INVESTIGATIONS OF NATURAL VARIATIONS OF CESIUM-137 CONCENTRATIONS IN RESIDENTIAL SOILS

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INVESTIGATIONS OF NATURAL VARIATIONS OF CESIUM-137 CONCENTRATIONS IN RESIDENTIAL SOILS

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1.0 SUMMARY AND INTRODUCTION

Radiological surveys to characterize the radiological condition of properties contaminated with residual radioactive material have to some degree used regional and world-wide fallout deposition estimates establish background concentrations for radionuclides such as ^{137}Cs in soil. Use of these historical deposition estimates or related soil sampling efforts to project background concentrations and to make comparisons to local sampling and measurement results from decontamination or remedial action studies is not appropriate when different sampling protocols are used, which is the case for most decontamination surveys.

The study (Wallo 1993) summarized in this report investigated ^{137}Cs concentrations in the residential environment and demonstrated that normal variations of soil concentrations (due to fallout deposition) of ^{137}Cs are likely to vary by orders of magnitude within a local residential area and peak concentrations would expect to be more than 10 times that predicted from fallout deposition studies.

Section 2 of this report discusses regional ^{137}Cs soil concentration estimates based on historical measurements of fallout deposition, soil sampling and associated protocol used to estimate the concentration of cesium in regional soils. It also discusses reasons why results that are based on these data are not comparable to results from radiological surveys conducted in support of remedial actions or decontamination activities. Section 3 discusses the results of this investigation of ^{137}Cs concentrations in soils in residential environments. Section 4 discusses the conclusions and findings of the study.

To characterize ^{137}Cs concentrations in residential environments, survey data from three states were evaluated. Data included about 600 sample locations from over 200 properties in central New York, 26 properties in Beverly, Massachusetts, and 10 properties in northeastern Pennsylvania. The New York and Massachusetts data were obtained from surveys conducted by Oak Ridge National Laboratory for the Department of Energy. The Pennsylvania data was collected and analyzed by Georgetown University. The analysis indicates that cesium moves slowly in the soil and unless physically disturbed remains in the surface. The data also indicated that ^{137}Cs concentrations in drainage areas (e.g., roof driplines and drain spout discharge locations) are significantly higher than concentrations in open areas. More specifically, the study resulted in 5 general conclusions or findings:

- The analysis indicates that fallout deposition data do not adequately predict the variability in local background concentrations for ^{137}Cs in soil. Surface samples from undisturbed soil produce the greatest variability and can differ by several orders of magnitude. Surface sample geometric mean concentrations are in the range from 0.3 to 3 pCi/q [10 to 110 Bq/kg] with the range of the 95th percentile concentrations extending to about 20 pCi/g [700 Bq/kg].

- Areas that collect rain water have significantly higher concentrations of ^{137}Cs in soil than open areas. The geometric mean concentrations in drainage areas are typically 3 times that of nondrainage areas.

- The concentration of ^{137}Cs in soil decrease [sic] significantly with depth. In general, most of the cesium is contained in the top 15 cm of undisturbed soil.

- Surface samples taken from the 0 to 5 cm depth in undisturbed soil had significantly higher concentrations than those taken at the same depth in disturbed soil. However, surface samples taken over the 0 to 10 cm or 0 to 15 cm range were less sensitive to soil disturbance.

- The lognormal distribution is generally more representative of environmental concentrations of ^{137}Cs than the normal distribution.

1.0 BACKGROUND

2.1– Cesium Concentrations and Variability

Local or regional measurements of ^{137}Cs are typically compared to baseline estimates of ^{137}Cs concentrations world-wide which are calculated from deposition measurements of ^{90}Sr (Eisenbud 1987, UNSCEAR 1982). These estimates use a well established ^{137}Cs: ^{90}Sr deposition ratio of 1.6 (Hardy 1968, UNSCEAR 1982, 1988).[2] Table 2.1 provides such estimates of ^{137}Cs depositions by latitude integrated to 19880 (UNSCEAR 1977, 1972). Deposition of cesium from fallout peaked in the United States in the mid-1960's and contributions following 1980 are generally insignificant. The possible exception was depositions resulting from the Chernobyl nuclear reactor accident in 1986. However, while small increases could be measured in the United States (Carlton et al. 1992), the increases were not significant in comparison to depositions from weapons testing fallout (Eisenbud 1987, UNSCEAR 1989, NCRP 1987A).

Table 2.1
Estimates of Potential Cs-137 Concentrations in
Soils by Latitude and Assumed Depth of Distribution

LATUTUDE BAND	Deposition (a)		Concentrations if distributed from 0 to 5cm (b)		0 to 30 cm (b)	
Degrees	Cs-137 Bq/cm2	(pCi/cm2)	pCi/g	(Bq/Kg)	pCi/g	(Bq/Kg)
70-80N	0.11	2.9	0.20	7.4	0.03	1.2
60-70N	0.28	7.5	0.51	18.8	0.08	3.1
50-60N	0.46	12.5	0.85	31.3	0.14	5.2
40-50N	0.52	14.0	0.94	35.0	0.16	5.8
30-40N	0.37	10.1	0.68	25.3	0.11	4.2
20-30N	0.28	7.6	0.52	19.2	0.09	3.2
10-20N	0.19	5.1	0.35	12.9	0.06	2.1
0-10N	0.13	3.5	0.24	8.8	0.04	1.5
0-10S	0.08	2.1	0.14	5.2	0.02	0.9
10-20S	0.07	1.8	0.12	4.5	0.02	0.8
20-30S	0.11	3.0	0.20	7.6	0.03	1.3
30-40S	0.12	3.3	0.22	8.2	0.04	1.4
40-50S	0.14	3.8	0.26	9.6	0.04	1.6
50-60S	0.08	2.0	0.14	5.1	0.02	0.8
60-70S	0.06	1.5	0.10	3.8	0.02	0.6
70-80S	0.04	1.0	0.06	2.4	0.01	0.4

(a) Cs-137 Deposition estimate from Sr-90 assuming a ratio of 1.6 Cs-137 to Sr-90 integrated to 1980

(b) Soil concentration estimated assuming an average soil density of 1.6 g/cm3 and the deposition averaged over the entire depth. The values are corrected for decay to 1991.

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1 - The deposition ratio between radionuclides (1.6 for ^{137}Cs: ^{90} SR) does not represent the cesium to strontium concentration ratio in the soil; different fate and transport mechanisms cause the ratio to change significantly after deposition.

These estimates project variations in cesium deposition of about 1 order of magnitude between the highest values [14 pCi/cm^2 (0.52 Bq/cm^2) in the 40º to 50º North Latitude] and the lowest values [1 pCi/cm^2 (0.04 Bqcm^2) in the 70º to 80º South Latitude]. The specific sites reviewed in this study all are in the 40º to 50º North Latitudinal region. Cesium deposition in latitudinal regions to the north and south of this region differ by less than 30%.

However, the range of surface deposition rates is not a true representation of actual variation in cesium concentrations in the soil. Several factors influence the actual range or variation. Transport of the cesium in the soil, once it is deposited, is affected by many site specific factors including soil type, rainfall, drainage, terrain, vegetation and local activities and conditions. Furthermore, local meteorological conditions can have significant impact on the fallout deposition and transport in a given area. Finally, sampling protocol significantly effects the reported soil concentrations. Since the early years of the environmental sampling programs, researchers, recognizing the effects of environmental factors such as those noted above, specifically designed their sampling programs to minimize the impact of these compounding factors on deposition estimates. They were interested in average values and not variations that might occur in single samples.

