ACKNOWLEDGEMENTS

I would first like to thank my research advisor, Dr. Douglas J. Crawford-Brown for his insight and guidance, along with Dr. James E. Watson, Jr. for his personal concern and interest. Special thanks goes to Brookhaven National Laboratory who made the measurements possible and to the many people there for all their help: Lori Breiner, Frank Marotta, Michelle Johnson, John Aloi, Joe Klemish, Paul Zahra, and especially Ted Lazo for his computer expertise and persistence. Thanks also to Andreas George at the Environmental Measurements Laboratory for his help with measurement techniques. Tremendous gratitude goes to the Department of Energy and to Oak Ridge Associated Universities for the fellowship which has made my education and this project possible. I would like to express special thanks to the two New York families for allowing me to make measurements in their homes. Thank you to Lloyd and Helen Wright for the use of their computer and their generous help. I also want to thank my family and friends, and especially my husband for his support and patience.

The research was performed under appointment to the Nuclear Engineering and Health Physics Fellowship program administered by Oak Ridge Associated Universities for the U. S. Department of Energy.

ABSTRACT

The purpose of this project is to present a simple and specific method to assess the radon progeny hazards in the home and to apply this method. Equations presently are available to calculate lung dose for adults using a typical particle size distribution. Using these equations for children results in an underestimation of lung dose. In order to determine the lung dose for any age individual and particle size distribution, this research developed equations using a lung model by D. Crawford-Brown. These equations may be used to estimate annual lung dose from information concerning the radon progeny concentration, unattached fraction, and aerosol size distribution. Measurements of radon and radon progeny were performed in two upstate New York homes which were identified as having potentially elevated radon concentrations. Sampling procedures for unattached fractions developed by A. George and a computer program to determine working levels from gross alpha counts on air filters were applied to obtain the necessary parameters for the lung dose calculations. Estimates of lung dose equivalent to the subsegmental bronchioles for the two families were calculated from these specific measurements, with the assumption of a typical particle size distribution. Therefore, a method both for sampling radon progeny and for calculating lung dose to various groups under differing particle size distributions and unattached fractions is presented.

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1 INTRODUCTION

Indoor Rn-222 (radon) recently has been the focus of nationwide attention, since it comprises the largest single source of exposure to ionizing radiation to the general population. The average effective whole body dose equivalent from radon, 200 millirem per year, is larger than all other natural sources combined, as well as industrial and medical sources (NCRP-93,1987). Radon-222 is the decay product of radium-226 which is part of the uranium series starting with uranium-238. The actual hazard is not the radon gas, which does not readily interact chemically with other elements, but the particulate progeny to which it decays. As shown in Figure 1, two daughters, polonium-218 and polonium-214, decay by alpha emission. While all the radon progeny are breathed into the lung, these two daughters are responsible for most of the radiation dose received by the lung. The Environmental Protection Agency estimates the annual lung cancer deaths from radon in the United States to be in the range of 5,000 to 20,000 (Bodansky et al,1987).

While previous attention to indoor radon has been focused on homes built above uranium mill tailings or phosphate deposits and homes in which construction materials contained uranium, it is now widely accepted that the most common source of indoor radon is from the natural uranium in soil and rocks under homes (personal communication, Watson). One of the most publicized of

