concentrations are indicated by an L. In a few cases, the gummed papers were inadvertently exposed for two or more days, in that event the average daily values are shown in parentheses.

On each of the maps, a solid line outlines the area with activity greater than 1000 d/m/ft²/day on the gummed papers, a dashed line the area with more than 100 d/m/ft²/day. Areas of precipitation in the United States are indicated by shading. (Precipitation

areas are based on reports from the sampling stations only, and interpolation between the stations is approximate.)

4.4.2 Interpolation of Activity Between Stations

The drawing of isolines of activity implicitly assumes that it is possible to interpolate between stations. It is, therefore, necessary to examine the validity of this assumption. For this purpose, several groups of stations were selected, each group consisting of three stations at the vertices of a triangle and a fourth station near the center. Three such triangles were studied, selected because the stations were close together and not near the test site. These groups of stations were: 1) Goodland, Des Moines, Wichita, and Concordia, 2) Milwaukee, Alpena, Fort Wayne and Grand Rapids, and 3) Terre Haute, Dayton, Nashville and Louisville. The gummed paper activity expected at the fourth station of each group was computed by assuming a uniform gradient of activity within the triangle defined by the first three stations. Table 4.3 gives the results of these studies. The first column shows the computed activity at the fourth station, the second column the value actually observed, and the third column the ratio of the computed to the observed value.

TABLE 4.3

Interpolation Between Stations

Computed (d/m/ft ² /day)	Observed (d/m/ft ² /day)	Ratio (computed/observed)
360	160	2.2
67000	12000	5.6
660	290	2.3
240	670	0.4
7400	11000	0.7
58000	120000	0.5
5000	6200	0.8
21000	280000	0.1
140000	400000	0.4
84000	34000	2.5
3100	3300	0.9
310	360	0.9
680	620	1.1
2700	600	4.5
900	1100	0.8
5400	2800	1.9
34000	13000	2.6
30000	14000	2.1
2000	1600	1.2

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These results indicate that linear interpolation between stations is a valid first approximation and in general will be in error by less than an order of magnitude.

4.5 DISCUSSION OF INDIVIDUAL BURSTS

All references to dates of sampling in the discussion to follow are to the date of the beginning of the sampling period. It should be noted that since the sampling period started at 1830 GCT, the larger part of the collection was actually made on the following date.

4.5.1 First Burst

The first burst of the Snapper-Tumbler series, an air drop, was detonated at 800 feet above the ground at 1700 GCT on 1 April 1952. The resulting mushroom attained a maximum altitude of 16,000 feet above sea level. Figure 4.3 shows a radiosonde observation for this time. Trajectories of the primary cloud, computed for the 700-mb (10,000-foot) level and the 16,000-foot level, are shown in Figure 4.4. The 16,000-foot trajectory indicated that the debris in the mushroom moved rapidly eastward and reached the East Coast in two days. However, the 700-mb trajectory became involved in a cyclonic circulation in the Great Lakes region and the primary cloud at this level remained in the United States for more than five days.

Since this was the first burst of the series, and the background observation prior to this date indicated no appreciable radioactivity, there is no problem in the assignment of the activity to the proper burst. Certain observations are, however, difficult to explain, unless it is assumed that contamination of the sample occurred in some stage of the processing. For example, the high activity observed at Spokane, Washington; Billings, Montana; Bismarck, North Dakota; and Tucson, Arizona on observations started 1830 GCT 1 April 1952 would not have been possible from the existing flow patterns. Also, in all of the cases mentioned, the high activity was confined to only one of the three papers exposed; the actual measured activity on the most active paper was of the order of a few hundred $\text{d/m/ft}^2/\text{day}$; and the average of all three papers was about one hundred in each case. However, since the observations were made immediately following the burst, and not counted until 6-8 days later, extrapolation of the activity to the sampling date resulted in recorded values in the neighborhood of 1,000 $\text{d/m/ft}^2/\text{day}$.

Figure 4.3 Radiosonde Observation for 1800 GCT, 1 April 1952

FIGURE 4 4 PRIMARY CLOUD TRAJECTORIES FOR THE FIRST BURST

Considerable activity not associated with rain was found in New Mexico and the Texas panhandle on 2 April; in most of Texas on the 3rd and in Louisiana on the 4th. This activity was apparently associated with a rapidly-moving, dry cold front with strong surface winds from the Northwest. This front passed Amarillo, Texas, at 1300 GCT, 3 April 1952.