2.2 – Sampling for Fallout Deposition

Beginning as early as 1945 the United States, the former Union of Soviet Socialists Republic and other nuclear powers have conducted numerous atmospheric nuclear weapons test. These tests have caused fission products to become airborne. These airborne radionuclides eventually decay or settle to earth (fallout). From the early 1950's to the present, organizations including the Department of Energy's Environmental Measurements Laboratory (formerly the Atomic Energy Commission's Health and Safety Laboratory) (Meyer et al. 1968), the Public Health Service (Federal Radiation Council 1963, 1964) and the Environmental Protection Agency (1977) have implemented relatively comprehensive programs in the United States and throughout the world to trace and measure fallout resulting from atmospheric detonation of nuclear weapons. In some cases, these programs have involved collections of data on radionuclides in the air and precipitation at long term monitoring stations and supplemental environmental sampling to establish impacts on hiota and domestic livestock and dairy products. In other instances, fairly detailed localized data collection efforts were conducted over short periods to identify or assess local impacts or characterize regional or local parameters such as uptake factors or environmental fate of selected radionuclides (e.g., Beck et al.1980).

Most of these evaluations are reported in the open literature and compilations of the data are provided by organizations including the National Council on Radiation Protection and Measurements (NCRP), (1987A, 1987B, 1975) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), (UNSCEAR 1977, 1982, 1989). These reports give average data on radionuclides and sometimes provide regional ranges or averages for specific radionuclides.

Sampling and data collection efforts to support the studies cited above were specifically designed to obtain a reasonable estimate of regional fallout levels (Environmental Measurement Laboratory 1990, Ragaini 1976, Beck 1966, Hardy 1968, Klement 1965). No attempt was made to characterize local variations due to human development and environmental transport and fate characteristics. Researchers at the time were aware that drainage and pooling of rainfall, varied soil conditions and selected construction features in areas could result in significant local variation in residual concentrations in the soil. Hence, every attempt was made to avoid these areas. The goals of the projects were to provide an estimate of worldwide and regional deposition of fallout. Classical criteria used for sample collection to estimate radionuclides in soil due to fallout (Environmental Measurement Laboratory 1990) were:

1) Location should have been undisturbed for at least the time interval of interest.

2) Location should be in a center of a largo open flat area and away from buildings, trees, or slopes.

3) Location should be such that deposited material is likely to remain in place (vegetated and moderate to good permeability).

In most cases, to minimize variations in the data, samples analyzed were a composite of multiple samples collected in the area of interest. These practices are common even when researchers are attempting to determine local concentrations of fallout. Background sampling for many Department of Energy environmental surveillance programs use composite sampling to ensure uniform, consistent and representative results and to minimize sampling cost and time. Carlton et al. (1992) indicated that soil sampling around the Department of Energy's Savannah River site was done by compositing 10 soil plugs (8 cm by 8 cm each) and analyzing a 500 g aliquot of the composite soil. Researchers attempting to characterize ^{137}Cs in soils of regions in Chile similarly composited nine 10 cm deep cores for each sample (Schuller et al. 1993). The goal was to obtain a homogeneous sample that represents average soil concentrations of cesium and minimizes the effect of the compounding factors discussed above.

2.3 – Soil concentration Estimates, Measurements and Variability:

Soil concentrations of cesium, as noted above, are effected by site specific factors and also by local variations in fallout concentrations that are not apparent in the generalized compilations of fallout data. It is well known that ^{137}Cs from fallout is not uniformly distributed (Carlton 1992). Such unpredictability of cesium has been known at least since the early 1960's (Bruner 1963).

To estimate average soil concentrations, it is necessary to estimate the depth to which the cesium has migrated through the soil column. Several researchers reported that most of the cesium concentrates in the top few centimeters of soil and nearly all is bound to the top 30 cm. Integrated accumulations in cesium in soils in the top 30 cm of undisturbed soil in the Hudson River watershed area was estimated to be nearly equivalent to quantities of deposited fallout (Eisenbud 1987). Such findings are consistent with those of Hardy (UNSCEAR 1977), who measured ^{137}Cs concentrations in Massachusetts soils. He estimated that in

sandy loans, 84% of the ^{137}Cs was distributed in the top 4 cm of soil and 97% was contained in the top 30 cm.

Models have been used to estimate the distribution of cesium in the soil column (Beck 1966, Rogowski and Tamara 1970). Both of the reference models assume an exponential relationship between radionuclide concentration and depth and derived characteristic coefficients of distribution for the soil type and specific time period. Distribution coefficients and hence, vertical movement of the cesium through the soil columns vary significantly with soil type and time. Velasco et al. (1993) modeled the distribution of cesium in northeastern Italy following the Chernobyl accident. While similar to previous models, the model they employed assumed to distribution coefficients were a function of time. Konshin (1992a, 1992b) modeled migration through soil of ^{137}Cs from Chernobyl and found that migration parameters increase as radionuclides penetrate the soil column and decrease with time. His data suggested a nonlinear lognormal relationship with depth. While the Konshin and Velasco studies suggest for more complex processes are involved in the migration of cesium through the soil column than diffusion with linear sorption, these studies, like the others, do not suggest significant vertical movement beyond the top 15 cm. Qualitative comparison of all these studies suggest that migration of cesium through the soil column is relatively slow and that most of the cesium from fallout would be in the top 5 to 10 cm (assuming the soil is undisturbed by human activity).

On the basis of these data and models, the deposition estimates in Table 2.1 were computed as soil concentrations, assuming that the cesium was uniformly distributed in the top 5 cm of soil (to estimate a high average ^{137}Cs concentration) and in the top 30 cm of soil (to estimate the low concentration). These concentrations provide a reasonable estimate of the range of regional concentrations that might be encountered in soil samples given undisturbed conditions and open terrain. Within the region of interest for this study, (40º to 50º North Latitudes) and given normal soil variability, soil concentration would be expected to range from about 1 pCi/g to less than 0.2 pCi/g. These estimates assume an average soil density of 1.6 g/cm3 which is reasonable for U.S. soils. However, soil density can vary significantly in local areas and may commonly range from about 1 to more than 2 g/cm3. Such variations can cause concentrations to vary several fold more. For instance, varying the soil density over this range changes the estimated range of ^{137}Cs concentrations in the soils to 2 pCi/g to 0.1 pCi/g. However, as noted above cesium migrates slowly and is not evenly distributed by depth. Using Hardy's measurements, one would predict 0.8 pCi/g [30 Bq/kg] in the first .5 cm of surface soil and about 0.1 pCi/g [3.7 Bq/kg] in soil at the 5 to 30 cm depth.

U.S. Department of Energy (DOE) facilities implement environmental surveillance programs and report results annually. As part of this activity, "background" soil samples are collected from areas that are known not to be affected by annual releases from the facilities. The sampling locations are beyond the perimeter of the facilities, typically 50 to 100 miles (80 to 200 km) away. Table 2.2 provides ranges reported in these studies. These data are in general agreement with values predicted by deposition

estimates (Table 2.1). As previously noted, most sampling protocols used are similar to those established by the Environmental Measurements Laboratory and hence the ranges measured only reflect that for open areas not that which would be found in a residential community.

Table 2.2
Measured Cesium-137 Soil Concentrations

Area (Reference)	^{137}Cs pCi/g Range due to fallout	Degrees N. Latitude
Georgia/South Carolina (Arnett et al. 1992, Cummins et al. 1991)	<0.001 to 0.8	30 to 35
Northern, NM (Purtyman et al. 1987)	0 to 1.4	35 to 40
Eastern Washington (Price 1988)	0.1 to 0.7	45 to 50
Santa Monica Mountains, CA (McLaren/Hart 1993)	<0.03 to 0.6	30 to 40

3.0 - ANALYSES AND RESULTS:

3.1 – Data Sets:

To investigate the variation in ^{137}Cs concentrations in residential environments, three data sets were reviewed; one from central New York (Colonie/Albany area), one from Beverly, Massachusetts and one from Northeastern Pennsylvania (Luzerne County). The data from New York and Massachusetts were compiled from unpublished radiological survey data collected by Oak Ridge National laboratory (ORNL) as part of two Department of energy sponsored surveys. The Pennsylvania data resulted from samples collected and analyzed as part of this study.

