final report

December 1967

SRI

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D.C. 20310

TRC-68-15

final report

THE MASS CONTOUR RATIO FOR FALLOUT AND FALLOUT SPECIFIC ACTIVITY FOR SHOT SMALL BOY

By: Carl F. Miller and Oliver S. Yu

SRI Project No. MU-6358
Contract No. N0022867C1143
OCD Work Unit No. 3119A

December 1967

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D.C. 20310

Through:

TECHNICAL PLANNING AND
MANAGEMENT OFFICE
U.S. NAVAL RADIOLOGICAL
DEFENSE LABORATORY
SAN FRANCISCO, CALIFORNIA 94135

STANFORD
RESEARCH
INSTITUTE

SRI

MENLO PARK
CALIFORNIA

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

In the construction of some fallout models,[1] the approach taken is to use a number of basic parameters to establish standard intensity contours. Specifically, these basic parameters are weapon yield, fission yield percentage of total yield, height of burst, fallout particle terminal velocity, and wind velocity. The intensity contours obtained are then related to additional fallout properties. Among the latter, one of the most important is the mass surface density of fallout deposited at a location on the ground after a nuclear attack. This type of information is necessary for a number of civil defense protection evaluations, such as fallout shelter design and planning decontamination operations. In the Miller fallout model,[1] the relation between the mass surface density and the radiation intensity at various points of interest is referred to as a mass contour ratio.

The mass contour ratio is defined as the ratio of the total fallout weight per unit area deposited at a location inside the fallout region to the observed radiation intensity generated by the fallout at a time after detonation. Mathematically, it may be expressed as

$$M_r(t) = \frac{m}{I(t)} \quad \frac{\text{gm/sq ft}}{\text{r/hr at t}} \tag{1}$$

where

$M_r(t)$ is the mass contour ratio at time t after detonation

m is the total fallout mass per unit area deposited

I(t) is the measured ionization rate at 3 ft above the ground at time t after detonation.

The mass contour ratio at a particular location may be determined by direct measurements of its elements. However, it is desirable to express $M_r(t)$ as a general function of the basic parameters of the fallout model. Thus, Equation 1 may be written in the equivalent form

$$M_r(t) = \frac{m/a_f}{I(t)/a_f} \quad \frac{\text{gm/fission}}{\text{r/hr at t per fission/sq ft}} \tag{2}$$

where a_f is the total number of fissions per unit area at the point of desposition.*

If the numerator of Equation 2 is defined as the reciprocal of fallout specific activity, c_f, and the denominator as the intensity-activity conversion factor, $K_s(t)$, the mass contour ratio may be expressed as

$$M_r(t) = \frac{1}{K_s(t)\ c_f} \quad \frac{\text{gm/sq ft}}{\text{r/hr at t}} \tag{3}$$

The evaluation of the mass contour ratio is thus reduced to the analysis of the two components: fallout specific activity and the intensity-activity conversion factor. The purpose of this report is to present data on fallout specific activity from Shot Small Boy with the immediate objective of expressing c_f as a function of some of the basic parameters of the fallout model. The various parameters on which the evaluation of $K_s(t)$ depends are discussed in Reference 1.

In spite of the discussions in Reference 1 and in other previous presentations regarding the significance of these parameters, developed almost a decade ago, little attention has been given to their evaluation. The occasional rediscovery of the principles on which these parameters are based[2,3] and their neglect in subsequent fallout studies, with few exceptions, should hopefully be discontinued.

---

* The term fissions, as used here, refers to the initial number of fissions occurring in a detonation or the number of atoms of fissile material that fissioned.

THEORY

In the Miller theory of fallout formation for a surface nuclear detonation,[1] soil particles are entrained by the fireball (and rising cloud) created by the detonation and a small percentage of the total is vaporized. In the subsequent condensation process, very fine particles with fission products fused within or attached to their surfaces are created; many of these coalesce with other larger melted and unmelted particles (together with residual vapors of the more volatile elements). The soil particles that are not vaporized generally reside in the fireball and cloud for a shorter period of time and constitute the larger fallout particles. The latter are soil particles that enter the fireball at later times and leave the cloud at earlier times. As a result, many of these particles are only partially melted or are not melted at all. This being the case, the fission products are only fused into the outer layer or attached to the surfaces of these particles.

From this qualitative description, it may be concluded that the radio nuclide concentration of the fallout should decrease approximately as an inverse function of particle diameter for the medium to large particles and approach a constant value for small particles. The theory also indicates that two general forms of particles should exist: (1) glasses and (2) crystals. The glass particles are formed from vaporized and melted soil; the crystal particles are formed from vaporized and melted soil; the crystal particles are from soil grains that were not exposed to melting point temperatures. The crystalline particles, regardless of size, would be expected to collect late-condensing fission product elements on their surfaces and their concentration should vary inversely with particle diameter. A similar relationship should occur for the larger glass particles where only a thin layer of glass is formed on the surface partially melted; interior of particle is still crystalline).

The radio nuclide concentrations of smaller glass particles are expected to be constant unless the late-condensing fission products contribute significantly to the amounts of each carried by the particles (these elements would condense on the surfaces of the glass particles in the same way as they do on the crystalline particles). Their concentrations would then have some dependence on particle diameter. The distribution of the radionuclides in a sample of fallout that consists of a mixture of both types of particles thus may not be readily specified although it would appear that all combinations would result in an average concentration that decreased with particle size.

Since there is a definite relationship between particle diameter and average particle terminal falling velocity for a particular weapon detonation,[4] the terminal velocity may be used as a parameter of the fallout model instead of particle size. Velocity is more convenient than size in the model under consideration,[1] and is thus considered a basic parameter. The radionuclide concentrations in fallout, in consequence, should be a decreasing function of the particle terminal velocity.

As a first step in the analysis and correlation of specific activity data, as a gross measure of radionuclide concentration, it is hypothesized (in spite of the complications discussed above) that a unique functional relationship exists between the specific activity and the particle diameter. It is further assumed that this function is related to the average specific activity by

$$c_f(d) = c_f^* \; f(d) \text{ fissions/gm} \tag{4}$$

where

- d is the particle diameter in microns
- c_f^* is the average specific activity defined as the ratio between the amount of fission products produced and the total weight of soil material drawn into the fireball and cloud to form fallout,*

and

- $f(d)$ is a characteristic weighting function that is essentially independent of weapon size and burst condition, but depends on the characteristics of the soil at ground zero and on the particle diameter.

---

* By defining c in terms of fissions, it is clear that unfractionated fission product mixtures are being represented by Equation 4; in this definition, fractionation effects are included in f(d).

Because of statistical fluctuations and possibilities of wide variations in detonation conditions, the hypothesis for which Equation 4 is written may not be strictly valid in any given case, such as for large particles in which the radionuclide distribution is highly nonuniform. However, it has been observed[5] that for most nuclear detonations, more than 90 percent of fallout activity is associated with particles whose diameters are smaller than 1,000 microns. It will also be seen later in the current study that the gross specific activity does not vary greatly for particles whose diameters are between about 100 and 1,000 microns. Therefore, the above assumptions serve as a reasonable starting point for investigating the effects of weapon yield and burst height on the gross specific activity of local fallout.

The weight of soil drawn into the rising fireball may be estimated either by the amount of soil removed on forming the apparent crater or by the amount of soil that can be melted in the fireball. These estimates constitute upper and lower bounds on the total weight of the particles in the fallout, and the gross specific activity is thus also limited by these constraints.

According to Reference 1, for a surface burst with a soil density of 110 lb/cu ft and a fission equivalent yield of 1.4×10^{23} fissions KT, the maximum and minimum gross specific activities as functions of weapon yields are

$$c^*_{f\ max} = \frac{1.4 \times 10^{23}\ BW}{m_f} = 7.29 \times 10^{14}\ BW^{-0.014}\ \frac{\text{fissions}}{\text{gm}} \qquad (5)$$

$$c^*_{f\ min} = \frac{1.4 \times 10^{23}\ BW}{m_c} = 2.74 \times 10^{13}\ BW^{0.083}\ \frac{\text{fissions}}{\text{gm}} \qquad (6)$$

where

$c^*_{f\ max}$ is the maximum gross specific activity

$c^*_{f\ min}$ is the minimum gross specific activity

B is the fraction of fission yield

W is the total weapon yield in KT

m_f is the weight of soil that may be melted by energy in the fireball

and

m_c is the weight of soil removed from the crater

Since the weight of material removed from the crater would, in most cases, be the controlling factor of the amount of material available as condensation sites for the radioactivity, the value of c_f^* should increase slowly with yield in the same fashion as $c_{f\ min}^*$. Thus, as a first approximation, c_f^* may be expressed as

$$c_f^* = c_{fo}^* \ BW^{0.083} \ \frac{\text{fission}}{\text{gm}} \tag{7}$$

where c_{fo}^* is the gross specific activity of a 1 KT, 100 percent fission yield surface burst (i.e., ideally, for a uniform mixing of the radionuclides with a given fraction of the material removed from the crater).

For a subsurface burst, the amount of soil available for fallout formation increases with increasing depth of burst until a maximum is reached, then starts decreasing as less soil is thrown out of the crater area. Therefore, the gross specific activity decreases rapidly as the burst depth increases, until the maximal amount of soil available for fallout is reached. At greater depths, only the more volatile radionuclides escape and the concept of the average specific activity has no further application. Also, the application is of no interest here.