By 4 April, the radioactive fallout became spotty and virtually disappeared by the 5th, as the rain ended, with the exception of the Great Plains region.

In this area, the continued presence of fallout for several days after the burst must have been due to the effect of local winds in picking up and redepositing the debris. Perhaps, even the test site itself continued to act as a source of wind-borne contamination. This latter effect could also account for the high activity found at Grand Junction, Colorado, on April 7.

By 11 April, only ten days after the burst, deposited activity was virtually the same as during the pre-test background observations, with a few exceptions.

4.5.2 Second Burst

The second burst of the series, at 1730 GCT, 15 April 1952, was an air drop detonated at 1,050 feet above the ground. The resulting mushroom attained a maximum height of 15,500 feet above sea-level, although the radiosonde observation indicated no pronounced layer of atmospheric stability at or near this height (Figure 4.5).

The meteorological trajectories for this burst proved to be the most uncertain of any computed for this series of tests. It was originally assumed that the 16,000-foot primary cloud moved east and somewhat north to the upper mid-western states, and forecasts of deposited activity were made on this basis. When debris was not found at the expected locations, but instead was found in the far western states beginning on 18 April, a careful re-examination of the flow patterns was made. This revealed indications of the formation of a small cyclonic disturbance in the upper flow just to the east of the test site on 16 April which moved slowly southwestward on subsequent maps. The existence of this disturbance was later confirmed by a study of the supplementary wind observations made by the Air Weather Service at several stations in the vicinity of the test site in connection with the tests. These observations were not available at the time of the original forecast. Recomputed trajectories at 700 mb and at 16,000 feet are shown in Figure 4.6. The complex and confused paths followed by these trajectories are the result of a light, poorly defined wind

Figure 4.5 Radiosonde Observation for 1200 GCT, 15 April 1952

FIGURE 4.6 PRIMARY CLOUD TRAJECTORIES FOR THE SECOND BURST

field, and not too much credence can be placed in the exact position shown. However, the general area containing debris is indicated. It is interesting to note that the 16,000-foot trajectory stayed within a few hundred miles of the test site and did not pass near any stations of the monitoring network until 18 April. Prior to this date, the only activity found was in the extreme southern part of California, in agreement with the 700-mb trajectory.

From 18 April to 20 April, debris was deposited in Nevada, Idaho and adjoining states, in general agreement with the movement of the primary cloud at 16,000 feet. On 21 April, a strong current of air from the north became established over the western states and swept the 700-mb debris southward over Mexico. By 22 April, there was almost no significant activity attributed to this burst over the United States.

4.5.3 Third Burst

The third burst of this series was detonated at 1730 GCT, 22 April 1952. This burst was also an air drop, detonated at a height of 3,450 feet above the surface. The cloud top reached 42,000 feet above sea level, approximately the level of the tropopause (Figure 4.7). Trajectories of the primary cloud, computed for all standard meteorological levels from 700 to 200 mb are shown in Figure 4.8. The 300- and 200-mb trajectories indicate that the upper part of the cloud moved eastward, the primary cloud reaching the east coast in less than three days, while the lower portion moved northward along the Pacific Coast into Canada, then east and south through the Mississippi Valley.

Debris from the lower portion of the cloud was found in Southern California on the 23rd and northward to southern Oregon on the 24th. On both days, the appearance of debris at the ground occurred about 24 hours after the computed passage of the 700-mb trajectory. The absence of any debris north of Medford, Oregon, on these or succeeding days is probably a result of the fact that the wind in the very lowest layers shifted from southerly to southwesterly shortly after the beginning of the sampling period of 25 May, bringing uncontaminated air in from the Pacific along the Oregon and Washington coastline.