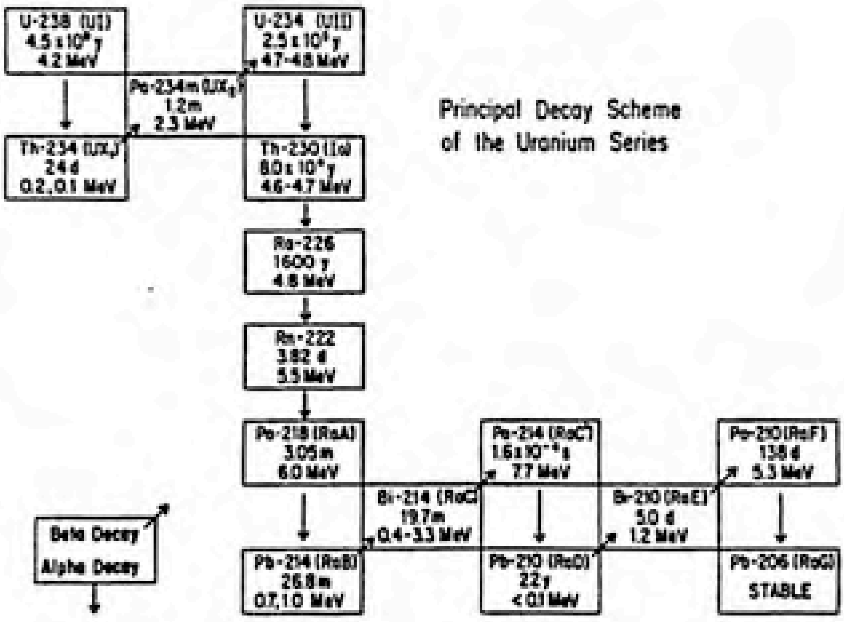


Figure 1 Uranium-238 decay scheme (NCRP-77,1984)

such areas is the Reading Prong, an underground granite formation which is highly permeable and enriched with uranium. It extends under eastern Pennsylvania, northern New Jersey, and southern New York (Cothern,1987).

The primary mechanism through which radon enters the home from the ground is through gaps in the building structure. Lesser amounts often enter from building materials and from the water supply. Weatherization of homes for energy conservation possibly can lead to elevated radon levels due to a decreased rate of air exchange with the outdoors. Radon concentrations differ greatly among homes due to differing rates of radon entry and varying locations. It is estimated that the average radon concentration for a single family home is 1.5 picocuries per liter (pCi/l) (Bodansky et al,1987). One extensive study of annual and normalized average concentrations found most of the single-family homes to have a concentration in the range of 0.2 pCi/l to 4 pCi/l, with about 9% having higher concentrations. Of those having higher concentrations, around 2% have levels greater than 8 pCi/l. This corresponds roughly to one million homes. It should be noted that the Environmental Protection Agency (EPA) recommends that action be taken when radon levels exceed 4 pCi/l on an annual average basis (Bodansky et al,1987).

Even within a single home, radon concentrations can differ greatly. In general, homes demonstrate higher levels during the winter months when the house is more tightly closed. In addition, higher concentrations are often observed during the early morning hours and the lowest concentrations are found in the late afternoon, with concentrations about one-third the peak morning values (Eisenbud,1987).

The concern about radon began in the mining industry when it was observed that certain mining populations were developing an elevated number of lung cancers (Cothern,1987). However, radon exposure in the home differs from that in mining atmospheres. Generally, in the home, a smaller aerosol median particle size (0.1 micron versus 0.2 to 0.4 micron) is found (NCRP-78,1984). Also, the fraction of radon progeny not attached to aerosol particles (unattached fraction) is larger in homes (0.07) than in mines (0.04). In addition, home atmospheres constitute continuous exposures as opposed to occupational mining exposures.

While these differences increase the lung dose per unit of radon concentration, this increase is compensated by generally lower concentrations of radon progeny in the home.

The primary unit used to describe radon concentration is the working level (WL). A WL is defined as "any combination of short-lived radon daughters in one liter of air that will result in the emission of 1.3 X 10^5 MeV of potential alpha energy" (NCRP-78,1984). To describe cumulative exposure, the unit of working level month (WLM) is used. A WLM is an exposure to one WL for one working month (170 hours). Working levels relate to pCi/l of short-lived radon progeny by the equation:

$$WL = 0.00103\ (RaA) + 0.00507\ (RaB) + 0.00373\ (RaC)$$

(Evans,1969); where (RaA), (RaB), and (RaC) is the concentration of RaA, RaB, and RaC, respectively, in units of pCi/l. As shown in Figure 1, the radionuclides corresponding to RaA, RaB, and RaC are, respectively, Po-218, Pb-214, and Bi-214. The unit of WL is defined in terms of potential alpha energy which includes the RaB and RaC beta emitters since they eventually decay to an alpha emitter. The alpha emitter RaC' (Po-214) is in equilibrium with the much longer-lived RaC. Therefore, with each RaC decay, an almost instantaneous RaC' decay occurs.