3.1.1 – New York Data:

The New York data was collected from surveys of about 217 properties (ORNL 1984-1987, reports on properties AL001 through AL217) conducted in the vicinity of a former uranium processing facility. The primary purpose of the ORNL surveys was to characterize uranium concentrations on these properties. Several thousand samples were collected and analyzed for uranium. The referenced survey reports provide the location and description of samples and the analytical results for 238U and 226Ra. The facility in question processed primarily natural and depleted uranium for military and other industrial uses. However, in a number of instances unirradiated low enriched fuel was also processed. The facility operated from 1961 to the early 1980's. While complete gamma spectrometry analyses were completed for many of the samples, no ^{137}Cs date were reported in the survey reports because there was no evidence of cesium use at the subject facility. Surface soil samples were typically taken over the first 5 cm of soil and subsurface over the next 10 cm of soil (5 to 15cm). A few deep samples (greater than 15 cm in depth) were taken typically in 15 cm increments (15 to 30 cm).

The analytical logbooks from these surveys were reviewed in detail. Of the several thousand samples collected and analyzed, gamma spectrometry data for 463 samples were found to contain data on ^{137}Cs measurements. These samples were taken from over 300 different sampling locations. The gamma spectrometry analyses for multiple radionuclides including cesium analyses were conducted for samples selected on a random/systematic basis (note: not statistically random); and for typically one or two samples per property. In many cases, it appeared, the first sample taken or logged for a given property was selected for the subject analyses. Surface (0 to 5 cm) or subsurface (5 to 15 cm) samples were, in many cases, alternately chosen and cesium analysis was rarely completed on both surface and subsurface samples from the same location. For a number of properties, a significantly number of samples were analyzed. In these cases, one sample was analyzed for every two or three samples listed in the log book. As before, it was rare for a surface and subsurface sample from the same location to be selected for the gamma spectrum analyses.

The New York data set contained the most samples of three sets analyzed. There were sufficient data to compare average cesium concentrations for suspect areas [areas believed to be drainage areas (driplines or drain spout locations) to open areas (lawns, parking areas and fields)]. However, there were also limitations to the data's value for certain comparative analyses. For example, because surface and subsurface samples from the same location were rarely analyzed for cesium, direct comparisons of surface to subsurface summary statistics to assess vertical migration was of limited value.

Sampling locations for this survey project were selected in a systematic manner to characterize uranium concentrations over the individual property. During the survey "biased" samples were also taken at locations having elevated external gamma levels. For the purposes of this research project, identification of suspect drainage and nondrainage (open areas) was made on the bases of the figures showing locations contained in the radiological survey reports. Because the radiological investigations were conducted in the mid 1980's, historical knowledge on specific properties surveyed was limited. Discussions with personnel and team leaders provided general confidence that the criteria used for selecting these areas (classifying data into drainage and nondrainage areas) were correct. In addition, it was not possible to determine, with absolute confidence, whether or not the buildings were in existence and remained unchanged from the period when atmospheric fallout was greatest (1950's to early 1960's) to the present. However, the community surveyed is generally composed of buildings and structures that were built in or predate the 1950's.

3.1.2 – Massachusetts Data:

Theses [sic] data are from a more recent ORNL data set. The data were from surveys of 26 properties in the vicinity of a former uranium slug production and uranium scrap recovery facility that operated from 1942 to about 1954. The facility handled primarily natural uranium metal and there was no history involving cesium. As with the New York surveys, the Massachusetts surveys were conducted to characterize residual uranium levels in the soil as a result of the operations at the former uranium

processing facility. The surveys were completed in the 1989 to 1991 time frame and published in 1992. The 26 published survey reports (ORNL 1991-1992) describe the sampling locations and properties and report measured concentrations for ^{238}U, ^{232}M, and ^{226}Ra. Because there was no history of ^{137}Cs use at the subject processing facility cesium concentrations were not reported in the published ORNL survey reports. However, gamma spectrum analyses were conducted for essentially all samples collected and ^{137}Cs concentration were found for 313 samples of which about 249 samples were useful for comparisons in this study. (Sample results were not used if a drainage or nondrainage areas classification could not be assigned and one property was almost entirely in a tidal area.) These samples were from approximately 130 sampling locations. Surface samples were taken from the first 15 cm of soil (0 to 15 cm) and subsurface samples from the next 15 cm increment (15 to 30 cm). A few deep samples were also taken in 15 cm increments (e.g., 30 to 45 cm); however, less than a 15 cm increment was taken in those areas where bedrock was encountered.

The Massachusetts data set contained many more multiple depth samples for the same sampling location than the other data sets. The sampling locations were selected systematically (points within a grid on the specific property. Biased samples were taken at selected locations where external gamma levels were elevated. Identification of drainage and nondrainage areas was made using figures and information provided in ORNL survey reports and on the basis of survey personnel's knowledge of the properties. Because the surveys were performed within three years of this investigation, interviews with survey personnel were able to confirm the location of drainage areas (driplines, drain spouts and areas of standing water) and hence, provide more confidence that the data set classification was correct. As a result of experience gained from the New York surveys that showed uranium concentrations tended to be higher in drainage areas, the ORNL survey teams in Massachusetts were conscious of the need to sample these areas. There was no specific confirmation on the age of the houses or any post-1960's modifications to the structures that might change the sample area classifications; however, the area is an old community and there is reasonable confidence that construction for most of the area surveyed was pre-1950's.

3.1.3 – Pennsylvania:

The Pennsylvania data were collected as part of this research effort. A total of 53 samples were collected at approximately 40 sampling locations on 10 properties. Samples were collected where the history of the construction and associated drainage location were known with reasonable confidence. Drainage area samples and background samples (nondrainage areas) were collected from 9 properties known to have been constructed prior to 1950. The structure on one of the ten properties was constructed in the mid-1960's. Samples in the dripline at this property were used for confirmation that the concentration phenomena resulted primarily over the period prior to 1963.

Care was also taken to differentiate areas where considerable soil mixing occurred. These areas were identified as "disturbed" and include flower gardens on the residential properties and an area used for bus parking in a school yard.

Surface samples were taken at two depths, 0 to 5 cm and 0 to 10 cm. Subsurface samples were taken at 5 cm increments below the surface samples.

3.2 – RESULTS:

Each data set was separated into data segments or subsets and analyzed on the basis of drainage condition and depth of sample. Measures of central tendency and variance were calculated. Summary statistics are presented and discussed in this section.

The arithmetic mean, variance and standard deviation were calculated for each data set and subset and are presented in Tables 3.1 through 3.3. These statistics are presented for purposes of comparison only because the mean and standard deviation are almost always presented in other references. They assume that the data are normally distributed. In most cases, experience has shown that environmental data are more likely to be approximated buy the lognormal distribution (DOE 1991). Graphical and statistical[3] tests verified that the data in this study are best summarized by lognormal rather than distributions. Therefore, for the purposes of analyzing and describing the data, the geometric mean, the geometric standard deviation and the range of concentrations (in pCi/g) for the central 95% of the data are presented for each data set and subset in the tables.

3.2.1 – New York:

The New York data were divided into suspected drainage areas and non-drainage areas and then further subdivided by depth of the sample. While both the arithmetic and geometric mean are presented in Table 3.1, data comparisons are discussed using the geometric mean as it is the measure of central tendency for the lognormal distribution.