Even more interesting is the history of the upper portion of the cloud. As can be seen from the maps of the 23rd and 24th, no debris is found under the 300-mb and 200-mb trajectories, which is not surprising in view of the lack of precipitation in these areas. As the high-level debris moved over the eastern states it encountered rather heavy and widespread rain. On the 24th, activity

Figure 4.7 Radiosonde Observation for 1500 GCT, 22 April 1952

FIGURE 4.8 PRIMARY CLOUD TRAJECTORIES FOR THE THIRD BURST

was found at three stations--Montgomery, Alabama; Atlanta, Georgia, and Richmond, Virginia, although the rain was somewhat more widespread. However, by the 25th, activity was general over the Middle Atlantic and Southeastern States, again associated with rain. On succeeding days, spotty activity was found in various sections of the country, including some debris apparently associated with the trajectories of the lower half of the stem as it moved southward through the Mississippi Valley.

4.5.4 Fourth Burst

The fourth burst of this series occurred at 1630 GCT, 1 May 1952. This shot was also an air drop, detonated at 1,050 feet above the terrain. The resulting cloud reached an elevation of 43,500 feet above sea-level, again about the level of the tropopause (Figure 4.9). Trajectories of the primary cloud are shown in Figure 4.10 for all standard meteorological levels from 700 to 200 mb.

From 1 May to 4 May, observed activities were in accord with the computed trajectories, assuming that local winds and low-level flow patterns in the Southwest account for the moderate activity there. However, on 5 May, most of the Western states reported moderate concentrations of debris, whereas on the preceding day the values were near zero at many of the stations. The appearance of activity in this region was in apparent contradiction to the expected movement of debris from the fourth burst. It can be seen that there actually were two distinct areas of activity, one associated with the trajectories from the fourth burst, and the other apparently centered over the Pacific northwest. By 6 May, these two areas merged and by the end of this observation period debris from the fifth burst (see below, section 4.5.5) has reached Salt Lake City. It is difficult to reconcile the appearance of the debris in the Northwest, and its subsequent eastward movement, with the trajectories from the fourth burst at any level. However, the 200 mb trajectory of the third burst can actually be followed completely around the earth, and was computed to cross the California coast at about 1900 GCT, 4 May moving towards the northeast. Although considerable uncertainty is attached to so long a trajectory and to one computed over regions of such sparse meteorological data as exists in Asia and the Pacific Ocean, it still offers the most plausible explanation of the appearance of activity in the northwestern states on the 5th.

No attempt has been made to distinguish between the debris from the third and fourth bursts in extrapolating the activity to the observation date on 5 May or on succeeding days. However, since this is so long after either burst, the correction would have the effect of reducing the extrapolated values at most by about 25% for those stations which had debris from the third burst.

Figure 4.9 Radiosonde Observation for 1300 GCT, 1 May 1952

FIGURE 4 10 PRIMARY CLOUD TRAJECTORIES FOR THE FOURTH BURST

4.5.5 Fifth Burst

The fifth burst of the series was detonated from a 300-foot tower at 1215 GCT 7 May 1952. The atomic cloud attained a maximum altitude of 34,000 feet several thousand feet below the level of the tropopause (Figure 4.11).

Since this was the first tower burst of the series, more debris was expected than was associated with the two preceding bursts, both because of the vaporization of material from the tower and from the increased amount of terrestrial debris resulting from the closer proximity of the blast to the ground. Figure 4.12 shows the computed trajectories of the primary cloud for all standard meteorological levels from 700 mb to 300 mb. Debris at the three upper levels moved almost directly eastward, the primary cloud reaching the coast within about two days. The 700 mb (10,000 feet) trajectory moved somewhat slower, but over the same general region.

Debris from the burst produced the highest deposited activity at the fixed stations in the vicinity of the test site of any of the tests. This was due to the combined effects of having a tower burst, almost no wind shear from 15,000 to 30,000 feet and to the occurrence of widespread light precipitation in the area. Almost eight million d/m/ft²/day were observed at Salt Lake City in the observation started on 8 May; activities of several hundred thousand d/m/ft²/day were observed as far away as western Nebraska and South Dakota, all associated with rain.

Moderate activity was observed throughout most of the United States until 10 May, and persisted in the area near the test site and in the eastern states for several subsequent days. This activity, although primarily from the fifth burst, contained remnants of debris from the fourth burst and also from the third, as described in the preceding section. It is quite possible that the activity observed in the southeastern states from 8-10 May, somewhat to the south of the computed trajectories, is in reality debris from an earlier burst but has been erroneously extrapolated as debris from the fifth burst, making for fictitiously large reported activity at these stations.