On the other hand, for an aboveground burst, the amount of soil available for fallout decreases with increasing height of burst. However, the soil particles enter the fireball at increasingly later times as the height of burst increases and the relative amount of radionuclides intercepted will decrease. Therefore, the gross specific activity should increase with height of burst until a maximum is reached and then start to decrease with further increases in burst height (all for a given detonation yield).

To correct the change in gross specific activity due to height of burst (burst depth is defined as the negative of burst height) a burst height correction factor, $K_{f\lambda}$, is defined by

$$c_{f\lambda}^* = K_{f\lambda} c_f^* \tag{8}$$

where $c_{f\lambda}^*$ is the gross specific activity at the scaled height given by

$$\lambda = h/W^{\frac{1}{3}} \quad ft(KT)^{-\frac{1}{3}} \tag{9}$$

with h equal to the height of burst in feet and W equal to the total weapon yield in KT.

In summary, the specific activity function for a nuclear detonation of the types discussed may be expressed as

$$c^*_{f\lambda} = K_{f\lambda}\, c^*_{fo} B W^{0.083} \tag{10}$$

ANALYSIS

General Procedures

The first step in the analysis of the data consisted of tabulating the radioactive and weight measurements of the Small Boy fallout samples as a function of particle diameter. The radioactivity data were then decay-corrected to a common time and compared to eliminate apparent inconsistencies and to minimize the effect of experimental error.

The data were then analyzed according to the hypothesis that each sample consisted of three separate physical components: (1) nonactive or extraneous soil particles and other debris, (2) intact fallout particles, and (3) fallout particles broken during analysis. These three components were known to be present by observation of the presence of inactive sand, smaller rocks, and twigs; by discontinuities in the activity-particle size and weight-particle size distribution curves; and by the persistence of small particles in the samples of very close-in fallout. The contribution of each component in each set of sample data was determined by graphical analyses and correlation of the cumulative activity and mass distributions, so that the relative amounts of the discrete or intact fallout particles (which are viewed as the original fallout particles arriving on the ground) could be estimated.

The reduced data were re-examined for consistency and correlated to show variations with particle diameter and terminal falling velocity. The resulting specific activities finally were compared with computed theoretical limits for Shot Small Boy.

Data Collection and Reduction

Relatively complete sets of data on the activity and weight of fallout particles as functions of their sizes were collected for the fallout from Shot Small Boy.[6,7] The fallout samples were collected on trays placed at various locations downwind from ground zero. The radioactivity content of the samples was first measured with a gamma scintillation counter. Then each sample was separated into various size fractions by sieving, and each size fraction was weighed and its activity measured in a 4-pi gamma ionization chamber. Finally, portions of several of the samples were analyzed by radiochemistry, and the fission content as well as the degree of fractionation were determined for each size fraction of these samples.

Since the above constitute three separate measurements of sample activity, the reliability of each may be evaluated by a comparative process.

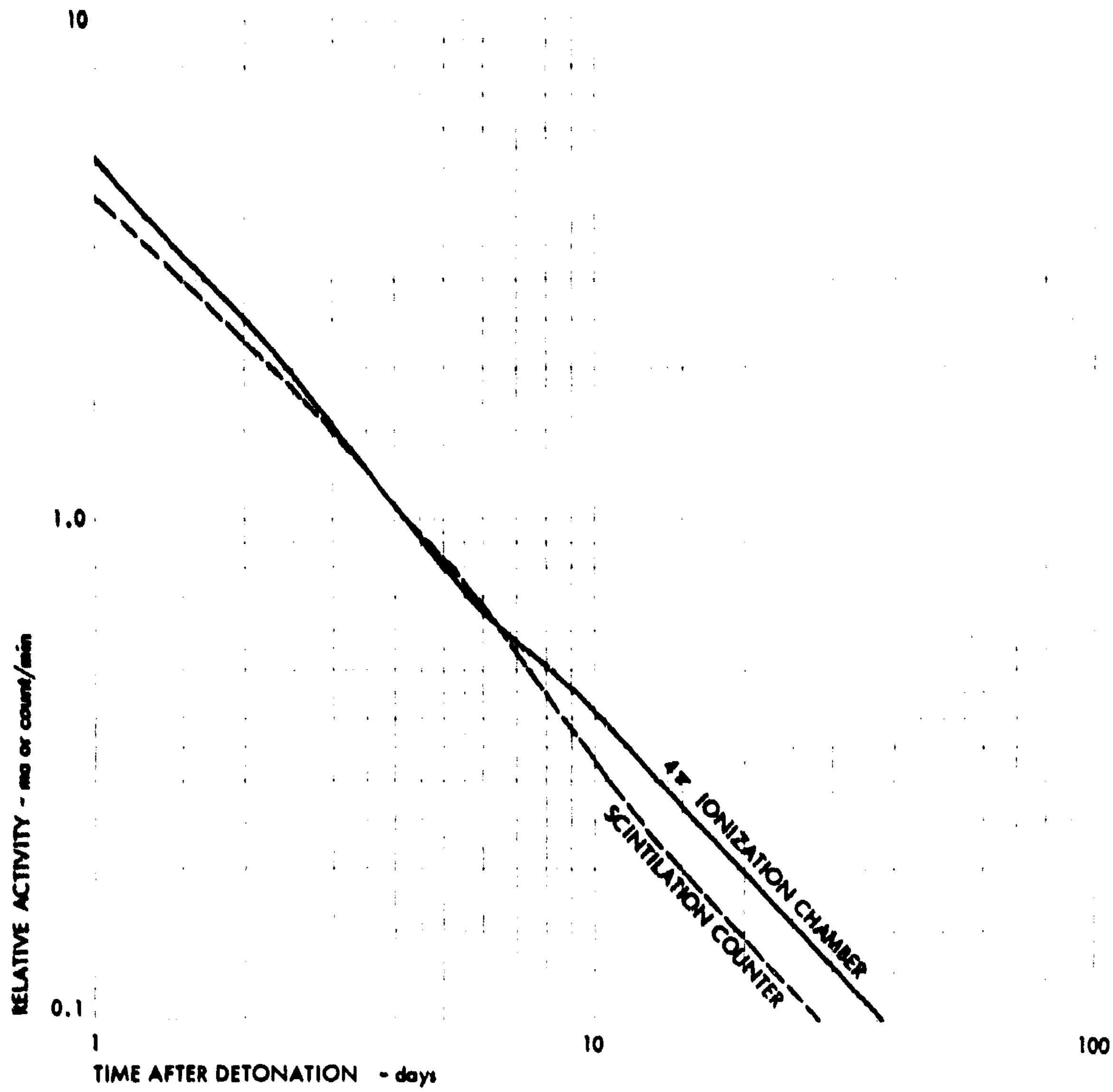
To obtain the relative amount of radioactivity in each sample, the measurements were all corrected to the common time of H + 100 hours. To do this, a composite decay curve applicable to all size fractions was constructed. The decay rate for subsieve size particles (i.e., those with diameters of less than 40 microns) was found to be particularly rapid, and although the decay rates of the other size fractions did not deviate greatly from one another, the differences did reveal that various degrees of fractionation occurred in each size group. However, since almost all the measurements were made near H + 100 hours, the decay correction factors were not very large, and the use of the composite decay curve presented in Figure 1 was considered to be applicable to all measurements to an accuracy of within 10 percent.

Radiochemical analyses were performed by three laboratories: Tracerlab, Incorporated; Hazleton Nuclear Science Corporation; and Nuclear Science and Engineering Corporation. The fission equivalents of Sr-89, Sr-90, Y-91, and Zr-95 were measured by all three laboratories. In addition, the fission equivalents of Mo-99, Ru-103, Ru-106, Te-132, Cs-136, Cs-137, Ba-140, Ce-141, and Ce-144 were measured by the first two laboratories, and of Te-131 by Tracerlab and Nuclear Science and Engineering.

The three radionuclides, Zr-95, Mo-99, and Ce-144, appear to be unfractionated with respect to each other. Therefore, the fission equivalents of these three nuclides in each sample should be approximately the same. Since the measurements made by one of the laboratories showed close internal agreement, its data were used as standard ones, and adjustments were made in the results obtained by the other two laboratories.

Figure 1

COMPOSITE DECAY CURVE FOR SHOT SMALL BOY FALLOUT



Furthermore, the percentage yield of Mo-99 varies the least in various kinds of fission;* thus, the fission equivalents of Zr-95 and Ce-144 were corrected to those of Mo-99 to reduce further possible errors caused by inaccuracies in the assumed relative abundances of fission products.

Data Analysis and Correlation

Theoretically, for a given size of the particle cloud and known wind speeds, definite limits exist in the range of particle sizes of fallout that can deposit at a particular location. However, larger fallout particles can carry small particles on their surfaces, and when these small particles are rubbed off in dry sieving and washed off in wet sieving, their presence in the sample will be detected. Furthermore, the fallout from land bursts will contain fallout particles that are agglomerates of smaller particles (sintered to various degrees of adhesion). Many of these particles may be partly or wholly broken in sieving. Moreover, most fallout samples contain extraneous dust and sand particles. The source of these particles consists of debris raised by the blast wave passing over the collecting areas for the closer-in samples and of wind-blown debris at other collecting stations (especially if they are exposed in an open position for an extended period of time). The latter debris may be larger than the upper size limit of the fallout. When sieved, small amounts of fallout activity will often be found attached to these inert particles. Therefore, in the sieving analyses, not only particles but also radioactivity is found in all size fractions. If the measured activity data are expressed directly as a function of particle size, those data associated with sizes significantly smaller or larger than the theoretical minimum and maximum sizes for true fallout particles are obviously incorrect.