Equations presently are available to calculate the bronchial lung dose to adults if the unattached fraction and radon concentration are known. One such equation assumes a typical particle size distribution and applies only to adults (Maher et al,1987). Calculations have been performed by W. Hofmann

(Hofmann et al,1979) and N. Harley (Harley and Pasternack,1982) for the lung doses to children but not as a function of aerosol size distribution. The age-dependent lung model by Crawford-Brown (Crawford-Brown,1981) predicts lung dose for differing ages and aerosol sizes.

The general purpose of this study is to develop a method for calculating the dose delivered to the lung tissue of various age groups under any atmospheric conditions. These conditions would include the unattached fraction and particle size distribution. At the present, calculations of lung dose are available only under a single typical particle size distribution. The resulting equations presented in this report, therefore, may be used to calculate lung dose in homes in which the state of radon progeny has been measured. Since these equations require that the radon progeny concentration and unattached fraction be known, a method is also presented to obtain these parameters using two New York homes as examples. Combining the equations with the measurements yields an estimation of the annual lung dose equivalent for the members of two families at a radon progeny concentration specified as the action level by the EPA. Since no measurement of particle size distribution has been obtained here, only a single example of the application of the general method may be given.

2 THEORETICAL DEVELOPMENT OF AGE-DEPENDENT LUNG DOSE EQUATIONS

2.1 LUNG ANATOMY AND MODELLING

The respiratory system can be divided into three parts. The naso-pharyngeal region consists of the nose, mouth, throat, pharynx, and larynx, and in these areas air flow is most likely to be turbulent. The tracheo-bronchial region extends from the trachea through the lobar, segmental, and subsegmental bronchi to the terminal bronchioles. The third area is the pulmonary region which consists of the alveoli where carbon dioxide and oxygen are exchanged with the bloodstream. The area of interest for radon progeny deposition is the tracheo-bronchial region. In this region, the trachea divides into two main bronchi, which divide into five smaller bronchi to compose the lobar region of the lung. Further divisions continue and produce the segmental, subsegmental, and terminal bronchioles. As shown in Figure 2, the inner surface wall of the airways in this region is composed of a layer of pseudostratified columnar epithelial cells above a layer of basal cells. These basal cells divide to replace the epithelial cell layer. Goblet cells, which function to secrete mucus, can also be found in the columnar layer. Cilia lie above these columnar cells and propel mucus upward along the passageways. Since the basal cells are undifferentiated and rapidly dividing, it is often assumed that they are the critical cells in radon dosimetry, although this is not certain (Crawford-Brown,1987).

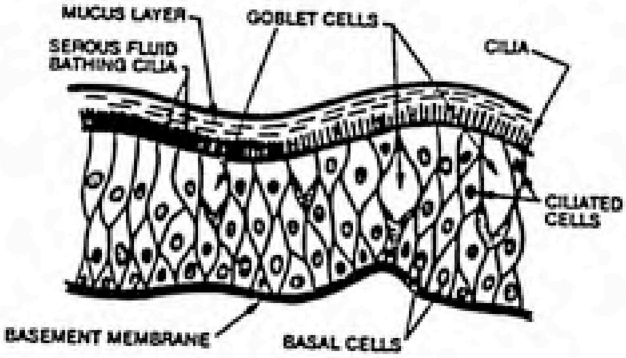


Figure 2 Cross-section of the epithelial layer of the lung (Crawford-Brown,1987)

The lung model by Crawford-Brown is comprised of twenty generations beginning with the mouth and ending in the terminal bronchioles. The area of interest here is in generation 7, which is the subsegmental region. This region is important because many of the lung tumors in uranium miners are assumed to have developed in this area (NCRP-78,1984). This lung model incorporates several important steps. First, it is necessary to calculate the amount of radon progeny deposited in each generation of the lung. Deposition modelling depends on the size of aerosol particles to which radon progeny attach, the unattached fraction, the volume of air breathed, and the age of the individual (which influences airway diameters and lengths).

Transport processes in the lung must also be described since the mucociliary blanket can move a particle from its original site of deposition. From calculations of deposition and mucociliary blanket movement, the number of disintegrations in the generation of interest (generation 7) can be estimated. Using this information on the total number of disintegrations in a generation, it then is possible to calculate the dose to cells in that generation. This calculation requires the use of depth-dose curves which describe the dose to cells located at different distances from the lung passageway walls (Crawford-Brown,1987).