Deposited activity of several hundred d/m/ft²/day was observed at various stations throughout the country for at least fifteen days following the fifth burst.

4.5.6 Sixth Burst

The sixth burst of the series, also a tower shot, was detonated at 1200 GCT, 25 May 1952. The cloud from this burst attained a maximum altitude of 41,000 feet, approximately the level of the tropopause (Figure 4.13).

Figure 4.11 Radiosonde Observation for 1200 GCT, 7 May 1952

FIGURE 4.12 PRIMARY CLOUD TRAJECTORIES FOR THE FIFTH BURST

350 642

Figure 4.13 Radiosonde Observation for 1200 GCT, 25 May 1952

The trajectories of the primary cloud from this burst are shown in Figure 4.14. In general, they are similar to those of the preceding burst, indicating little wind shear in the first 1,000 miles from the test site, but moving somewhat more slowly, the upper trajectories crossing the Atlantic Coast in about three days.

Agreement between areas of observed activity and the computed trajectories was quite good. The lack of wind directional shear in the first part of the trajectories resulted in a narrow area of ground contamination on 26 May. On 27 May, heavy rains in the Great Lakes region were responsible for the increased activity there. Fairly strong activity from the burst was general over most of the United States at least until 1 June, undoubtedly the result of the great amount of debris from a tower burst as compared with an air burst.

4.5.7 Seventh Burst

The seventh burst was detonated at 1155 GCT, 1 June 1952. The cloud from this tower shot reached 37,000 feet, approximately the level of the tropopause (Figure 4.15). The trajectories associated with this burst, which also indicated little directional shear in the wind field, are shown in Figure 4.16.

The results of the fallout monitoring network for this burst also clearly illustrate the greater amounts of debris associated with a tower burst. High activity was found under the primary cloud trajectories on all days following the burst. The almost complete lack of vertical shear in the trajectories until they reached the Ohio valley, coupled with widespread rain, resulted in the greatest concentration of deposited activity in the Illinois, Indiana, Michigan, and Wisconsin area observed for any of the bursts. Activities of several hundred thousand d/m/ft²/day were found in each of these states on 2 June. Strong concentrations of both deposited and airborne debris from the seventh burst were found over much of the country on succeeding days.

4.5.8 Eighth Burst

The eighth and last burst of the series was a tower shot detonated at 1155 GCT, 5 June 1952. The resulting mushroom reached to 41,500 feet, again near the level of the tropopause (Figure 4.17). The trajectories of the primary cloud are shown in Figure 4.18. The trajectories are again characterized by little directional wind shear, as in the three previous bursts. In this case, however, the debris took a more northerly path, and reached Southern Canada before turning southeastward and passing over the Middle Atlantic states.

FIGURE 4.14 PRIMARY CLOUD TRAJECTORIES FOR THE SIXTH BURST

Figure 4.15 Radiosonde Observation for 1300 GCT, 1 June 1952

FIGURE 4 16 PRIMARY CLOUD TRAJECTORIES FOR THE SEVENTH BURST

Figure 4.17 Radiosonde Observation for 1300 GCT, 5 June 1952

FIGURE 4 18 PRIMARY CLOUD TRAJECTORIES FOR THE EIGHTH BURST

As with the other tower bursts, this test also produced heavy concentration of both airborne and deposited debris. Light rain to the north of the test site in the 24-hour period following the burst led to gummed paper activities of several million d/m/ft²/day at Great Falls, Montana, and Boise, Idaho, on 5 June. Also on this date by far the highest concentrations of airborne activity were found on the high-volume air-filter samples. Values greater than 1,000 d/m/meter³ were found at several stations to the north of the test site, and a value of 130,000 d/m/meter³ was observed at Elko, Nevada. High activity from this burst continued in the expected areas on the succeeding days. It is interesting to note that the southeastern boundary of the area of activity from the eighth burst progressed eastward in a regular fashion on the maps of 7 and 8 June. This boundary coincides in each case with the southeastern boundary, at the end of the sampling period, of a mass of cold air moving southeastward from western Canada. Since the trajectories of the primary cloud passed over or through this air mass which was characterized by considerable instability, it may be assumed that the debris was distributed throughout its vertical extent.