Once it is recognized that each fallout sample consists of three components (i.e., extraneous particles, intact fallout particles, and fallout particles broken during the sieving process), it follows that the fallout activity-particle size distribution curve of the sample will be a composite of three distinct distributions, each corresponding to one of the components. In some cases, the component distribution curves will cover different particle size ranges with the size range of the intact fallout particles lying between those of the extraneous and broken particles. Assumed component distribution curves for this case are shown in Figure 2 with their respective fractional contribution to the total sample indicated. By direct computation, it can be shown that the composite of these three component curves will not be a continuously smooth curve but rather a curve with break points occurring at the size range limits of the intact fallout particles, as can be seen from the composite curve in Figure 3. This is the typical characteristic of all the activity-size distribution curves of the fallout samples from Shot Small Boy. By using the percentages at the break points to estimate the fractional contributions of the three components and by redistributing the activity associated with the extraneous and broken particles back onto the intact fallout particles, a first estimate of the activity-size distribution of the true fallout particles (that is, the original fallout particles before sieving) can be derived.

The described method would not be applicable if the activity associated with the particles of one of the three component distributions were not the major portion of the total activity. However, the analysis of gamma ion current data in the manner described above showed that, for most of the fallout samples collected, more than 90 percent of the total activity was associated with particles of the middle-sized distribution. Usually, about 5 percent was associated with smaller broken particles, and less than 3 percent of the total activity was associated with larger extraneous particles. This separation of components, however, does not eliminate inactive extraneous particles with diameters that are the same as those of original fallout. The amounts of these particles present can only be estimated through comparison of the specific activity of each size group from all samples, as discussed below.

The fission equivalents and gamma ion current data were measured according to size fraction. If both measurements are accurate, their ratio within the same group should be similar since there is no a priori reason

Figure 2

A TYPICAL SET OF COMPONENTS OF THE FALLOUT ACTIVITY-SIZE DISTRIBUTION

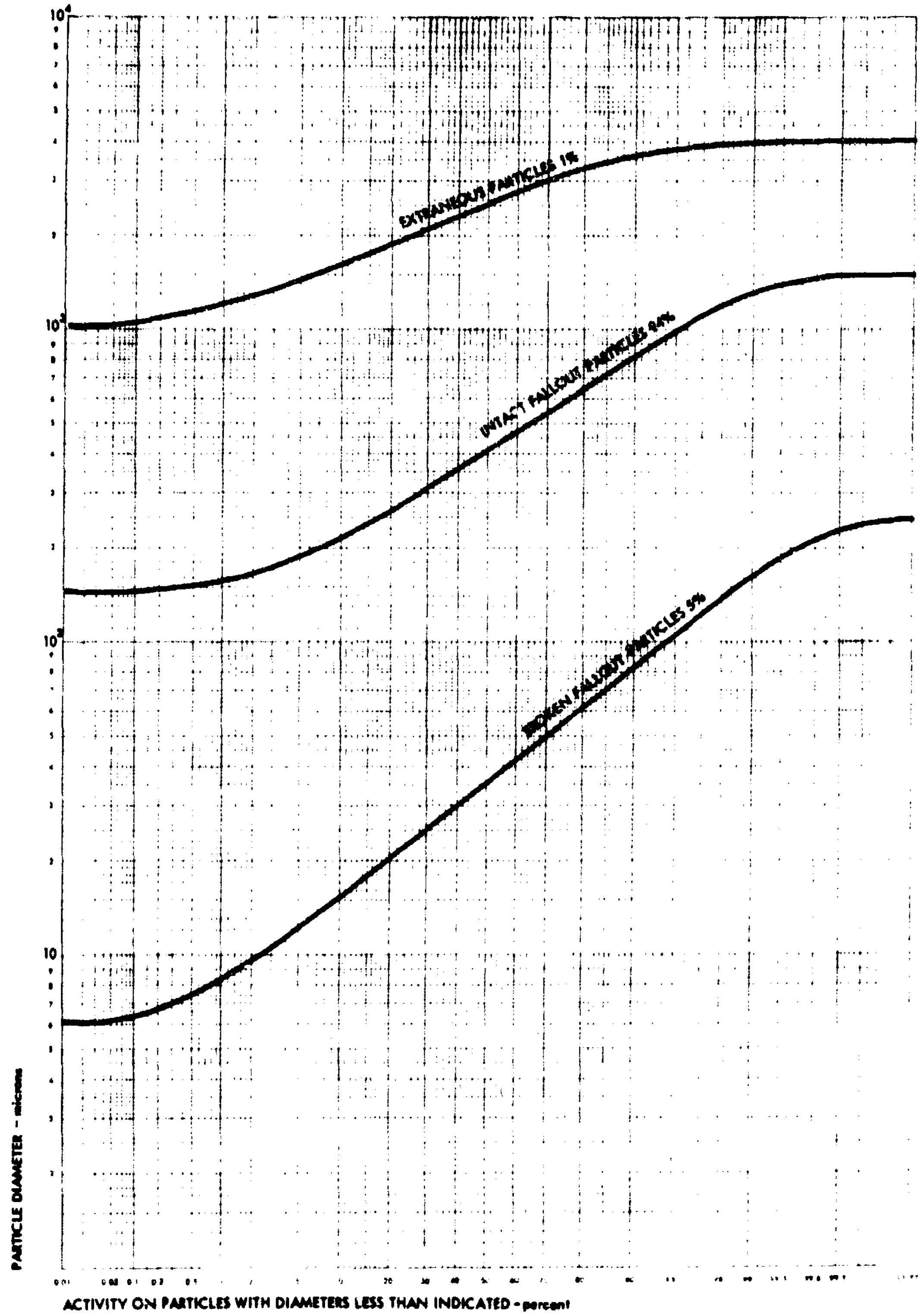
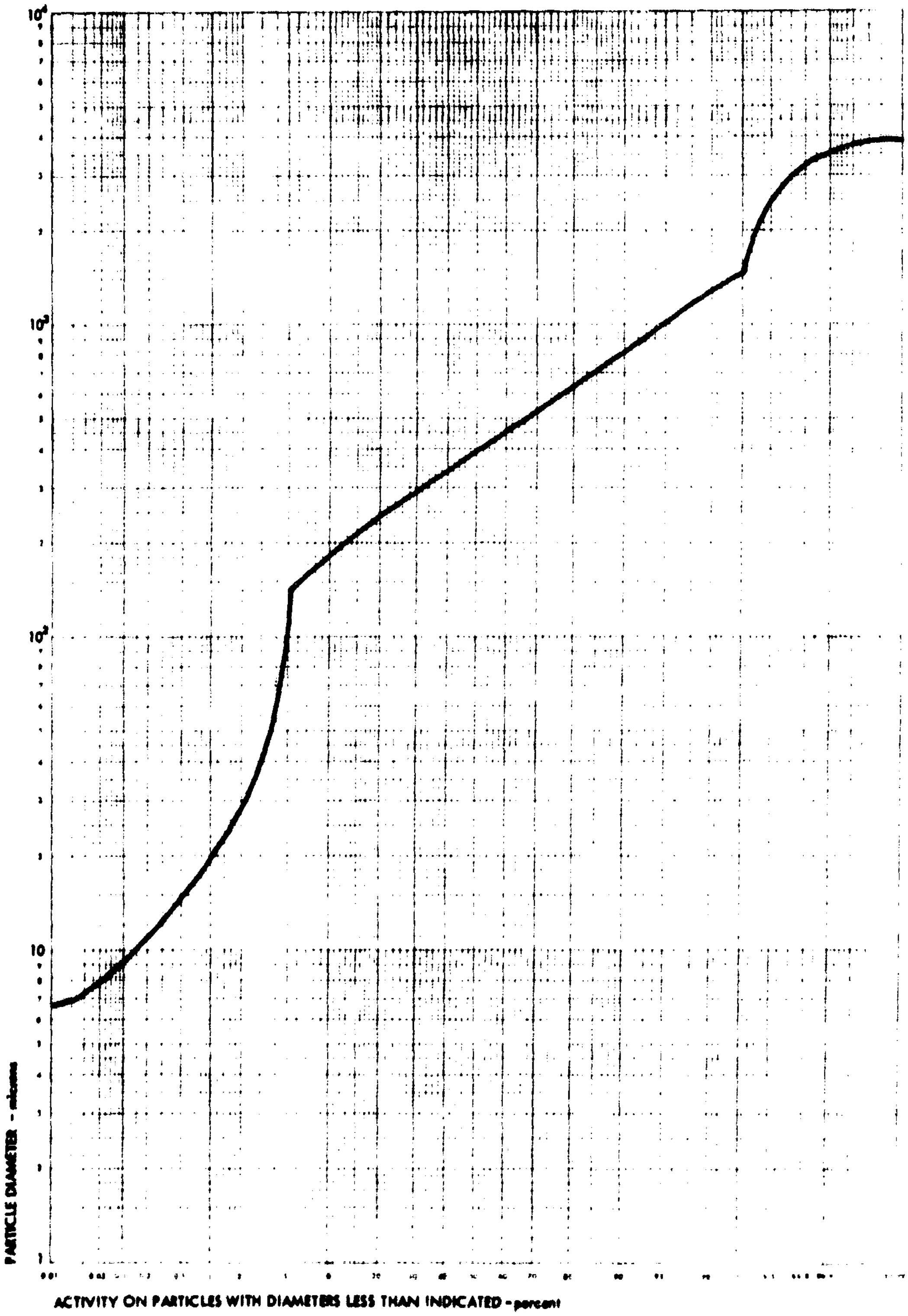


Figure 3

A TYPICAL COMPOSITE ACTIVITY-SIZE DISTRIBUTION CURVE



(at this point) to believe that this ratio should be different for a large number of particles of a given size range simply because of a difference in location in the fallout area. These ratios have been computed for samples collected at various downwind locations and are presented in Table 1 along with the estimated limiting particle sizes for the respective sample. The data are also shown in Figure 4.