For this research, the most important feature of the model is the calculation of the number of disintegrations per inhaled atom of radionuclide for various particle sizes and ages. The model yields estimates of the number of disintegrations for a wide range of aerosol particle diameters and also considers the effects of breathing characteristics. Both light and resting states of physical activity are specified in the model, but only resting states are considered in this report due to the focus on the home. This model also calculates disintegrations for various radiological decay constants. The decay constants of RaA (0.227 per minute), RaB (0.026 per minute), RaC (0.035 per minute) were summed and resulted in an average decay constant of 0.096 per minute. The closest value examined by Crawford-Brown is a radiological decay constant of 0.07 per minute. Therefore, the relative values of dose to the lung at various ages calculated using a decay rate constant of 0.07 per minute will be used in the present report. As long as the decay constant for the radon progeny is within 50% of that given in the lung model, the relative values of dose to the various generations will be the same (personal communication, Crawford-Brown). In other words, the ratio of the dose at age "a" to the dose in an adult will be correct. The absolute value of the adult is taken from NCRP-78 (NCRP-78,1984). The absolute value at any other age may then be calculated by multiplying the adult value by the ratio mentioned above.

In summary, the model yields estimates of the number of disintegrations in the subsegmental bronchioles for any aerosol diameter and age. If this number is divided by the surface area of that generation, a measure of the dose to that generation is obtained.

2.2 STATISTICAL ANALYSIS OF PARTICLES

Since the Crawford-Brown lung model considers various particle diameters, lung dose equations may be formulated for different particle size distributions. This requires information on the fraction of particles at any size. Particle size distributions generally follow a log-normal distribution, which means that the logarithm of the particle sizes is normally distributed (Crow and Shimizu,1988). In such a distribution, the geometric mean, or median diameter, is used to describe the data. This median diameter corresponds to the size at which 50% of the particles have smaller diameters and 50% have larger diameters.

The arithmetic mean diameter is not particularly useful in these distributions since it is influenced greatly by outliers. The geometric standard deviation is used in log-normal distributions to describe the variability or spread in the data. A common way to display these parameters graphically is with a cumulative plot on log-probability paper. This plot displays the particle size logarithmically and the probability or percent of particles less than the stated size on a probit scale. If this cumulative plot is a straight line, then the data are truly log-normal (Crow and Shimizu,1988).

In the present research, three aerosol median diameters were considered: 0.05 micron, 0.1 micron, and 0.5 micron. These median diameters should closely approximate the range of most aerosol size distributions found in the home (personal communication,Crawford-Brown). In addition, geometric standard deviations of two, three, and four were applied to each median diameter, resulting in a diversity of possible distributions. As shown in Figure 3, NCRP-78 considers a typical particle size distribution in the home as approximately 0.1 micron median diameter with a geometric standard deviation (GSD) of two.

The medians and geometric standard deviations for the nine aerosol size distributions considered here are displayed on log-probit paper as shown by the nine figures in Appendix A. The aerosol diameters ranged from 0.001 micron to 10 microns and were divided into 16 different intervals. Particle sizes greater than 10 microns were not considered because the majority of these

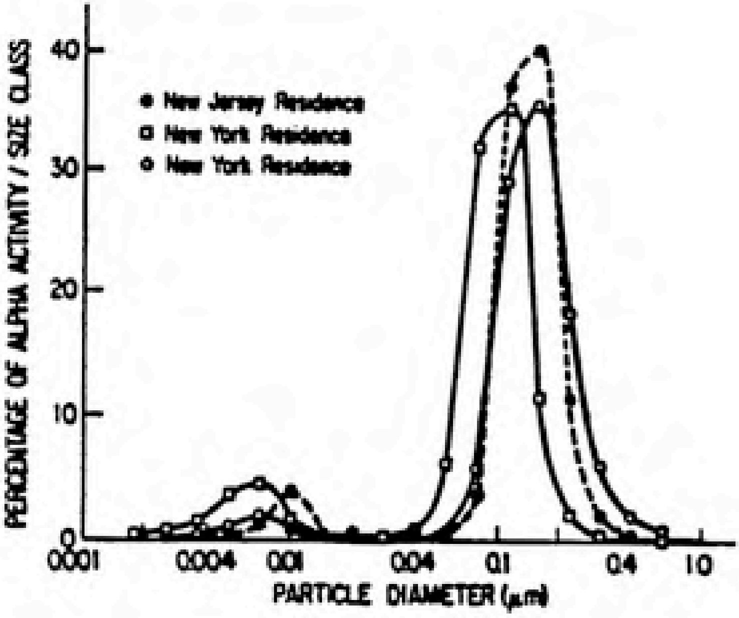


Figure 3 Particle size distribution for a typical home (NCRP-78,1984)