Activity in appreciable amounts continued to be present in the United States for many days after the last test. Although at quite a few stations activity began to approach the pre-test background levels by 12 June, spotty activity of more than 1,000 d/m/ft²/day on the gummed papers and more than 2.0 d/m/meter³ on the air filter continued until at least 18 June, the end of sampling for these tests.

4.6 OVERSEAS MONITORING PROGRAM

In addition to the stations in Canada and Bermuda, reported in the preceding sections, gummed paper observations were made at three stations in Europe and Africa and at one in the Canal Zone by the USAF Air Weather Service and at seven locations in Mexico, Central and South America. [REDACTED] No attempt has been made to extrapolate the activity at any of these stations to the sampling date because of the difficulty in determining which burst the debris came from. Since there was a minimum of at least five or six days between the burst date and the date activity was first detected at any of the stations, the maximum extrapolation factor (if the sample were not counted until several weeks later) would be of the order of ten, and in almost all cases would be considerably less.

4.6.1 Europe and Africa

The locations of the stations in Europe and Africa are shown in Figure 4.19, together with the trajectory of each of the clouds which could be tracked across the Atlantic. Only the topmost

FIGURE 4.19 PRIMARY CLOUD TRAJECTORIES ACROSS THE ATLANTIC OCEAN

trajectory for each cloud is shown since this represents the level of maximum initial concentration and also, presumably, (in the case of the seventh and eighth bursts, lack of wind data at 200 mb made it necessary to use the 300-mb trajectories) the level of maximum wind speed. The gummed paper activity, uncorrected for decay, at each of the stations,--Prestwick, Scotland; Rhein-Main, Germany; and Wheelus AFB, Tripoli;--are shown in Figures 4.20-4.22, together with the amount of precipitation observed during each sampling period.

4.6.2 Mexico, Central and South America

The results of the fallout monitoring program at stations in Mexico, Central and South America are given in Table 4.4.

The table gives the unextrapolated activity measured on the gummed paper, together with the concurrent precipitation (see figures in the Appendix for code table). At several stations where no rain gage was available, the amounts of precipitation were estimated by the observer.

The paucity of meteorological data makes it impossible to compute trajectories in these regions. However, trajectories of several of the bursts (e.g., Figs. 4.6 and 4.16) indicated a southward movement of some portion of the primary cloud, and in other cases debris which passed eastward over the Atlantic may have recurved to the south and west around the Bermuda anticyclone, so that primary cloud debris as far south as Central America is a possibility, although such movement would be slow compared to the average mid-latitude movements.

Much of the debris which reached the Central and South American stations, and probably all that reached the two southernmost stations of South America arrived as the result of more complex flow patterns. One process by which debris could be carried to southern latitudes is by the diffusion and/or fallout of debris into the northeast trades of the northern hemisphere. There, winds would carry the debris southward to the intertropical convergence zone, where mixing with southern hemisphere air would occur. Debris could also be brought to southern latitudes by diffusion and fallout from the north winds which are frequently observed at high levels in the tropics.

Significant activity was found at La Paz, Bolivia, and Lima, Peru, during the first week of May, but it is impossible to determine if there was a southward progression of debris, since these two stations began observations several days before the other