Measured minimum concentrations in samples from all depths for both the drainage and non drainage [sic] areas were less than the detectable limit (less than 0.01 pCi/g ^{137}Cs in soil [0.4 Bq/kg]). However, the maximum measured concentration in the drainage area samples was approximately 3 times greater than the nondrainage areas (12 pCi/g [440 Bq/kg] for drainage areas versus 4.4 pCi/g [160 Bq/kg] in non-drainage areas). The geometric means were 0.94 pCi/g and 0.39 pCi/g [35 and 14 Bq/kg] for the drainage and non-drainage areas respectively. A statistical analysis of the data predicts a much wider spread in the concentrations in drainage areas than non-drainage areas. The analysis predicts that 95% of the distributions of concentrations in the drainage areas will be between 0.05 pCi/g [1.9 Bq/kg] and 17 pCi/g [630 Bq/kg].

[3] For the graphical test, the numerical concentration value of the data were transformed into its natural logarithm (y=ln(x), where x is the concentration) and were plotted on probability graph paper. If the transformed data set or subset approximated a straight line, the data could be assumed to be lognormally distributed (DOE 1991). Each data set or subset were [sic] also tested using the Sahpiro and Wilk "W Test" or D'agonstino's Test (Y statistic). The W Test was used when the data set or subset being analyzed contained less than 50 data points (Gilbert 1987) and the Y statistic was used for those sets having more than 50 data points (Gilbert 1987).

Table 3.1 – Colonie, NY – Summary Cesium-137 in Soil Data and Statistics
Units pCi/g

Condition [1] & Depth (cm)	Number of Samples	Measured Range (pCi/g)	Arithmetic Mean (pCi/g) ± (1 Sigma)	Geometric Mean (pCi/g)	Range (pCi/g) for 95% of Distribution
Drainage Areas					
All Samples	109	<0.01 – 12	2.1 ± 2.1	0.94	0.05 - 17
0-5 cm	83	<0.04 – 11	2.1 ± 2.4	1.1	0.09 – 13
5-15 cm	12	0.4 - 12[2]	2.8 ± 3.3	1.7	0.23 - 12
>15 cm	10	<0.010-00.8[3]	<0.15 ± 0.24	0.07	0.01 – 0.75
Non-Drainage Areas					
All Samples	347	<0.01 – 4.4	0.66 ± 0.70	0.39	0.05 – 3.3
0-5 cm	277	<0.01 – 4.4	0.74 ± 0.75	0.47	0.07 – 3.4
5-15 cm	58	<0.01 – 2.1	0.41 ± 0.24	0.25	0.04 – 1.9
>15 cm	17	<0.02 – 0.7[3]	<0.2 ± 0.21	0.12	0.01 – 1.0

Units Bq/kg

Condition [1] & Depth (cm)	Number of Samples	Measured Range (Bq/kg)	Arithmetic Mean (Bq/kg)	Geometric Mean (Bq/kg)	Range (Bq/kg)for 95% of Distribution
Drainage Areas					
All Samples	109	<0.4 – 440	78	35	1.9 – 630
0-5 cm	83	<1.5 – 418	78	44	3.3 - 480
5-15 cm	12	<15 - 440[2]	100	63	8.5 - 440
>15 cm	10	<0.04 - 30[3]	<5.6	2.6	0.4 - 28
Non-Drainage Areas					
All Samples	347	<0.4 - 160	24	14	1.9 – 120
0-5 cm	277	<0.4 – 160	27	17	2.6 - 130
5-15 cm	58	<0.4 – 78	15	9.6	1.5 - 70
>15 cm	17	<0.7 - 26[3]	<7.4	4.4	0.4 - 37

1 - Conditions include drainage areas (locations that collect water) and nondrainage areas (open areas such as lawns and fields.
2 - Subsurface samples where [sic] taken from high concentration area, and, hence, are biased high in comparison to surface samples.
3 - About 40% of the samples contained cesium-137 at levels below detectable limits.

Table 3.2 – Beverly MA – Cesium 137 in Soil Summary Data and Statistics

Units pCi/g

Condition [1] & Depth (cm)	Number of Samples	Measured Range (pCi/g)	Arithmetic Mean (pCi/g) ± (1 sigma)	Geometric Mean (pCi/g)	Range (pCi/g) for 95% of Distribution
Drainage Areas					
All Samples	32	0.02 – 11	1.5 ± 2.4	0.53	0.02 - 11
0-15 cm	19	0.02 – 11	1.7 ± 2.7	0.63	0.04 - 11
15-30 cm	12	0.02 – 4.6	1.1 ± 1.6	0.34	0.01 – 9.0
Non-Drainage Areas					
All Samples	195	<0.01 – 2.8	0.32 ± 0.38	0.19	0.02 – 1.6
0-5 cm	104	0.04 – 2.8	0.43 ± 0.41	0.31	0.06 – 1.6
15-30 cm	84	<0.01 – 2.5	0.19 ± 0.31	0.11	0.04 – 0.317
>30 cm	7	0.07 – 0.32	0.12 ± 0.09	0.11	0.04 – 0.31
"Wet" Areas (Tidal/Beach)	21	0.01 – 0.12	0.04 ± 0.04	0.04	0.01 – 0.16

Units Bq/kg

Condition [1] & Depth (cm)	Number of Samples	Measured Range (Bq/kg)	Arithmetic Mean (Bq/kg)	Geometric Mean (Bq/kg)	Range (Bq/kg)for 95% of Distribution
Drainage Areas					
All Samples	32	0.7 – 410	56	20	0.7 - 410
0-15 cm	19	0.7 – 410	63	23	0.7 - 410
15 – 30 cm	12	0.7 – 170	44	13	0.04 - 330
Non-Drainage Areas					
All Samples	195	<0.04 – 100	12	7	0.7 - 59
0-15 cm	14	1.5 – 100	16	11	2.2 – 59
15 - 30 cm	84	<0.4 – 93	7	4.1	0.4 - 31
>30 cm	7	2.6 – 12	4.4	4.1	1.5 - 11
"Wet" Areas (Tidal/Beach)	21	0.4 – 4.4	1.5	1.5	0.4 – 5.9

1 - Conditions include drainage areas (areas that collect water) and nondrainage areas (open areas such as lawns and fields). Wet areas are those that are frequently under water (tidal and beach front areas).

Table 3.3(a) – Luzerne County, PA – Cesium-137 in Soil Summary Data and Statistics
Units pCi/g

Condition [1] & Depth (cm)	Number of Samples	Measured Range (pCi/g)	Arithmetic Mean (pCi/g) ± (1 sigma)	Geometric Mean (pCi/g)	Range (pCi/g) for 95% of Distribution
Drainage Areas					
All Samples	33	0.16 – 7.5	2.5 ± 2.0	1.8	0.33 - 10
Subsurface Samples	22	0.16 – 7.5	2.7 ± 2.1	2	0.33 – 12
0-5 cm	12	0.16 – 7.5	3.1 ± 2.6	2	0321 – 19
0-10 cm	10	0.8 – 4.7	2.2 ± 1.2	1.9	0.7 – 5.3
Subsurface	8	0.32 – 7.2	2.6 ± 2.2	1.8	0.3 – 12
5-15 cm	4	0.68 – 7.2	3.0 ± 3.3	2.1	0.21 – 20
10-15 cm	3	0.32 – 2.3	1.6 ± 1.1	1.2	0.13 - 11
Non-Drainage Areas					
All Samples	21	0.08 – 1.5	0.62 ± 0.4	0.47	0.1 – 2.4
Subsurface Samples	18	0.19 – 1.5	0.67± 0.39	0.56	0.16 – 2
0-5 cm	10	0.13 – 1.5	0.73 ± 1.4	0.56	0.11 – 2.8
0-10 cm	8	0.39 – 1.00	0.59 ± 0.48	0.55	0.28 – 1.1
Subsurface >5 cm	3	0.08 – 0.77	0.32 ± 0.77	0.18	0.02 – 2.1

Units Bq/kg

Condition 1 & Depth (cm)	Number of Samples	Measured Range (Bq/kg)	Arithmetic Mean (Bq/kg)	Geometric Mean (Bq/kg)	Range (Bq/kg)for 95% of Distribution
Drainage Areas					
All Samples	33	5.9 - 280	74	67	12 – 370
Surface Samples	22	5.9 – 280	74	74	12 – 440
0-5 cm	12	5.9 – 280	110	74	78 – 700
0-10 cm	10	3 – 170	81	70	26 - 200
Subsurface	8	12 – 270	96	67	11 – 440
5-15 cm	4	25 – 270	110	78	7.8 – 710
10-15 cm	3	12 – 85	59	44	4.8 - 410
Non-Drainage Areas					
All Samples	21	3 – 56	23	17	4 – 89
Surface Samples	18	7 – 56	25	21	5.9 – 74
0-5 cm	10	4.8 – 56	27	21	4.1 – 100
0-10 cm	8	14 – 37	21	20	10 – 41
Subsurface > 5 cm	3	3 – 28	12	6.7	0.7 - 78

1 - Conditions include Drainage areas (areas that collect rain water) and nondrainage areas (open areas such as lawns and fields). Some areas were also classified as disturbed and undisturbed (See Table 3.3 (b)).