The values of the ratio for particle sizes smaller than the upper limit of the respective sample are generally in good agreement. The inconsistent values shown in sizes larger than the upper limit reinforce the argument that the larger sizes in the sample were not part of the true fallout size distribution.

A smoothed curve is drawn through the geometric means of the ratios in Figure 4. Because of the wide spread in the size range, the curve is only suggested as a first approximation of the variation in ion current per fission at H + 100 hours with particle size for the Shot Small Boy fallout. The mean values of the ratios can be checked independently by using decayed sample size fractions in the following way.

The decay of the gamma ion current and gamma count rates per fission for an unfractionated fission product mixture was computed using data from References 1 and 6. In the period of D + 150 days to D + 300 days, about 70 percent of the total gamma ion current is contributed by Zr-95 (Nb-95) and 25 percent by Ru-103 and Ru-106. The degrees of fractionation of the latter two radionuclides in the various size fractions of fallout particles can be estimated from the radiochemical analyses. These estimated fractionation numbers* are presented in Table 2. Since Zr-95 and NB-95 are assumed to be unfractionated with respect to Mo-99, the approximate gross fractionation numbers (see Reference 9 for the definition of the gross fractionation number as applied to a previous analysis

* The ratio of the activity of the nuclide in question to that of a reference nuclide (e.g., Zr-95) as observed in a fallout sample relative to the same ratio estimated for an unfractionated sample.

Table 1

ION CURRENT PER FISSION FOR SIEVED FRACTIONS AND ESTIMATED FALLOUT PARTICLE SIZE LIMITS OF SHOT SMALL BOY FALLOUT SAMPLES

(10^{-20} ma/fission at H + 100 hours)

Station	Mean Particle Size of Sieved Fraction (microns)								Estimated Size of Fallout Particles	
	22	66	132	264	530	1,060	2,120	~3,400	Maximum	Minimum
100	3.50	4.04	1.15	0.990	0.848	1.06	1.28	-	2,300	230
101	3.78	1.81	1.36	1.05	-	-	-	1.43	4,000	460
201	3.53	2.47	1.24	0.811	0.800	0.850	1.00	19.5[a]	3,000	265
203	0.336[a]	2.06	1.62	0.862	0.822	0.830	1.30	-	2,700	310
305	5.45	2.93	1.76	1.32	0.917	0.965	0.915	1.05	4,000	320
403	3.57	3.56	1.02	0.911	0.846	1.37	4.51[a]	2.95[a]	1,000	160
505	3.93	2.81	0.842	0.749	0.943	20.5[a]	8.63[a]	4.61[a]	700	150
507	1.03[a]	1.73	-	1.32	0.859	0.907[a]	19.8[a]	-	700	140
507	-	-	-	1.03	-	-	-	-		
603	3.21	2.09	0.757	0.507[a]	0.883	47.5[a]	0.326[a]	-	500	120
707	5.19	2.15	1.13	1.25	0.731[a]	9.11[a]	-	-	250	90
813	3.72	1.13	1.24	0.994	3.63[a]	1.62[a]	1.56[a]	-	250	40
Mean	3.92	2.30	1.17	1.01	0.864	0.998	1.11	1.23		

a Values not used in calculating mean values

Figure 4

VARIATION OF ION CURRENT PER FISSION WITH PARTICLE SIZE FOR SHOT SMALL BOY FALLOUT

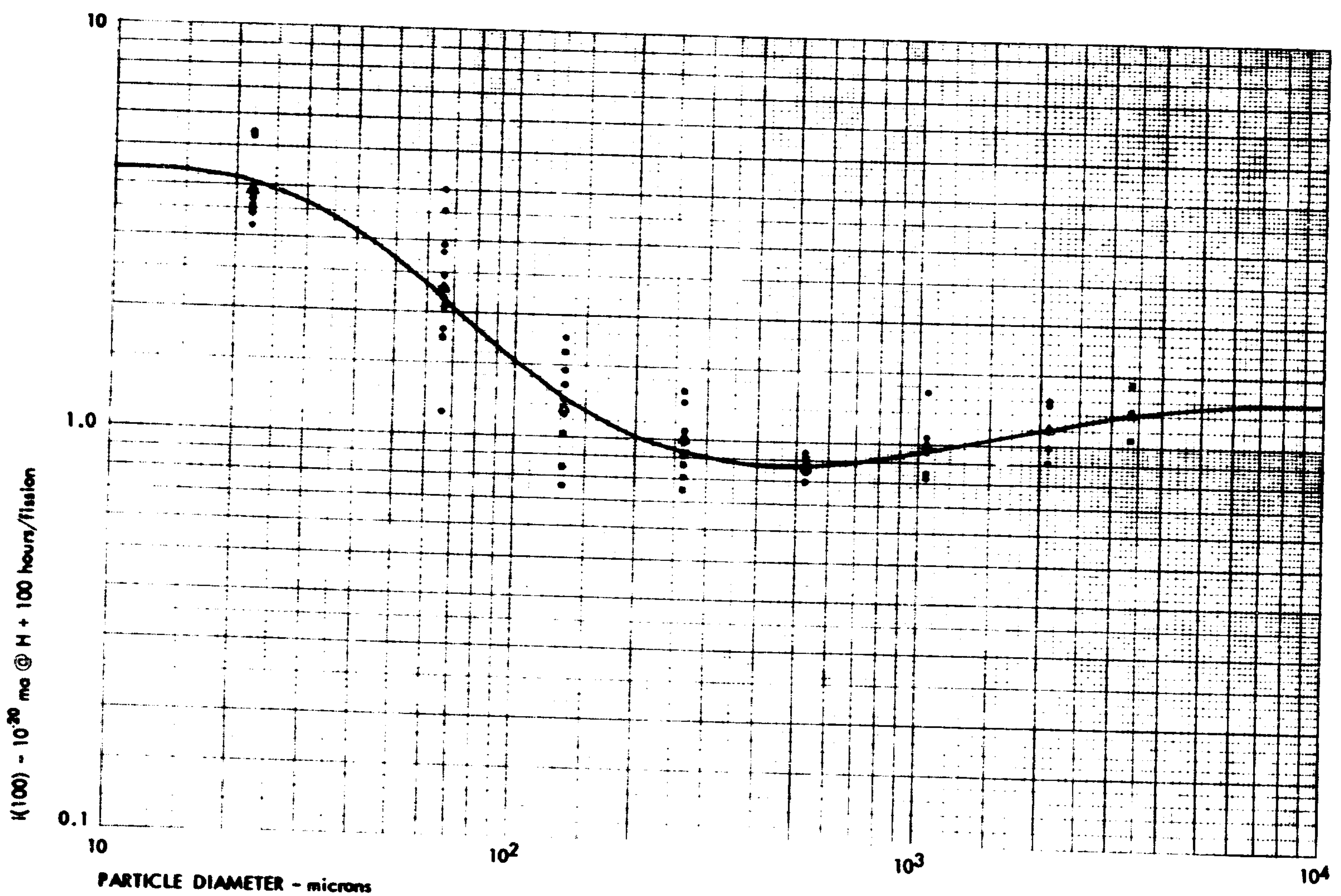


Table 2

ESTIMATED FRACTIONATION NUMBERS OF Ru-103 AND Ru-106 RELATIVE TO Zr-95 IN VARIOUS SIZE FRACTIONS OF SHOT SMALL BOY FALLOUT

Nuclide	Mean Particle Size of Sieved Fraction (microns)							
	22	66	132	264	530	1,060	2,120	>3,400
Ru-103	1.73	1.05	0.680	0.433	0.375	0.482	0.480	0.222
Ru-106	1.49	0.690	0.298	0.108	0.091	0.137	0.180	0.067

of the Small Boy fallout data) of the fission products mixture in this period of time may be computed, and they are tabulated in Table 3.