FIGURE 4.20 UNEXTRAPOLATED GUMMED PAPER DATA FROM PRESTWICK, SCOTLAND

FIGURE 4.21 UNEXTRAPOLATED GUMMED PAPER DATA FROM RHEIN-MAIN, GERMANY

FIGURE 4.22 UNEXTRAPOLATED GUMMED PAPER DATA FROM WHEELUS AFB, LIBYA

TABLE 4.4

Unextrapolated Gummed Paper Activity at Central and South American Stations

	Mexico City		San Jose		Canal Zone		Bogata		Quito		Lima		La Paz		Santiago	
	19°26' N 99° 8' W		9°58' N 84° 4' W		8°58' N 79°33' W		4°32' N 74°15' W		0°10' S 78°30' W		12°00' S 77°00' W		16°29' S 68° 3' W		33°28' S 70°45' W	
Date	Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation		Activity (d/m/ft ² /day) Precipitation	
May																
2																
3																
4													1400	1		
5													0	1		
6			12 mod.				0	4			51	1	16	1		
7			4 hvy.				29	6			37	1	62	1	45	1
8			4 none				6	1			5	1	55	1	0	1
9			56 mod.				0	4			420	1	13	1	0	1
10			8 mod.				0	4			6	1	8	1	} 0	1
11			18 hvy.				0	6			12	1	0	1		
12	170	1	4 hvy.				6	5			0	1	0	1		
13	34	1	0 hvy.				13 mod.	0	1		0	1	0	1	8	4
14			4 mod.				13 tr.	0	2				5	1	21	5
15	120	1	8 mod.				13 none	4	5		9	1	8	1	13	5
16	64	1	0 none				0 lgt.	0	4		13	1			8	4
17	16	1	8 hvy.				4	1			4	1			} 2	3
18	330	1	0 lgt.				0 tr.	9	1		2	1				
19	79	1	0 lgt.				10 mod.	0	1		0	1	0	1		
20	26	1	0 mod.				0 hvy.	48	5		0	1	0	1	0	1
21	13	1	65 lgt.				9 mod.	24	5		14	1	7	1	} 33	1
22	13	1	100 lgt				25 lgt.	86	3		7	1	25	1		
					17	5	18 lgt.	77	2		29	1				

TABLE 4.4 (cont'd)

	Date	Mexico City		San Jose		Canal Zone		Bogata		Quito		Lima		La Paz		Santiago	
		Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.
55	May																
	23	270	3	39	none	12	5	80	lgt.	72	1	8	1			}	4 1
	24			8	hvy.	27	2	160	lgt.	520	2	16	1				
	25	95	4	71	mod.	14	1	68	lgt.	12	6	13	1				
	26	170	2	15	mod.	0	1	19	lgt.	30	2	10	1	9	2		
	27	170	2	58	mod.	17	2	36	tr.	22	1	38	2				
	28	65	3	38	hvy.	38	1	120	tr.			0	1				
	29	15	6	110	lgt.	20	1	24	mod.	45	3	10	1			}	1 4
	30	120	5	62	mod.	230	2	190	hvy.	16	3	21	1	30	1		
	31	29	6	58	hvy.	480	4	18	lgt.	17	1	11	1	5	1		
	June																
	1	310	3	49	lgt.	175	1			28	1	110	1	560	4		
	2	34	1	28	hvy.	38	1			5	1	28	2	19	1		
	3	24	2	35	mod.	34	1			12	1	28	2				
	4	39	6	57	hvy.	49	7	12	hvy.	5	2	74	2				
	5	22	4	17	mod.	80	4	41	mod.	11	1	10	1				
	6	13	4	22	hvy.	90	1	6	lgt.	18	2	35	1				
	7	150	4	9	hvy.	130	5	9	hvy.	21	4	}	2				
	8	390	2	6	hvy.	100	1	4	mod.	27	4			140	1		
	9	67	2	0	mod.	38	2	16	mod.	0	5	11	1				
	10	110	4	6	hvy.	92	4	25	tr.	0	2	20	1	17	1		

TABLE 4.4 (cont'd)

	Mexico City		San Jose		Canal Zone		Bogota		Quito		Lima		La Paz		Santiago	
Date	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.	Act.	Prec.
June																
11	9	2	0 hvy.		110	5	11 lgt.		4	1	45	1	6	1		
12					42	5	0 tr.		0	1	5	1	6	1		
13	11	2	17 tr.		15	1	6 none		0	1	6	1				
14			26 hvy.		1400	1	6 lgt.		4	2	17	1				
15	35	1	6 hvy.		12	1	0 mod.		120	2	9	2	0	1		
16					11	1										
17					6	1										
18					23	1										

Central and South American stations. Of course, it is always possible that some of the activity, which was relatively low in most cases, was a result of contamination during the counting procedure. However, there did seem to be a southward progression of activity which was first observed at San Jose, Costa Rica, on 21-22 May; at Bogota, Columbia, on 23 May; at Quito, Ecuador on 24 May; and at Lima and La Paz on 1 June. The first three stations were north of the intertropical convergence zone, effectively in Northern Hemisphere air, while Lima and La Paz were in Southern Hemisphere air.