Table 3.3(b) – Luzerne County, PA – Cesium-137 in Soil Summary Data and Statistics
Disturbed Versus Undisturbed Soil
Units pCi/g

Condition [1] & Depth (cm)	Number of Samples	Measured Range (pCi/g)	Arithmetic Mean (pCi/g) ± (1 sigma)	Geometric Mean (pCi/g)	Range (pCi/g) for 95% of Distribution
Drainage Areas					
Surface 0-5 cm					
Undisturbed	9	0.7 – 7.5	± 2.9	3.1	0.58 - 17
Disturbed	3	0.16 – 0.99	0.65 ± 0.14	0.5	0.1 - 3.6
Surface 0-10 cm					
Undisturbed	6	– 4.7	2.4 ± 1.4	2.1	0.75 – 6.1
Disturbed	4	– 2.8	3.9 ± 0.81	1.7	0.59 – 4.8
Non-Drainage Areas					
Surface 0-5 cm					
Undisturbed	4	0.58 – 1.4	0.9 ± 0.37	0.85	0.39 – 1.8
Disturbed	6	0.13 – 1.5	0.62 ± 0.56	0.43	0.07 – 2.8
Surface 0-10 cm					
Undisturbed	6	0.39 – 1.1	0.61 ± 0.26	0.57	0.26 – 1.3
Disturbed	2	0.45 – 0.57	0.51 ± 0.08	0.51	0.39 – 0.7

Units Bq/kg

Condition [1] & Depth (cm)	Number of Samples	Measured Range (Bq/kg)	Arithmetic Mean (Bq/kg)	Geometric Mean (Bq/kg)	Range (Bq/kg)for 95% of Distribution
Drainage Areas					
Surface 0-5 cm					
Undisturbed	9	26 – 280	150	110	21 – 630
Disturbed	3	5.9 – 37	24	19	3.7 – 130
Surface 0-10 cm					
Undisturbed	6	44 – 170	89	78	28 – 230
Disturbed	4	29 - 100	70	63	22 - 180
Non-Drainage Areas					
Surface 0-5 cm					
Undisturbed	4	21 – 52	33	31	14 - 68
Disturbed	6	4.8 – 56	23	16	2.6 - 100
Surface 0-10 cm					
Undisturbed	6	14 – 41	23	21	9.6 – 48
Disturbed	2	17 - 21	19	19	13 - 26

1 - Conditions include drainage and nondrainage areas and disturbed (normally flower beds or areas where there was evidence of fill material) and undisturbed areas (those with no evidence that the soil was excavated or filled).

and in the non-drainage areas between 0.05 pCi/g (1.9 Bq/kg) and 3.3 pCi/g (120 Bq/kg). This implies that one may reasonably expect background concentration of cesium to vary by nearly 3 orders of magnitude in a drainage area and just less than 2 orders of magnitude in non-drainage areas (open areas and lawns in residential communities). Overall concentrations of ^{137}Cs in residential areas would be expected to vary over three orders of magnitude from 0.01 pCi/g to concentrations of nearly 20 pCi/g.

Analysis of the data sets divided by depth provided similar results for the surface samples (0 to 5 cm) and the 5 to 10 cm subsurface samples suggested similar ranges. However, it is noted that subsurface and surface samples concentrations which form the basis of the summary statistics in the table were measured, for the most part, at different locations. Hence, the data are not used for direct representation of the relationships between ^{137}Cs concentration at the surface and in the subsurface. In general, however, the data may be useful to establish a range of expected values especially in those cases were a large number of samples were taken randomly.

In the drainage areas, the predicted surface sample distribution (95% of the distribution) ranged for 0.09 pci/g (3 Bq/kg) to 13 pci/g (480 Bq/kg) with a geometric mean of 1.1 pci/g (41 Bq/kg). In the non-drainage areas, the distribution ranged from 0.07 pci/g (3 Bq/kg) to 3.4 pci/g (130 Bq/kg) and the geometric mean was 0.47 pci/g (17 Bq/kg). As would be expected, the mean is slightly higher in the surface only data than for the data set for the combined surface and subsurface samples because the subsurface samples (particularly those greater than 15 cm) contain significantly lower concentrations of ^{137}Cs.

In the non-drainage areas, as expected, the 5 to 15 cm subsurface sample distribution was predicted to be lower than the surface or total data set. (0.01 pCi/g [1.5 Bq/kg] to 1.9 pCi/g [70 Bq/kg]) and the geometric mean was about half (0.26 pCi/g [9.6 Bq/kg]) that of the surface samples. However, in the drainage area samples, the minimum values in the range was predicted to be higher than in either other drainage area data sets which in turn caused the mean (1.7 pCi/g [63 Bq/kg]) to be higher also. This is believed to be the result of a skew in the data caused by the small number of samples (12) and because most of the 5 to 15 cm subsurface samples were selected from high concentration locations. This position is supported by the analysis of matched data sets by depth.

Table 3.4 compares concentration ratios for those samples that had both surface and subsurface samples for all three databases investigated. Sampling locations that had surface to subsurface ratios of less than 0.8 were not used to develop the summary statistics presented in Table 3.4. These ratios were censored because they were indicative of disturbed soil conditions (e.g., clean fill or excavation). Other samples may also have been disturbed; however, if the ratio was greater than 0.8, it was felt that the concentration ratio alone was an insufficient basis for censoring the data.

Table 3.4 – Variation of Cesium – 137 Concentrations with Depth
Ratio of Surface to Subsurface Concentrations for Matched Sample Pairs

Location and Condition	Ratios for Depths (cm)[3]	Number of Locations	Range of Ratios (pCi/g:pCi/g)	Geometric Mean Ratio	Range for 95% of the Distribution
NY – Drainage					
Surf: Subsurf	2.5 to 10	4	– 12	2.4	0.5 – 12
Surf:Deep	2.5 22.5	5	3 – 135	27	2.7 - 270
Nondrainage					
Surf: Subsurf	2.5 to 10	8	1 – 270	4.8	0.2 – 120
Surf:Deep	2.5 to 22.5	11	1.5 – 120	9.2	0.9 - 91
MA – Drainage Surf:Subsurf	7.5 to 22.5	11	0.9 – 7.5	1.9	0.7 - 8
Nondrainage					
Surf: Subsurf	7.5 to 22.5	85	0.08 – 25	3.1	0.9 – 11
Surf:Deep	7.5 to 3.75	5	2.5 – 5.1	3.9	2 – 7.7
PA – Undisturbed					
Surf:Subsurf	2.5 to 7.5	7	– 12	1.9	0.5 – 8.2
Drainage					
Surf:SubSurf	2.5 to 7.5	6	– 2.8	1.4	0.5 – 4
Surf:Deep	2.5 to 12.5	2	– 7.4	4.7	1.7 – 13.4
Nondrainage	2.5 to 7.5	3	0.8 - 12	2.5	0.5 – 13

(1) Ratios are stated from the center of each sampling depth (e.g., the ratio 2.5 to 10 indicates comparison of concentrations from surface samples in the 0 to 5 cm depth to subsurface samples from 5 to 15 cm deep).