Combining the values in Table 3 with the computed unfractionated gamma ion current gives the decay of the gamma ion current per fission in the period of D + 150 to D + 300 days for the fractionated fission product mixture associated with the different particle size fractions. The actual measured gamma ion current of a size fraction sample in this period should be proportional to that computed for the size fraction, and their ratio should give the fission content of the sample. Since decay data from D + 2 to D + 200 days were measured for each size fraction sample, the fission contents of the samples and values of gamma ion current per fission at H + 100 hours may be estimated. The variation of ion current per fission with particle size obtained by this treatment are shown in Table 4. These data appear to be in complete agreement with the mean values given in Table 1.

A few cloud samples were collected by airplanes flown through the radioactive cloud. These samples consisted of fallout particles with diameters of less than 40 microns. Their fission contents and gamma ion currents at H + 100 hours are listed in Table 5. The ratios of these two sets of data are consistent with the mean value for particles of less than 44 microns given in Table 1.

The spread in the ion current per fission values for each particle size in Table 1 may be partially caused by spread in the radiochemical results and partially by the artificial selection of mean particle sizes for various sieved fractions. Furthermore, the spread in the values is largest for the smallest and largest particle diameters. This fact may indicate that there are small particles mixed into the large size fractions and that the mean diameter of the small particles in each sample is quite variable (subsieving analysis was not performed).

The major significance of the variation in ion current per fission with particle diameter is that it indicates the manner in which the fractionation depends on particle size. The curve first decreases with particle size to a minimum at about 450 microns. It then increases slightly

Table 3

ESTIMATED GROSS FRACTIONATION NUMBERS

Time after Detonation (days)	Mean Particle Size in Sieved Fraction (microns)							
	22	66	132	264	530	1,060	2,120	~3,400
97.3	1.19	0.996	0.894	0.829	0.815	0.842	0.843	0.780
143	1.16	0.985	0.892	0.836	0.824	0.846	0.849	0.796
208	1.14	0.966	0.878	0.829	0.821	0.838	0.843	0.803
301	1.15	0.928	0.818	0.761	0.754	0.770	0.780	0.741

Table 4

ION CURRENT PER FISSION ESTIMATED FROM ION CHAMBER MEASUREMENTS
AND COMPUTED ION CHAMBER DECAY CURVE

(10^{-20} ma/fission at H + 100 hours)

Station	Sample Number	Mean Particle Size of Sieved Fraction (microns) 22	66	132	264	530	1,060	2,120	~3,400
100	PO-1	4.60		0.885	1.04	0.890	0.910	1.14	
201	AO-9								1.13
201	AOC					0.830		1.05	
303	AOC					0.830		1.26	
503	AOC					1.04			
505	AO-3	4.60							
507	PC-4	4.44		1.00					
601	AOC					1.20			
705	AOC				0.940				
815	LAC			0.990	1.11				

Table 5

ACTIVITY DATA FOR SHOT SMALL BOY CLOUD SAMPLES

Sample	Fission Content (10^{13} fissions)	Ion Current (10^{-7} ma at H + 100 hrs)	i(100) (10^{-20} ma/f)
827-L1-2A	9.91	46.6	4.70
837-L1-1A	3.22	41.1	12.8
837-L1-2A	8.85[a]	36.4	4.11
842-R1-1A	2.32	17.9	7.72
842-R1-1C	2.47	11.3	4.57
842-R1-1D	4.48	17.4	3.88
245-L1-2	2.32	14.7	6.34

a Value estimated from decay data

at very large particle sizes. A similar variation with particle size in the gross solubility of the radionuclides is observed.[6,7]

By using the mean ion current per fission values in Table 1, the fission contents can be estimated for samples for which no radiochemical analyses have been made. The fission content along with ion current and gamma count rate densities for all fallout samples are summarized in Table 6. The values for each fallout collection station are generally consistent with one another. Their mutual ratios as a function of median sample particle diameter are shown separately in Figures 5, 6, and 7. The data of Table 6 are similar to those previously deduced by Miller and Sartor[7] although the revised fission contents are generally 10 to 20 percent lower.

To evaluate the amount of inactive particles present in the fallout samples and the true specific activity of the particles, the gross particle weight distributions for all samples were analyzed. Since the weight of the smaller broken fallout particles was generally negligible compared with the weight of the intact fallout particles and of the background dirt, the gross weight distribution is primarily the composite of the distributions of the latter two. As noted above, the intact fallout particles have a definite size range at a particular location while the background dirt may be present in all particle sizes. Therefore, break points will still occur at the size limits of the intact particles on the distribution curve, but the distinctness of the break points will depend on the relative abundance of the two kinds of particles. In the actual data studied, break points were observed for most of the fallout samples. Moreover, the break points on the weight distribution curve for a sample appear at the same sizes as they do on the activity distribution curve. A first order estimate of the weight percentage of background dirt in a fallout sample may also be estimated from the weight distribution curve. The percentage varies considerably with the location where the sample was collected and with the amount of fallout. For samples collected along the hot line and from points less than five miles from ground zero of Shot Small Boy, the background dirt in each sample was generally less than

Table 6

SUMMARY OF RADIOACTIVITY CONTENT OF SHOT SMALL BOY FALLOUT SAMPLES

Station	Sample Number	d_{50} (μ)	$I_1(100)$ (10^{-8} mr/ft^2)	$I_2(100)$ (10^{-8} mr/ft^2)	$I'(100)$ (10^{8} c/m/ft^2)	A_1 (10^{14} f/ft^2)	A_2 (10^{14} f/ft^2)	$i_1(100)$ (10^{-20} mr/f)	$i_2(100)$ (10^{-20} mr/f)	$i_1'(100)$ (10^{-6} c/m/f)	$i_2'(100)$ (10^{-6} c/m/f)	$r_1(100)$ (10^{-11} mr/c/m)	$r_2(100)$ (10^{-11} mr/c/m)
100	PC-1	610	208	219	2,18	2,12	2,23	0,960	0,985	1,03	0,978	0,954	1,00
	PC-2	(610)		230	2,34		2,35[b]		0,979		1,00		0,983
	PC-4	(610)		235[a]	2,47		2,39[a]		0,985		1,03		0,951
	PC-5	610	232		2,06	2,39		0,968		0,858		1,13	
	PO-1	920	312		3,70	3,17		0,987		1,17		0,843	
101	OC-1	1,130	2,170		23,8	2,15		1,01		1,11		0,912	
	AO-1	(1,130)			19,9		2,00[b]				1,00		
	AO-4	(1,130)		2,070[a]	19,2		1,97[a]		1,05		0,975		1,08
	AO-6	1,130	2,020	1,970	20,0	19,9	1,94	1,01	1,01	1,00	1,03	1,01	0,985
201	AO-4	650	837		7,14	8,87		0,943		0,806		1,17	
	AO-7	(650)			8,24		8,27[b]				0,996		
	AO-8	(650)		850[a]	8,37		8,00[a]		1,06		1,06		1,02
	AO-9	650	895	837	8,10	9,45	8,79	0,947	0,952	0,887	0,922	1,10	1,03
	AO-10	650	853	914	8,40	8,94	9,66	0,953	0,948	0,940	0,870	1,02	1,09
203	PC-16	600	242	254	2,42	2,72	2,75	0,925	0,924	0,890	0,880	1,00	1,05
	PC-21	(600)		278	2,73		2,98[b]		0,933		0,916		1,02
	PC-22	(600)		254[a]	2,84		2,70[a]		0,941		1,05		0,894
	PO-2	730	390		3,54	4,14		0,942		0,856		1,10	
305	AO-1	(540)		379[a]	3,41		3,81[a]		0,995		0,895		1,11
	AO-2	(540)			4,01		4,77[b]				0,841		
	AO-3	540	429	435	9,18	4,69	4,75	0,915	0,916	1,96[c]	1,93[c]	0,467[c]	0,473[c]
	AO-4	540	440	467	4,41	4,60	5,02	0,956	0,930	0,959	0,878	1,00	1,06
	AO-6	540	445	452	4,46	4,92	4,99	0,904	0,906	0,907	0,892	1,00	1,01
	AO-9	(540)		445	4,90		4,90[b]		0,908		1,00		0,908
401	OC	420	474		4,81	5,27		0,899		0,913		0,985	
	AO-9	(420)		463	4,90		5,39[b]		0,859		0,909		0,945
403	OC	310	600		8,16	6,26		0,955		1,30[c]		0,735[c]	
	AO-1	(310)		603[a]	5,95		6,12[a]		0,985		0,972		1,01
	AO-2	(310)			3,19		6,40[b]				0,498[c]		
	AO-4	310	614	614	5,93	6,33	6,35	0,970	0,967	0,937	0,934	1,04	1,04
405	OC	360	220		2,11	2,37		0,931		0,890		1,04	
	AO-9	(360)		188	1,91		2,14[b]		0,650		0,879		0,984
506	AO-1	(225)			3,36		3,51[b]				0,957		
	AO-2	225	303	343	3,37	2,65	3,18	1,06	1,08	1,18	1,06	0,899	1,02
	AO-3	225	345	350	1,90	3,23	3,24	1,07	1,06	0,588[c]	0,586[c]	1,82[c]	1,84[c]
	AO-4	(225)		338[a]	3,51		3,38[a]		1,00		1,04		0,965
	AO-6	225	320	350	3,44	2,97	3,28	1,08	1,08	1,16	1,06	0,930	1,02
507	PC-1	(215)		132	1,55		1,33[b]		0,992		1,17		0,852
	PC-2	(215)		130[a]	1,50		1,42[a]		0,921		1,06		0,867
	PC-4	215	127	128	1,49	1,20	1,21	1,06	1,06	1,24	1,03	0,852	0,859
	PC-5	215	156	157	1,49	1,50	1,51	1,04	1,04	1,00	0,987	1,06	1,06
603	AO-1	175	167	162	1,89	1,51	1,46	1,11	1,11	1,25	1,29	0,885	0,857
	AO-2	175	160	155	1,83	1,45	1,55	1,11	1,00	1,26	1,18	0,874	0,847
	AO-3	(175)		160[a]	1,84		1,60[a]		1,00		1,15		0,870
	AO-4	(175)			1,92		1,67[b]				1,15		
606	AO-1	165	152		1,81	1.37		1,11		1,32		0,840	
	AO-9	(165)		174	1,63		1,60[b]		1,09		1,02		1.07
707	AO-3	120	73,6	69,6	0,754	0,609	0,570	1,21	1,22	1,24	1,32	0,976	0,923
	AO-6	(120)			0,868		0,643[b]				1,05		
	AO-8	120	74,5	86,0	0,870	0,602	0,694	1,24	1,23	1,45	1,25	0,856	0,989
813	LAC	100	8,61	9,51	0,0979	0,0575	0,0626	1,50	1,52	1,70	1,56	0,879	0,971