particles are stopped by impaction in the nose before reaching the lung (personal communication, Crawford-Brown). Particle sizes less than 0.001 micron were assumed to be mostly unattached to aerosol particles. Since the unattached progeny are deposited with an efficiency similar to that of the 0.0001 micron diameter particles, the disintegrations corresponding to the 0.0001 micron diameter as predicted by the lung model were used to determine the bronchial dose contribution from the unattached fraction of the radon progeny (personal communication, Crawford-Brown). These particle size intervals are shown in Table 1.

Table 1 Particle Size Intervals Used In This Study

Interval	Range (micron)	Interval	Range (micron)
1	0.001-0.005	9	0.8-1.0
2	0.005-0.01	10	1.0-2.0
3	0.01-0.05	11	2.0-3.0
4	0.05-0.1	12	3.0-4.0
5	0.1-0.2	13	4.0-5.0
6	0.2-0.4	14	5.0-6.0
7	0.4-0.6	15	6.0-8.0
8	0.6-0.8	16	8.0-10.0

The fraction of particles in each size interval given in Table 1 was determined for each of the nine assumed aerosol distributions by the cumulative plot of each aerosol size distribution (Appendix A). Figure 4 shows an example of a cumulative plot of a particle size distribution.

For each interval shown in Table 1, the percent of particles less than the lower boundary of each interval was subtracted from the percent of particles less than the upper boundary of each interval. The difference is the fraction of particles in that interval. Using the seventh interval as an example, the cumulative percent corresponding to 0.4 micron for the particle distribution in Figure 4 is 37%. The cumulative percent for 0.6 micron in 60%. Therefore, the fraction of particles with diameters between 0.4 micron and 0.6 micron in this distribution is 60% - 37% = 23%. This methodology was used for each size interval in each distribution such that the fractions in each distribution summed to 100%.

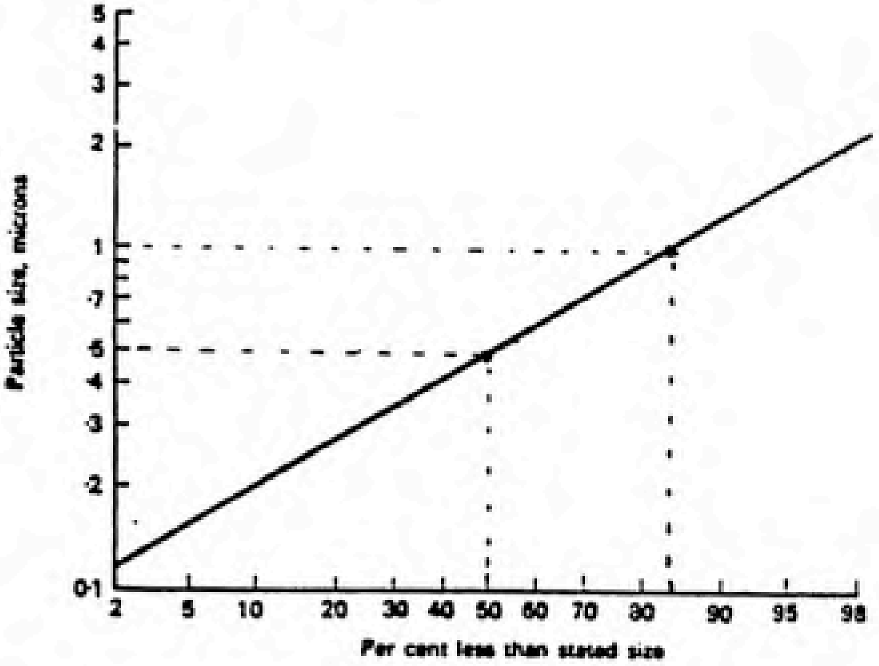


Figure 4 Cumulative plot of a particle size distribution. The particle size corresponding to the 50% point is the median diameter, 0.5 micron, and the ratio of the 84% size to the 50% size gives the geometric standard deviation as 2.