(2) Sampling locations with “matched data” were used – Samples taken at different depths from the same location.

(3) There were too few samples to separate drainage (areas where rain water collects or concentrates such as driplines) and nondrainage areas (open areas such as lawns or fields) for the “disturbed” soil set.

The ratios for the 0 to 5 cm surface sample concentrations to the 5 to 15 subsurface sample concentrations from the New York locations ranged from about 13 to 12 in from 4 sampling locations. The geometric mean ratio was 2.4. Comparison of New York sampling locations for the sample depths in the non-drainage areas indicated a higher ratio (4.8 surface to subsurface); however, the range of ratios for the 8 sampling locations investigated extended from 1 to 270. For two of the locations one measurement was less than detectable. One location was censored from the data set because both the surface and subsurface concentration were below the detectable limit for the analytical technique used.

In both major subsets of New York data (drainage and non-drainage areas, Table 3.1) the analysis of the deep samples (greater than 15 cm) indicated a significant difference in cesium concentrations in comparison to the surface samples. The measured maximum concentration was 0.8 pCi ^{137}Cs [30 Bq/kg] and the geometric means were 0.07 pCi/g [2.6 Bq/kg] and 0.12 pCi/g [4.4 Bq/kg] for the drainage and non-drainage area samples. Assuming the data distribution is lognormal, it is estimated that more than 955 of the distribution will be less than 1 pCi/g [40 Bq/kg]. This suggests that most of the cesium is held in the top 15 cm of the soil.

Five New York sampling locations in drainage areas and 11 sampling locations in don-drainage areas had both surface and deep subsurface (15 to 30 cm) concentration measurements. In the drainage areas, comparison of these samples, Table 3.4, produced surface to deep surface ratios from 3 to greater than 135. The geometric mean for the drainage area ratios was about 27. The ratios for the nondrainage samples ranged from about 1.5 to 120. The geometric mean for these ratios was about 9.2. However, for 5 of these 11 sample pairs, the subsurface concentration was below the detectable limit and the detectable limit was used as the basis for the ratio. Similarly, 2 of the five drainage area samples had deep surface samples that were below the detectable limit. This may have skewed the ratios toward the low end of the distribution. As a result, the most that can be concluded from the comparisons of the ratios of 0 to 5 cm surface samples to deep. 15 to 30 cm, subsurface samples is that the mean ratios for the drainage and non-drainage areas are greater than 27 and 9 respectively.

Analysis of the surface to 5 to 15 cm ratios and the surface to 15 to 30 cm ratios suggest that more than 90% of the ^{137}Cs is distributed in the upper 15 cm of the area soils and more than 80%.

3.2.2 – Massachusetts:

As with the New York data, the comparison of ^{137}Cs concentrations from all Massachusetts samples in the drainage and non-drainage areas suggested that the mean of the distributions are greater for the drainage area samples and the potential range of concentrations that may be encountered is significantly greater, see Table 3.2. the geometric mean for the drainage area data set was 0.53 pCi/g [20 Bq/kg] compared to the 0.19 pCi/g [7.0 Bq/kg] mean from the non-drainage area data set (dry area samples only, see discussion below). Measured concentrations of ^{137}Cs in the drainage area samples ranged from 0.02 to 11 pCi/g [0.7 Bq/kg to 410 Bq/kg] and the non-drainage area samples ranged from 0.01 to 2.8 pCi/g [0.4 Bq/kg to 100 Bq/kg]. Assuming a lognormal distribution of the data results in estimates that 95% of the distribution of

samples taken from drainage areas will have concentrations of ^{137}Cs between 0.02 and 11 pCi/g [0.4 an d 410 Bq/kg] while 95% of the nondrainage area samples should be between 0.02 and 1.6 pCi/g [0.4 and 59 Bq/kg].

The data from the Massachusetts surveys included a third subset identified in Table 3.2 as being from "wet non-drainage areas". Like the other non-drainage area samples these were taken from areas that are relatively open (e.g., no obvious areas were water collects or drains to them). However, several of the properties surveyed were along a shoreline. Based on the data presented in the individual survey reports, it was determined that the samples locations were in areas that are periodically covered with water either during high tides or high water periods. As would be expected, ^{137}Cs concentrations in these samples are very low in comparison to all other locations. This may be the result of continuous erosion of surface materials containing cesium, cesium going into solution, continual mixing with other eroded material or possibly the fact that the cesium simply does not have an opportunity to settle and absorb to the soil or sediment. The geometric mean for this data set was 0.04 pCi/g [1 Bq/kg], which is about a factor of 4 lower than the dry non-drainage areas and a factor of 12 lower that the drainage areas. Actual measured concentrations ranged from 0.01 to 0.12 pci/g [0.4 to 4.4 Bq/kg]. It was estimated that 95% of the distribution would be between 0.01 and 0.16 pCi/g [0.4 and 5.9 Bq/kg], or two orders of magnitude smaller that the range for drainage samples.

Comparison of Massachusetts drainage area surface samples (0 to 15 cm) to subsurface samples (15 to 30 cm0 indicated a marked reduction in cesium concentrations in the subsurface samples. The geometric mean concentration in surface samples is about a factor of two larger than the subsurface samples (0.63 pCi/g [23 Bq/kg] versus 0.34 pCi/g [13 Bq/kg]). The estimated range for 95% of the distribution is similar but lower for the subsurface sample subset (0.04 to 11 pCi/g [0.1 to 410 Bq/kg] for the surface samples versus 0.01 to 9.0 pCi/g [0.4 to 330 Bq/kg] for the subsurface samples).

Similar results were produced in an analysis of the non-drainage area samples (dry locations only). The geometric means of the concentration in the surface samples (0 to 15 cm) differed from the subsurface (15 to 30 cm) concentrations by nearly a factor of three (0.31 pCi/g [11Bq/kg] versus 0.11 pCi/g [4.1 Bq/kg] respectively). The range of the measured concentrations was similar, 0.04 to 2.8 pCi/g [1 to 100Bq/kg] in surface samples compared to 0.01 to 2.5 pCi/g [0.4 to 93 Bq/kg] in the 15 to 30 cm subsurface samples. The statistical analysis of the data subsets produced estimates that 95% of the non-drainage area surface samples would be expected to range from 0.06 pCi/g to 1.6 pCi/g [2 to 59 Bq/kg], while 95% of the non-drainage area surface samples would be expected to range from 0.06 pCi/g to 1.6 pCi/g [2 to 59 Bq/kg], while 95% of the subsurface samples would be between 0.01 pCi/g [0.4 Bq/kg] and 0.85 pCi/g [31Bq/kg].

These data (Massachusetts) show more of a difference between surface and subsurface soil concentrations than the New York data set. This is believed to be due largely to the difference in depth for the surface and subsurface samples. The New York surface samples were for 0 to 5 cm and the subsurface samples were between 5 and 15 cm. The Massachusetts surface samples were taken at a depth of 0 to 15 cm and the

primary depth for the subsurface samples was 15 to 30 cm. Furthermore, the greater depth of the Massachusetts surface sample will tend to mask variability from surface mixing or other disturbances. However, the 0 to 5 cm surface samples taken in the New York study are much more sensitive to these effects. Considering these difference and factors there is good agreement between the two data sets. As noted in the discussion of the New York survey results, comparison of samples above 15 cm to those few below 15 cm indicated that most of the cesium is retained by the soil at the surface above 15 cm. The comparison of the 0 to 15 cm surface samples in the Massachusetts data set to the subsurface samples leads to a similar conclusion.