Notes: (1) I_1 is based on the ion-chamber measurements by the radio chemical project (Reference 5).
(2) I_2 is based on the ion-chamber measurements by the field project (Reference 4).
(3) I' is based on the calibrated gamma-scintillation-counter measurements by the field project
(4) A_1 and A_2 are derived from I_1 and I_2 respectively.
(5) $i_1 = I_1/A_1$, $i_2 = I_2/A_2$, $i_1' = I'/A_1$, $i_2' = I'/A_2$, $r_1 = I_1/I'$, $r_2 = I_2/I'$.

a Value estimated from decay data.
b Value estimated from radiochemistry data.
c Value not used in computing mean value.

Figure 5

VARIATION OF ION CURRENT PER FISSION WITH MEDIAN PARTICLE SIZE FOR SHOT SMALL BOY GROSS FALLOUT SAMPLES

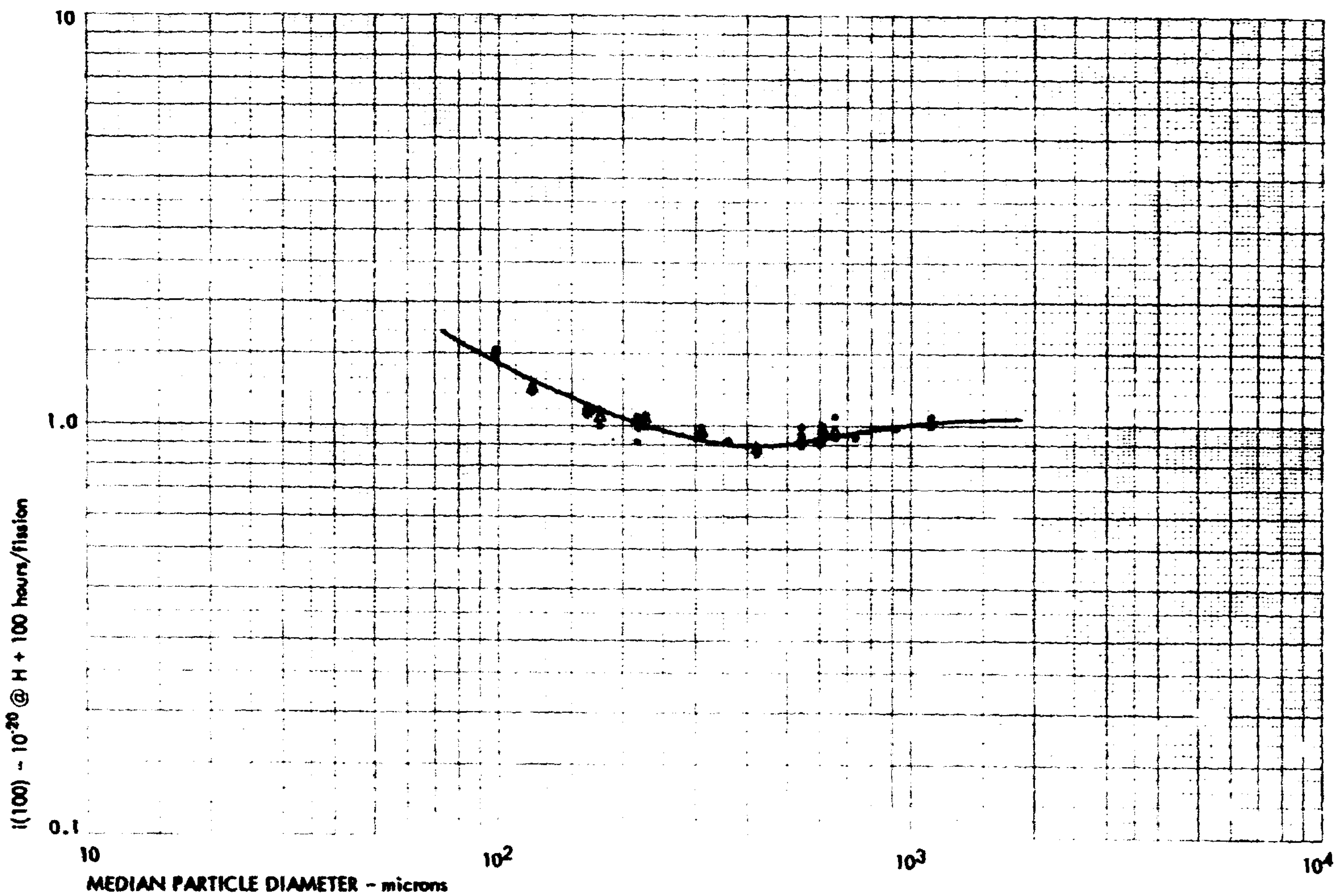


Figure 6

VARIATION OF GAMMA COUNT RATE PER FISSION WITH MEDIAN PARTICLE SIZE FOR SHOT SMALL BOY GROSS FALLOUT SAMPLES

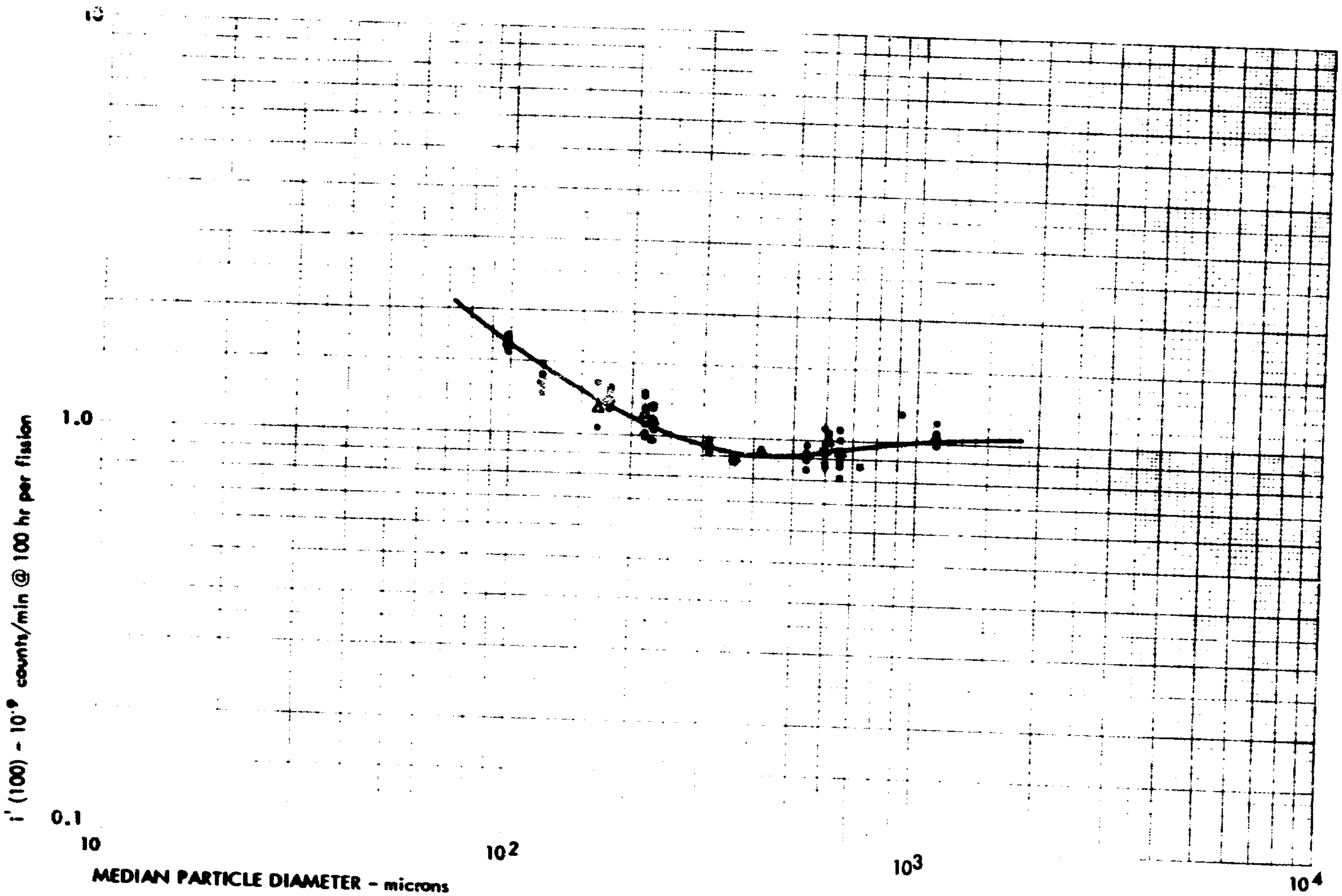
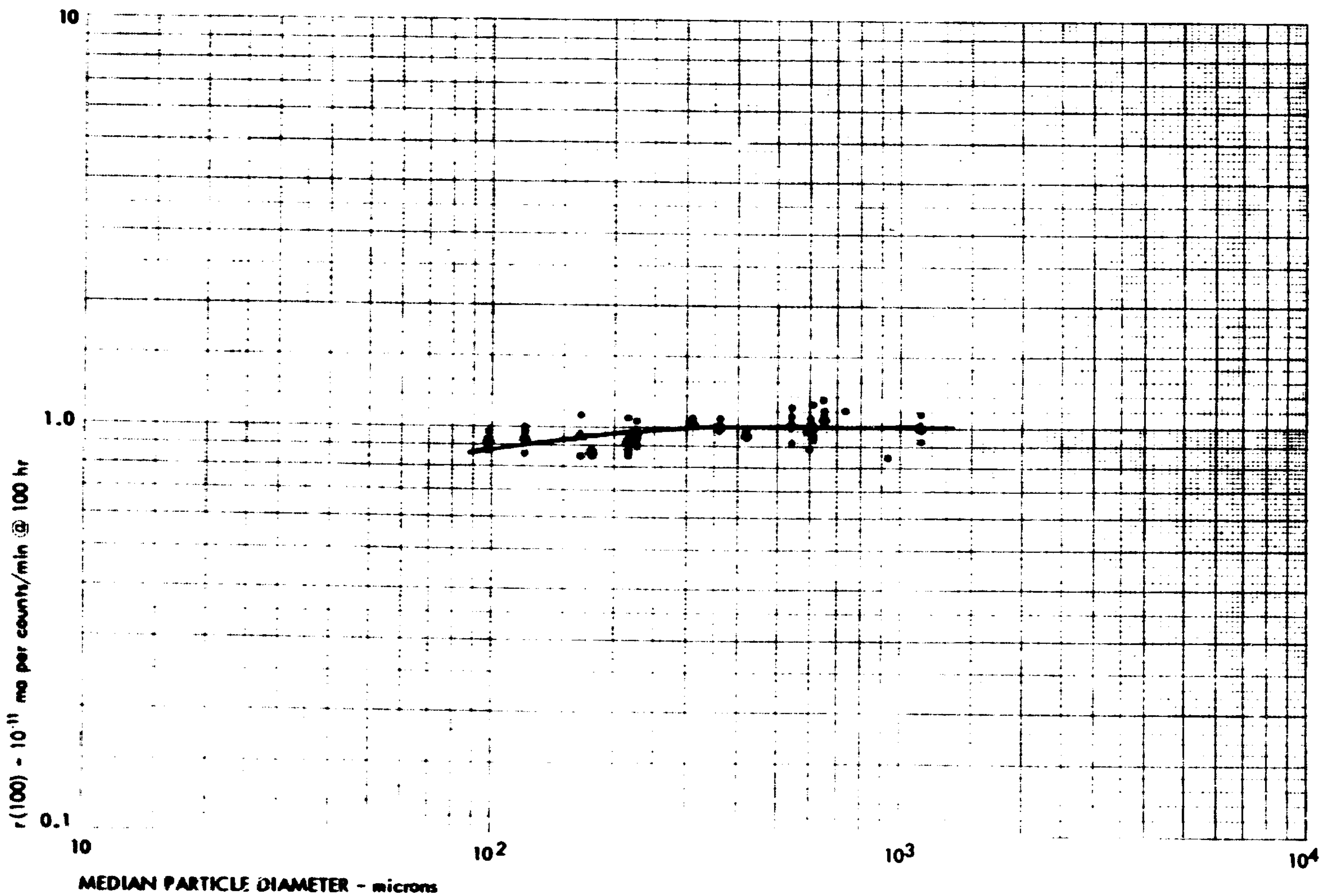


Figure 7

VARIATION OF ION CURRENT PER GAMMA COUNT RATE WITH MEDIAN PARTICLE SIZE FOR SHOT SMALL BOY GROSS FALLOUT SAMPLE



50 percent of the total sample weight; in others, it was generally in excess of 50 percent.

Estimation of Specific Activity

The major difficulty in estimating specific activity from measurements of the weight and activity of a fallout sample is in the determination of the weight of the fallout particles, given the total sample weight including that of the background dirt and debris. Virtually no experimental method, except the individual separation of the particles, is available for resolving this difficulty.

As described previously, the percentages of the total activity of a fallout sample that was attached to the broken particles and background dirt were estimated through graphical analyses of the distribution. The radioactivity of these two components was redistributed proportionally among the particles of the true fallout size distribution, and the specific activity of each size fraction was calculated. This corrected specific activity for each size fraction of a fallout sample is the first approximation of the average fallout specific activity of that size fraction. Since, for the size range of the fallout particles in the samples, the specific activity must be a monotonically decreasing function of particle size, the computed specific activity values that deviate from this criterion are discarded. The remaining values from all samples then give a spectrum of specific activity values when plotted as a function of particle diameter. Further, it is clear that combinations of values giving the highest specific activity in each size fraction should be the best estimate of the true average specific activity of the fraction, since it must contain the least percentage of extraneous inactive dirt. Also, since the samples with the highest specific activity were those containing background dirt in which the large-sized fraction amounted to less than 15 percent of the total sample weight, the error incurred by using the highest observed specific activity as the true average specific activity should not be very large. This technique was thus used to derive the specific activity as a function of particle size for the Shot Small Boy fallout.

During the process of analysis, several interesting observations pertinent to the basic assumptions of the present study were made.

1. Samples from the same location usually have different activity-particle size distributions but have the same limits of fallout particle sizes (at the break points in the distribution curve). This finding supports the argument in the analysis section about fallout particle size limits at a particular location.