2.3 METHODOLOGY FOR FORMULATING AGE-DEPENDENT LUNG DOSE EQUATIONS

In this report, the individual ages of 0 (newborn), 2, 8, 12, 16, and 32 (adult) will be considered. From the Crawford-Brown lung model, the number of disintegrations in each lung generation, $D_{i,a}^{*}$, are given at age "a" as a result of particles in size range "i". These are the total number of disintegrations per breath and assume a concentration of 1 particle per cc. Therefore, the number of disintegrations per breath at each age must be multiplied by the breathing frequency (breaths per year) for that age in order to estimate the total number of disintegrations per year ($D_{i,a}$). Figure 5 shows the breathing frequency in breaths per minute as a function of age. These values are converted into breaths per year for the specific ages considered as shown in Table 2.

Since the particle size endpoints of interest in the present study (Table 1) occasionally were different from the particle sizes given in the lung model, interpolation was necessary to determine the number of disintegrations associated with the particle size intervals considered. The midpoint of each interval in Table 1 was calculated. As described above, the lung model predicts the total number of disintegrations occurring in generation 7 for each age, "a", and particle size, "i" ($D_{i,a}^*$). When multiplied by the breathing frequency, this number becomes $D_{i,a}$, with units of disintegrations per year resulting from exposure at age "a" to an atmosphere of 1 atom per cc. Values of $D_{i,a}$ for the specific particle size intervals used in this study were obtained by interpolation between the values given by the lung model. The fraction of particles, f_i, in each size interval, i, as determined by the cumulative plot for each assumed particle size distribution in Appendix A then were multiplied by "$D_{i,a}$". These values, f_i,$D_{i,a}$, represent the total number of disintegrations in generation 7 from each size interval and age, weighted by the fraction of particles in each of these intervals for each particle size distribution. To obtain the total number

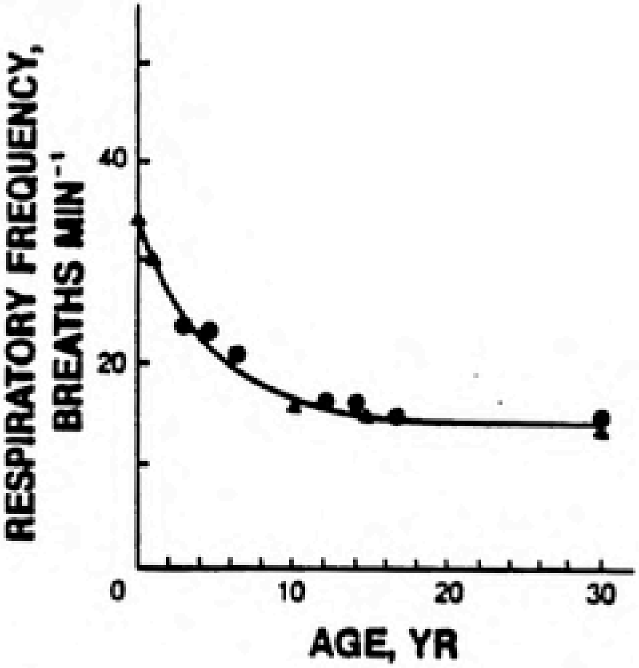


Figure 5 Breathing frequency as a function of age (Crawford-Brown,1987).

Table 2 Breathing Frequency for Specific Ages

Age	Breaths per minute	Minutes per year	Breaths per year
0	34	5.256 E 5	1.7870 E 7
2	27	5.256 E 5	1.4191 E 7
8	18	5.256 E 5	9.4608 E 6
12	16	5.256 E 5	8.4096 E 6
16	15	5.256 E 5	7.8840 E 6
32	14	5.256 E 5	7.3584 E 6

(Adapted from Crawford-Brown,1987)

of disintegrations corresponding to all size intervals at a given age, the values of $f_i, D_{i,a}$ were summed over all particle sizes (i.e. $\sum_i f_i, D_{i,a}$). The total dose from all size intervals then is proportional to this sum divided by the age-dependent regional surface area of the lung for generation 7 (SA_a). These surface area values are shown in Table 3. This dose, however, pertains to a radon progeny concentration of 1 atom per cc. Therefore, $\sum_i f_i, D_{i,a} / SA_a$ must be multiplied by the radon progeny concentration, C (in units of WL), and an arbitrary conversion factor, k, to obtain the total lung dose per year. The units of k will be rads per disintegration per square centimeter times atoms per cc per WL.