A small number of deep subsurface samples were taken from non-drainage areas in Massachusetts at depths greater than 30 cm. The range of concentrations is somewhat smaller in the deep subsurface samples as compared to the 15 to 30 cm samples (see Table 3.2). The measured maximum concentration and the calculated maximum concentration of 95% of the distribution, assuming a lognormal distribution, were both between a factor of 2 or 3 less in the deep samples. The geometric mean for both were essentially the same. This suggests that there is little migration of the cesium below the 15 cm depth. The geometric mean 0.11 pCi/g [4.1 Bq/kg] is similar to the means in the deep samples from the New York data which were 0.07 pCi/g [3 Bq/kg] and 0.12 pCi/g [4.4 Bq/kg] in the drainage and non-drainage sample sets respectively. "Wet non-drainage area" data sets showed no significant difference between surface and subsurface samples.

The surface and subsurface samples were more equal in number and sampling location in the Massachusetts data sets than in the New York data sets and therefore, provide a more representative comparison of differences between surface and subsurface conditions. However, subsurface and surface samples were not always matched, hence, a separate analysis was conduct using only matched surface and subsurface samples in order to provide estimates of vertical migration of cesium in the soil column.

Table 3.4 compares concentration ratios for those locations that had both surface (0 to 15 cm) and subsurface samples (15 to 30 cm) analyzed for ^{137}Cs. The ratios of the surface to subsurface samples in 11 drainage locations were computed and ranged from a low of less than 1 to a high of about 8. One sampling location was censored because the data indicated that no ^{137}Cs was present in the surface sample, suggesting recent fill had been added. The geometric mean ratio was 2.3. As in the New York data set, the geometric mean ration (for 0 – 15 cm to 15 – 30 cm samples) was higher for the matched non-drainage locations (3.1) than the for the drainage areas.

Five locations in the non-drainage areas had matched surface (0 -1 5 cm) and deep subsurface samples (30 to 45 cm or to bedrock). The ratios in these locations range from 2.5 to about 5 and the geometric mean ratio was 3.9.

Out of a total of 85 non-drainage locations ratios ranged from 0.8 to 25. Only two subsurface locations out of the 85 nondrainage locations were below detectable limits. These have minimal effect on the summary statistics. None of the drainage area samples were below detectable limits.

In the drainage areas, comparison of the cesium concentrations and ratios between 0 cm and 30 cm indicates that about 70% of the ^{137}Cs activity is in the upper 15 cm of the soil. Comparison of the ratios from the non-drainage areas suggested that over 60% of the ^{137}Cs is distributed in the top 15 cm of soil and 84% is in the top 30 cm of the soil. This data suggests that the ^{137}Cs is primarily bound to the upper 15 cm, however, less so than in the New York soils sampled.

3.2.3 – Pennsylvania:

The Pennsylvania data were subdivided into twenty-four different subsets on the basis of drainage and soil conditions. Table 3.3 presents summary statistics for these data. The Pennsylvania data were collected specifically for this analysis and, as a result, are accompanied by a greater degree of information pertaining to drainage conditions and soil conditions (disturbed or undisturbed). However, the data set is significantly smaller (especially for the non-drainage areas) and, hence, may not be appropriate for broad generalizations regarding very specific factors or large area averages. A primary drawback was the fact that sampling locations were selected in areas where cesium was likely to concentrate and only a few background samples (those representing open areas) were selected at each site. Calibration sources used were secondary sources (soil samples) analyzed at Oak Ridge National Laboratory. Cross sample analysis of 6 of the 53 soil samples at Georgetown and Oak Ridge National Laboratory produced results that were in excellent agreement. However, while, in some cases, data are stated to 2 significant digits to maintain calculation accuracy, results are only considered valid to only one significant digit given the system uncertainties.

Measured concentrations in known drainage areas ranged from 0.16 pCi/g [7 Bq/kg] to 7.5 pCi/g [280 Bq/kg] with a geometric mean of 1.8 pCi/g [67 Bq/kg]. The geometric mean for all drainage area surface samples (0 to 5 cm and 0 to 10 cm depths) from undisturbed soils was 2.7 pCi/g [100 Bq/kg]. Assuming a lognormal distribution, it was calculated that more than 95% of undisturbed drainage samples should be less than 11 pCi/g [410 Bq/kg]. These data were further divided into surface samples taken from 0 to 5 cm (shallow surface) and those from 0 to 10 cm (deep surface). The mean for the shallow surface undisturbed soil samples was 3.1 pCi/g [110 Bq/kg] and the estimated maximum for 95% of the samples in the distribution was estimated to be 17 pCi/g [630 Bq/kg]. This is markedly higher than the geometric mean (2.1 pCi/g [78 Bq/kg]) and the maximum for the distribution (6.0 pCi/g [220 Bq/kg]) derived from the deep surface samples. As would be expected, the surface concentrations for the disturbed soils was lower than for the samples from undisturbed soil. The difference was greater in the shallow surface samples (3.1 pCi/g [110 Bq/kg] undisturbed versus 0.5 pCi/g [19 Bq/kg] disturbed) than in the deep surface samples (2.1 pCi/g [78 Bq/kg] undisturbed versus 1.7 pCi/g [63 Bq/kg] disturbed). This is likely due to the fact that most of the disturbed areas were from residential flower gardening and physical investigations indicated that soil

mixing was generally limited to the top 10 to 15 cm of the soil. As a result, surface samples taken at 0 to 10 cm would still contain similar levels of cesium whether disturbed or undisturbed unless there was significant aerial mixing as well as vertical mixing.

Drainage area subsurface samples were taken at 5 to 10 cm and 10 to 15 cm depths. The 5 to 10 cm samples produced concentrations (geometric mean) similar to the deep surface samples. Concentrations from the 10 to 15 cm depth were 2 to 3 times lower than the undisturbed shallow surface sample concentrations.

The geometric mean for all non-drainage area samples was 0.5 pCi/g [19 Bq/kg]. It was calculated that 95% of the distribution for such samples would be between 0.1 pCi/g and 2.4 pCi/g [4 and 89 Bq/kg]. Samples were similarly taken at 0 to 5 cm and 0 to 10 cm. However, the differences in the geometric means and expected range of concentrations are, for the most part, less pronounced. They differ by only a few tenths of a pCi/g which is well within the uncertainty of these data. The undisturbed shallow surface (0-5cm) had the largest mean concentration (0.9 pCi/g [33 Bq/kg]). The disturbed shallow soil samples had a geometric mean of 0.4 pCi/g [15 Bq/kg], about half that calculated for the undisturbed sampling locations. All disturbed and undisturbed deep surface samples (0-10cm) from non-drainage areas had geometric means between 0.5 and 0.6 pCi/g [about 20 Bq/kg]. The geometric mean (0.2 pCi/g [7 Bq/kg]) and the range for the 3 subsurface samples were about one quarter that of the undisturbed shallow surface samples and about half that of the other surface samples.

In general, the mean concentration in the drainage area samples was from 2 to 4 times the concentrations measured in the non-drainage area samples. The estimated range of concentrations for the drainage area was also greater (ranging nearly 2 orders of magnitude) than the nondrainage areas which typically varied by slightly more than one order of magnitude.

Because the maximum sampling depth for the Pennsylvania data set was 15 cm, a limited amount of information regarding vertical distribution of ^{137}Cs in the soil column could be inferred from this data set alone. The ratios of ^{137}Cs concentrations over all 11 locations with matched surface (0 to 5 cm) samples and subsurface (5 to 10 cm) samples ranged from 0.7 to 12 with a geometric mean ratio of 1.5, indicating that about 60% of the ^{137}Cs in the top 10 cm was located in the top5 cm of the soil. Out of the 11 matched pairs of samples, 4 were from disturbed areas or were not true soil samples (e.g., decaying leaves). The 7 remaining matched sample pairs were from undisturbed areas and had ratios for the 0-5 cm: 5-10 cm depths in a range from 1 to 12. The geometric mean for the ratios in these locations was 1.9, indicating that about 60% of the ^{137}Cs surface activity is located in the top 5 cm of the soil column. Six of these pairs are from drainage areas and have a geometric mean ratio for the surface (0 to 5 cm) to subsurface (5 to 15 cm) of 1.4.