2. The estimated size limits of fallout particles decrease, and the size range narrows, with increasing downwind distance of the collecting stations. This observation agrees with the general theory of fallout distribution and lends further support to the size limit argument.

3. The samples that have size fractions with the highest specific activity are either those along the hot line (such as Stations 201, 305, and 505) or those near shelters that were collected at earlier times (such as Stations 100, 203, and 507, and OC samples). This observation is a result of the facts that a maximum amount of fallout was deposited on the former and a minimum amount of background dirt was introduced in the latter.

4. For close-in stations where the weight of fallout was relatively high, the average specific activity decreases with increasing particle size. This observation led to the assumption that, for the larger particles, the specific activity is a monotonically decreasing function of particle size.

5. For far-out stations such as Station 707, where the weight of fallout was very low, the fallout was generally obscured by the amount of background dirt. For these samples, the computed values of the specific activity decrease as the median particle size decreases and these computed values no longer represent the true specific activity of the fallout.

6. The estimated specific activity, at a maximum value of 2.4×10^{15} fissions/gm, exceeds the value of c_{max} of Equation 3 for B and W values of unity by about a factor of 3.4. Thus, the specific activity of the fallout apparently increases for detonations above ground surface. (The average specific activity would be less and can only be estimated from integrations of fallout patterns for each particle size group as described in Reference 9.)

RESULTS AND DISCUSSION

The specific activity of the various size fractions for fallout samples collected from Shot Small Boy are summarized in Table 7. The estimated specific activity of the fallout is plotted as a function of particle size in Figure 8. The two highest specific activity values for each size range are shown.

The curve in Figure 8 is given by

$$c_{fp} = \frac{3.5 \times 10^{18}(1 - e^{-6.91 \times 10^{-4} d})}{d}, \quad d \simeq 50 \text{ to } 10{,}000 \text{ microns} \qquad (11)$$

for d in microns and c_{fp} in fissions/gm. The form of Equation 11 and the values of the empirical constants indicate that, for particles with diameters of less than about 200 microns, the radioactive content of the particles is proportional to the particle volume or weight and that, for particles with larger diameters, the radioactive content becomes increasingly concentrated on the surface of the particles. For the particles with diameters larger than about 2,000 microns, the radioactive content is essentially proportional to the surface area of the particles (i.e., c_{fp} is essentially proportional to 1/d). The limiting value of c_{fp} in Equation 11 would be 2.42×10^{15} fissions/gm. However, it is not expected that Equation 11 would represent the specific activity of the Shot Small Boy fallout for particles with diameters of less than about 50 microns. The true value would be expected to increase again as the particle size decreased to values of less than 10 to 50 microns. However, from the limiting particles sizes given in Table 7, the representation of Equation 11 should apply to the entire region of heaviest fallout deposit from Shot Small Boy.