The discussion above has considered only radon progeny attached to aerosol particles. The contribution of the radon progeny unattached to aerosol particles was derived in the same manner as above with one alteration. For the unattached progeny, the disintegrations per year and per unit concentration for each age, $D_{f,a}$, were obtained by using only the disintegrations corresponding to the particle diameter of 0.0001 micron from the lung model, which is considered smaller than aerosol particles (personal communication, Crawford-Brown). Adding the contributions from the attached progeny and unattached progeny results in the total lung dose per year, $R_{p,a}$, specific for each particle size distribution and age. The following general equation illustrates the previous discussion:

Table 3 Age-Dependent Regional Surface Areas of the Lung

Age	Surface Area (cm^2)
0	2.6
2	4.5
8	11.4
12	15.9
16	20.1
32	28.7

(Adapted from Crawford-Brown, 1981)

$$R_{p,a} = (1-f)\ C\ k \sum_{i} f_i, D_{i,a} / SA_a + f\ C\ k\ D_{f,a} / SA_a, \qquad (1)$$

where f is the unattached fraction and C is the total concentration of the progeny in WL, regardless of the state of attachment. The only term left to determine is the conversion factor, k, which is independent of age and particle size distribution. This factor may be obtained by providing known values of $R_{p,a}$ and C and solving the above equation for k. NCRP-78 provides a factor for lung dose per unit radon progeny concentration of 0.5 rad per WLM for adults. Additional values are given corresponding to gender-specific environmental exposures (women = 0.6 rad/WLM and men = 0.7 rad/WLM) and could be used if desired. The conversion of 0.5 rad/WLM was chosen because it represents a consensus of values used by the NCRP and EPA (personal communication, Crawford-Brown). Since this NCRP conversion factor is expressed in units of rad per WLM, the radon progeny exposure also must be expressed in WLM. However, radon progeny concentration usually is expressed in WL, as is the case in Equation 1. Therefore, a conversion is needed to equate WL with WLM. A WLM corresponds to exposure at 1 WL for 1 month (170 hours). Since there are 52, 170-hour periods in a year for continuous exposure, a concentration of 1/52 WL will yield 1 WLM. Therefore, a concentration, C, of 1/52 WL was used in Equation 1 to solve for k, with R_p set equal to 0.5 rads.

Another factor needed to determine k (see Equation 1) is the unattached fraction, f, which for a typical home is 0.07 (NCRP-78,1984). The attached fraction is therefore 1-f or 0.93. Since 0.5 rad/WLM is a factor corresponding to adults, the surface area (SA_a) term that must be used is 28.7 cm^2 (Table 3). The only values left to be supplied for Equation 1 are $\sum_i f_i, D_{i,a}$ and $D_{f,a}$. These terms were explained previously and the values used here may be found in Appendix B. For purposes of solving for k in Equation 1, a typical particle size distribution with a median of 0.1 micron and GSD of 2 is used here. With the appropriate values inserted into Equation 1, it is possible to solve for k as follows:

$$0.5 \text{ rad/WLM} = (0.93)\ (1/52 \text{ WL})\ (1.1792 \text{ E6})\ k\ /\ 28.7$$
$$+ (0.07)\ (1/52 \text{ WL})\ (3.7271 \text{ E7})\ k\ /\ 28.7;$$
$$k = 2.0137 \text{ E-4}.$$