Two drainage area locations samples taken at depths from 10 to 15 cm. The ratio of surface sample (0 to 5 cm) concentration to subsurface samples from these two locations were 3 and 6. The geometric mean ratio

was 4.7. Analysis of the surface: subsurface: deep ratios suggest that nearly 90% of the ^{137}Cs is distributed in the top 10 cm of the soil column.

For drainage locations, it is distributed within the top 15 cm as:

Depth	Percentage Activity
0 to 5 cm	52%
5 to 10 cm	37%
10 to 15 cm	11%

If the data from the nondrainage and drainage locations are combined, the distribution is:

Depth	Percentage Activity
0 to 5 cm	58%
5 to 10 cm	30%
10 to 15 cm	12%

4.0 - Conclusions:

Based on analysis of deposition data, average concentrations of ^{137}Cs in the Northeastern United States should be between about 1 pCi/g [37 Bq/kg] and 0.1 pCi/g [3.7 Bq/kg] depending on the distribution over the soil column. This study indicated that mean soil concentrations in residential areas cover a larger range and that the variability in individual samples would be expected to extend over several orders of magnitude.

The mean surface concentrations for the three residential locations studied (New York, Massachusetts, and Pennsylvania) range from 4 pCi/g [150 Bq/kg] to 0.4 pCi/g [15Bq/kg]. However, analysis of the data indicated that the sample populations were better represented by the lognormal distribution than the normal distribution; the geometric mean is a more appropriate measure of central tendency. The geometric means for surface samples in the three locations ranged from 3.1 pCi/g [110 Bq/kg] to 0.3 pCi/g [11Bq/kg] depending on conditions.

As noted above, the range of individual measurements was much greater. Maximum measured concentrations were as high as 12 pci/g and statistical analyses predicted that the concentrations in the central 955 of the distributions could approach 20 pCi/g [700 Bq/kg] on the upper end of the distribution and about 0.02 pci/g [0.7 Bq/kg] at the lower bound.

The ^{137}Cs soil concentrations in local areas can be significantly higher than average concentrations predicted by fallout deposition data. Local concentrations can be several times higher than estimates based on fallout deposition and individual samples in an area can be expected to vary by as much as 4 orders of magnitude depending on the soil type, drainage conditions, and other factors.

In general, fallout deposition data can be used to predict total surface inventory in a large area but it does not provide a good measure of central tendency and variability for background ^{137}Cs concentrations for

remedial action or decontamination planning activities in residential, commercial or industrial areas. A reasonable estimate of such background variability can only be obtained by direct sampling and measurement of local data from a nearby area (with like soil and drainage conditions) that has not been effected by the operating facility.

For screening purposes, in residential/commercial areas in the Northeastern United States, the data indicates that geometric mean concentrations between 3 pCi/g [110 Bq/kg] and 0.2 pCi/g [7 Bq/kg] can normally be attributed to fallout. For concentrations of ^{137}Cs in individual samples or localize "hot spots", fallout cannot be off handedly discounted as the cause even up to about 20 pCi/g [700 Bq/kg]. Concentrations in this range should be evaluated statistically to determine if the geometric mean falls in the range of background concentrations. Comparisons should be made to background locations with similar conditions (e.g., drainage, soil, and so forth).

These results are based primarily on dripline and drain spout effects for primarily residential structures evaluated in this study. Concentrations may be conceivably exceed those computed here in cases were larger surfaces (e.g., industrial buildings or parking lots) drain to a single locations. Conversely, open areas would generally be expected to have lower mean (0.7 to 0.1 pCi/g [26 to 3.7 Bq/kg]) and peak concentrations (about 3 pCi/g [110 Bq/kg]) that are generally in the range predicted by world wide fallout estimates.

4.1 – Other Implications of the Data:

Rain Water Drainage Effects:

Analysis of the data indicated significant differences between drainage locations and nondrainage locations in residential areas. Areas such as driplines and drain spout outfalls from roofs, or low lying areas have higher concentrations of ^{137}Cs in the soil than open areas. As can be seen from Tables 3.1, 3.2, and 3.3, the geometric mean ^{137}Cs concentrations in drainage areas ranged from 2 to 10 times higher than nondrainage areas and peak concentrations were typically 6 or 7 times higher in the drainage areas.

The Massachusetts data set included a number of samples that were frequently under water (the shoreline of Beverly Harbor). These areas had concentrations that were more than an order of magnitude less than rain water drainage areas.

Distribution by Depth:

Analysis of data from all three regions analyzed, indicates that ^{137}Cs migrates slowly through the soil column. Most of the ^{137}Cs is concentrated in the top 10 to 15 cm of the soil column. Table 4.1 presents the percentage of ^{137}Cs by depth and the reduction in ^{137}Cs concentrations in soils as a function of depth in centimeters and normalized to surface concentrations for each of the three locations.

Table 4.1 - ^{137}Cs Concentration by Depth for Matched Pairs of Samples

Location, Condition and Depth	^{137}Cs Percentage in Depth Range	^{137}Cs Concentration Normalized to Surface (Surface activity = 1)
New York Drainage Areas		
0 to 5 cm	68%	1
5 to 15 cm	29%	0.42
15 to 30 cm	3%	0.04
New York Nondrainage Areas		
0 to 5 cm	76%	1
5 to 15 cm	16%	0.21
15 to 30 cm	8%	0.11
Massachusetts Drainage Areas		
0 to 15 cm	70%	1
15 to 30 cm	30%	0.43
Massachusetts Nondrainage Areas		
0 to 15 cm	64%	1
15 to 30 cm	20%	0.32
30 to 45 cm	16%	0.26
Pennsylvania Undisturbed Drainage Areas		
0 to 5 cm	52%	1
5 to 10 cm	37%	0.71
10 to 15 cm	11%	0.21

Differtent [sic] sampling depths for the three data sets evaluated made it difficult to compare soil column migration data between locations. Column 3 of Table 4.1 presents the concentration for the center of the vertical sampling depth assuming that the concentration in the surface sample was unity (i.e., 1 pCi/g or 1 Bq/kg). The New York and Massachusetts data are presented for drainage and nondrainage areas. The Pennsylvania data are are [sic] presented for all samples from undisturbed areas only; there were not sufficient data to separate drainage and nondrainage areas. In all cases, concentrations decrease rapidly in the first 10 cm. The slower decrease and greater depths in the New York and Massachusetts data sets may be an artifact of the low concentrations at these depths.

As can be observed in Tables 3.1 and 3.2, the average concentrations at greater than 15 cm drop to near zero (0.7 to 0.34 pci/g [2.6 to 12 Bq/kg]). This phenomenon is not observed in the Pennsylvania data because the maximum sampling depth was 15 cm.

Comparison of the surface concentrations in "disturbed" and "undisturbed" soils that were sampled at the 0 to 5 cm depth and the 0 to 10 cm depth showed that there is a significant difference for the shallow (0 to 5 cm) sampling depth surface samples but not the deep surface samples (table 3.3(b)). This is likely because soil disturbance in home gardens such as the those sampled in Pennsylvania is limited to about the top 15 cm and, therefore, integrating the sample over the entire mixing depth reduces the variation. This may be an important consideration for selecting the sampling depth when planning a radiological survey.

Statistical Analyses:

In general, the statistical analyses of the various data sets and subsets indicates that the concentration data are typically better represented by lognormal than normal distributions. As a result, the geometric mean may be a better measure of central tendency for these environmental data.

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