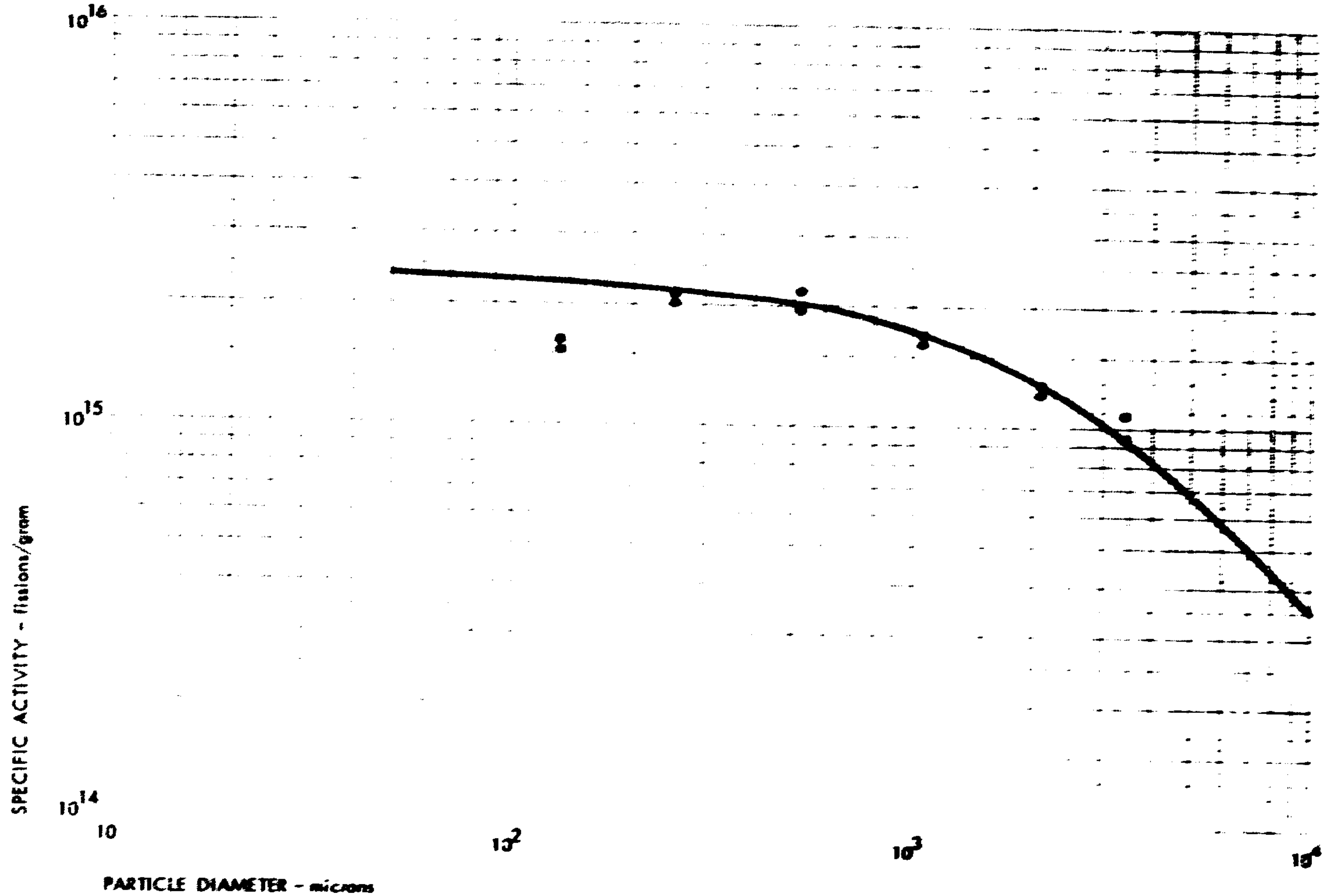
Table 7

FIRST APPROXIMATION OF SPECIFIC ACTIVITY FOR SIEVED FRACTIONS OF SHOT SMALL BOY FALLOUT SAMPLES (10^{15} fissions/gm)

Station	Sample Number	Mean Particle Size of Sieved Fraction (microns) 132	264	530	1,060	2,120	~3,400	Estimated Limiting Sizes of Fallout Particles Maximum	Minimum
100	PC-1			1.80	1.41	0.865		2,300	230
	PC-5			2.21	1.64	1.23		2,600	250
	PO-1			1.86	1.32	1.14		2,800	240
101	OC-1			1.67	1.22	1.13	0.571	4,000	460
201	AO-4			1.71	1.23	1.11	1.09	4,000	270
203	PO-2			1.82	1.42	1.27		2,700	310
	PC-16			1.74	1.39			2,700	310
301	OC			1.88	1.43	1.15		2,500	275
305	AO-3			2.01	1.49			2,000	320
	AO-4			1.70	1.54	1.10	0.937	4,000	320
	AO-6			2.01	1.38			1,500	330
401	OC		2.04	1.95	1.70			800	220
403	AO-4		1.79	1.58				1,000	160
505	AO-2		1.70	1.68				700	160
	AO-3		2.01	1.11				700	160
	AO-6		1.65	1.11				700	150
507	PC-4		1.78	1.35				700	135
	PC-5		2.17					700	140
603	AO-1		1.83	1.09				500	120
	AO-2		1.98					500	110
605	AO-1		2.07					300	130
707	AO-3	1.55	0.951					250	90
	AO-9	1.66						250	90

Figure 8

VARIATION OF ESTIMATED SPECIFIC ACTIVITY WITH PARTICLE SIZE FOR SHOT SMALL BOY



SUMMARY

In the analysis in this report of the specific activity of the fallout from Shot Small Boy that was collected in heavy fallout regions, it was found that, when Zr-95, Ce-144, and Mo-99 are not fractionated with respect to each other, the absolute fission content of the fallout can be accurately determined from detecting equipment without reference to a single radionuclide. The specific activity of the fallout was found to be essentially independent of particle size for particles with diameters from about 50 to 200 microns (i.e., the radioactive content is proportional to particle volume). For particles with diameters larger than about 2,000 microns, the radioactive content is essentially proportional to the surface area of the particles. An exponential function, fitted to the data, was used to represent the dependence of the specific activity on particle diameter in accordance with the observed shift in mode of the radioactive particle formation from volume to surface area incorporations.

REFERENCES

1. Miller, C. F., Fallout and Radiological Countermeasures, Volume I, Stanford Research Institute, Project No. IMU-4021, January 1963

2. Rapp, R. R., A Re-Examination of Fallout Models, RM-4910-TAB, February 1966

3. Cane, John W., Fallout Phenomenology: Nuclear Weapons Effects Research Project at a Crossroads, DASA 2003, October 1967

4. Clark, D. E., and W. C. Cobbin, Some Relationships Among Particle Size Mass Level and Radiation Intensity of Fallout from a Land Surface Nuclear Detonation, U.S. Naval Radiological Defense Laboratory, USNRDL-TR-639, March 21, 1963

5. LaRiviere, P. D., et al., Local Fallout from Nuclear Test Detonations, Volume V: Transport and Distribution of Local (Early) Fallout from Nuclear Weapons Tests (U), DASA 1251/NDL-TR-65/SRI-4-3338, Stanford Research Institute, Project No. IMU-4562, December 1964 (Classified)

6. LaRiviere, P. D., et al., Fallout Collection and Gross Sample Analysis (U), Project 2.9, Operation SUNBEAM, POR-2215, 1963 (Classified)

7. Freiling, E. C., et al., Physiochemical and Radiochemical Analysis (U) Project 2.10, Operation SUNBEAM, POR-2216, 1963 (Classified)

8. Miller, C. F., Biological and Radiological Effects of Fallout from Nuclear Explosions, Chapters 1 and 2, Stanford Research Institute, Project No. IMU-4536, March 1964

9. Miller, C. F., and J. D. Sartor, Shot Small Boy Fallout Research Program, Radioactive Fallout from Nuclear Weapons, Proceedings of the Second Conference, U.S. Atomic Energy Commission/Division of Technical Information, November 1965

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Stanford Research Institute, Menlo Park, California 94025	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP
3. REPORT TITLE The Mass Contour Ratio for Fallout and Fallout Specific Activity for Shot Small Boy	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)	
5. AUTHOR(S) (First name, middle initial, last name) Carl F. Miller and Oliver S. Yu	

6. REPORT DATE December 1967	7a. TOTAL NO. OF PAGES 35	7b. NO. OF REFS 9
8a. CONTRACT OR GRANT NO. N00228 67C1143	9a. ORIGINATOR'S REPORT NUMBER(S)	
b. PROJECT NO. OCD Work Unit No. 3119A		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.	TRC-68-15	
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Civil Defense, Office of the Secretary of the Army, Washington, D. C. 20310	

13. ABSTRACT

Data on the fallout specific activity from Shot Small Boy was analyzed. The specific activity for particles of about 50 to 200 microns in diameter was approximately constant, and for particles over 2,000 microns was approximately inversely proportional to particle diameter. An exponential function was fitted to the data to represent the dependence of specific activity on particle diameter in shifting from volume to surface area modes of incorporation of specific activity.

Unclassified
Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fallout						
Mass Contour Ratio						
Specific Activity						
Shot Small Boy						
Particle Size						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Unclassified
Security Classification