APPENDIX A

MAPS OF RADIOACTIVE FALLOUT IN THE UNITED STATES AND CANADA

Figures A.1-A.79 show the data from the fallout-monitoring stations in the United States and Canada, plotted in accordance with the key printed on each map. (Values in parenthesis indicate the average daily values for observations which inadvertently extended for more than one day.) Snow has been reduced to its water equivalent.

The dashed lines outline areas with radioactivity greater than $100 \text{ d/m/ft}^2/\text{day}$ on the gummed papers, the solid line areas with more than $1000 \text{ d/m/ft}^2/\text{day}$. Areas of precipitation are indicated by shading.

Figure A.1. Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 1 April 1952

Figure A.2 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 2 April 1952

Figure A.3 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 3 April 1952

Figure A.4 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 4 April 1952

Figure A.5 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 5 April 1952

Figure A.6 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 6 April 1952

Figure A.7 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 7 April 1952

Figure A.8 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 8 April 1952

Figure A.9. Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 9 April 1952

350 669

Figure A.10 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 10 April 1952

Figure A.11 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 11 April 1952

Figure A.12 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 12 April 1952

Figure A.13 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 13 April 1952

Figure A.14 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 14 April 1952

Figure A.15 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 15 April 1952

350 075

Figure A.16 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 16 April 1952

Figure A.17 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 17 April 1952

Figure A.18 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 18 April 1952

360 078

Figure A.19 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 19 April 1952

Figure A.20 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 20 April 1952

Figure A.21 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 21 April 1952

Figure A.22 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 22 April 1952

Figure A.23 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 23 April 1952

Figure A.24 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 24 April 1952

Figure A25 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 25 April 1952

Figure A.26 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 26 April 1952

Figure A27 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 27 April 1952

Figure A.28 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 28 April 1952

Figure A 29 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 29 April 1952

Figure A.30 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 30 April 1952

Figure A.32 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 2 May 1952

Figure A.33 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 3 May 1952

Figure A.34 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 4 May 1952

Figure A.35 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 5 May 1952

Figure A.36 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 6 May 1952

Figure A.37 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 7 May 1952

Figure A38 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 8 May 1952

Figure A.39 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 9 May 1952

Figure A.40 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 10 May 1952

Figure A41 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 11 May 1952

Figure A.42 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 12 May 1952

Figure A.43 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 13 May 1952

Figure A.44 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 14 May 1952

Figure A.45 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 15 May 1952

Figure A.46 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 16 May 1952

Figure A.47 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 17 May 1952

Figure A.48 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 18 May 1952

Figure A.49 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 19 May 1952

Figure A.50 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 20 May 1952

Figure A51 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 21 May 1952

Figure A.52 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 22 May 1952

Figure A.53 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 23 May 1952

Figure A.54 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 24 May 1952

Figure A.55 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 25 May 1952

Figure A.56 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 26 May 1952

Figure A.57 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 27 May 1952

Figure A.58 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 28 May 1952

Figure A.59 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 29 May 1952

Figure A60 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 30 May 1952

Figure A.61 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 31 May 1952

Figure A.62 Radioactive fallout in the 24-hour period beginning 1830 GCT, 1 June 1952

Figure A 63 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 2 June 1952

Figure A.64 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 3 June 1952

Figure A.65 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 4 June 1952

Figure A.66 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 5 June 1952

Figure A.67 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 6 June 1952

Figure A.68 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 7 June 1952

Figure A.69 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 8 June 1952

Figure A.70 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 9 June 1952

Figure A.71 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 10 June 1952

Figure A.72 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 11 June 1952

Figure A.73 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 12 June 1952

Figure A.74 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 13 June 1952

Figure A.75 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 14 June 1952

Figure A.76 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 15 June 1952

Figure A.77 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 16 June 1952

Figure A.78 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 17 June 1952

Figure A.79 Radioactive fallout in the 24-hour period beginning 1830 G.C.T., 18 June 1952

300 139

APPENDIX B

COMPARISON OF OBSERVED AND PREDICTED AREAS OF FALLOUT

Following each of the bursts of the Tumbler-Snapper series, an estimate of the areas likely to be affected by fallout or rainout of radioactive debris was prepared. These estimates were made after the receipt of all pertinent meteorological data, but before any radiological data was available. They were based primarily on the indications of the computed trajectories and modified for the effects of precipitation, diffusion and fallout. Estimates were prepared for successive 24-hour periods, following each burst until it was felt that significant activity was no longer present.

Figures B.1-B.11 show comparisons between the estimated areas of activity and those actually observed. The solid and dashed lines indicate observed activity of 1000 and 100 d/m/ft²/day respectively, on the gummed paper and are copied from the figures of Appendix A. The shading represents the estimated areas of radioactivity. It should be emphasized that the figures of Appendix B give an incomplete picture of the reliability of these estimates, since on many days significant activity was found at the ground although no such area was predicted, as can be seen from the figures in Appendix A.

No detailed discussion of all the individual estimates will be given, however several general observations can be made. The most evident error in the estimates arose from the continued deposition (or redeposition) of debris at the ground for long periods after it was thought to have left the country. Although the phenomenon was particularly marked following the tower bursts, it was evident in all cases. This error arises from several sources. The primary causes are the inability to follow the complex air trajectories found at low levels, i.e. within several thousand feet of the ground, and the complexities of atmospheric diffusion. Additional sources of error arise from the redeposition of debris by the winds and from the test site itself acting as a source of radioactive particles for several days following each burst. This latter effect is particularly pronounced for tower bursts. It is improbable that successful forecasts or estimates can ever be made of isolated patches of debris which are found many days after a burst, however, considerable improvement in the estimates of activity would result from more careful attention to the effects of low-level transport.

Another source of error, which is most evident when there is a vertical wind shear at the time of burst, is illustrated in Figure B.4. For the 24-hour period beginning 1830 GCT, 24 April 1952,

debris was predicted to fall on most of the eastern United States. This estimate was based on the 300- and 200-mb trajectories, at lower levels the trajectories indicated a westward movement of debris. Actually, only two isolated patches of activity were found in the East, both associated with heavy rain. As can be seen from Figure A.24, rain occurred over a large area, however, only three stations received significant amounts of radioactive rainout. It is evident that the rain was necessary to bring debris down rapidly from high elevations, although the lack of activity at the other stations in the rain area is difficult to explain. Where the air mass structure is vertically unstable, the downward transport of debris from high levels by turbulent mixing is more effective, as can be seen from the maps for the 24-hour periods beginning 1830 GCT, 7 May and 1 June 1952. However, in each of these cases, precipitation was also present, so that it was necessary only for debris to have been brought down to the levels at which the rain was formed.

An interesting example of our incomplete knowledge of air trajectories and flow patterns occurred in connection with the burst of 15 April 1952. As has been pointed out previously, the original estimates of the area of deposition of debris were greatly in error. Instead of moving eastward as predicted, the debris at 16,000 feet moved around a small cyclonic circulation which developed in Southwestern Utah and then westward over California. Figure B.12 shows the 16,000-foot winds for four successive six-hourly periods beginning on 0900 GCT, 16 April 1952. The winds are plotted in the conventional way, each full barb indicates ten knots, each half-barb five knots, of wind speed. The solid wind arrows represent the stations in the routine meteorological network, the dashed wind arrows indicate observations from the special stations established by the Air Weather Service in connection with the Tumbler-Snapper test series. These latter winds were not available when the original trajectories and the estimates of areas of contamination were made. The trajectory originally computed for the 16,000-foot level is shown by a dotted line, the revised trajectory based on the additional wind information and a knowledge of where radioactivity actually was found, is indicated by the solid line. Those portions of the trajectories from three hours before to three hours after each map time are indicated by heavier lines on the appropriate maps. Although the additional winds clearly serve to explain the manner in which the air moved, it is doubtful, even with these data, that the absence of debris at stations to the east of the test site would have been correctly predicted.

FIGURE B.1 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.2 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.3 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.4 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.5 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.6 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.7 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.8 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.9 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.10 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.11 OBSERVED AND PREDICTED AREAS OF FALLOUT

FIGURE B.12 ORIGINAL (DOTTED LINE) AND RECOMPUTED (SOLID LINE) 16,000-FT TRAJECTORIES FOR THE SECOND BURST, AND THE ASSOCIATED WIND FIELD