The conversion factor, k, may then be substituted back into

Equation 1 along with any desired age and/or particle size specific values for $\sum_i f_i, D_{i,a}$, $D_{f,a}$, and SA_a, in order to calculate $R_{p,a}$. In the present research, six ages and nine particle size distributions are considered. This yields a total of 54 different versions of Equation 1. The following example for adults and a typical particle size distribution illustrates the method used to develop these equations:

$$R = (1-f)\ C\ (k)\ (\sum_i f_i, D_{i,a})\ /\ SA_a + f\ C\ (k)\ (D_{f,a})\ /\ SA_a$$

$$R = (1-f)\ C\ (2.0137\ E-4)\ (1.1792\ E6)\ /\ 28.7 + f\ C\ (2.0137\ E-4)$$
$$(3.7271\ E7)\ /\ 28.7 \quad \text{or,}$$

$$R = (8.3 + 253.2\ f)\ C.$$

A similar calculation can be performed for each age/particle distribution combination. Each of the resulting 54 equations is of the form:

$$R = (A + B\ f)\ C. \tag{2}$$

The values for A and B, as calculated for this study, are given in Table 4 and are specific for each age and particle size distribution. Consider the previous example for an adult and a particle size distribution with a median diameter of 0.1 micron and a geometric standard deviation of 2. From Table 4, it may be seen that A equals 8.3 and B equals 253.2.

Table 4 Parameters for Age-Dependent Lung Dose Equations (Ages 0 - 8)

Age	Distribution (median, GSD)	A	B
0	0.05, 4	22.5	382.5
	0.10, 4	27.4	377.6
	0.50, 4	96.3	308.7
	0.05, 3	16.7	388.3
	0.10, 3	18.5	386.5
	0.50, 3	84.2	320.8
	0.05, 2	14.4	390.6
	0.10, 2	12.9	392.1
	0.50, 2	62.3	342.7
2	0.05, 4	37.5	460.6
	0.10, 4	61.0	437.1
	0.50, 4	231.0	267.1
	0.05, 3	25.1	472.9
	0.10, 3	38.3	459.8
	0.50, 3	214.6	283.4
	0.05, 2	19.4	478.7
	0.10, 2	23.0	475.0
	0.50, 2	170.4	327.7
8	0.05, 4	24.6	345.2
	0.10, 4	37.8	332.0
	0.50, 4	172.0	197.8
	0.05, 3	17.1	352.7
	0.10, 3	23.3	346.5
	0.50, 3	145.1	224.7
	0.05, 2	13.8	356.0
	0.10, 2	14.6	355.2
	0.50, 2	102.5	267.3

Table 4, continued
Parameters for Age-Dependent Lung Dose Equations
(Ages 12 - 32)

Age	Distribution (median, GSD)	A	B
12	0.05, 4	20.5	310.9
	0.10, 4	29.7	301.7
	0.50, 4	143.2	188.2
	0.05, 3	14.6	316.8
	0.10, 3	18.5	312.9
	0.50, 3	115.2	216.2
	0.05, 2	12.1	319.3
	0.10, 2	11.9	319.5
	0.50, 2	77.8	253.6
16	0.05, 4	18.7	294.7
	0.10, 4	26.4	287.0
	0.50, 4	133.3	180.1
	0.05, 3	13.5	300.0
	0.10, 3	16.3	297.1
	0.50, 3	104.0	209.4
	0.05, 2	11.4	302.0
	0.10, 2	10.8	302.6
	0.50, 2	67.4	246.0
32	0.05, 4	14.7	246.8
	0.10, 4	19.2	242.4
	0.50, 4	94.8	166.8
	0.05, 3	10.8	250.7
	0.10, 3	12.2	249.3
	0.50, 3	72.0	189.5
	0.05, 2	9.2	252.3
	0.10, 2	8.3	253.2
	0.50, 2	46.7	214.8

3 DETERMINATION OF RADON PROGENY CONCENTRATIONS IN HOMES

Radon progeny concentrations were determined in two New York homes. These homes were identified through the New York State Department of Health. Both homes had elevated charcoal canister readings in March of 1988. The Department of Health communicated to the families that these extensive measurements of the radon progeny concentration and unattached fraction were available to them if they were interested. These homes were located in West Chester County, New York on the edge of the Reading Prong. Radon progeny measurements were made using a filter technique and radon gas measurements were taken for comparison purposes. Unattached fraction measurements were also made using a wire screen technique. Particle concentration was determined in these homes to compare to the unattached fraction measurements.

3.1 FILTER TECHNIQUE AND COMPUTER PROGRAM

The filter method for determining radon progeny concentrations was originally developed by E. C. Tsivoglou (Tsivoglou et al, 1953) and consists of sampling the air through a filter at a fairly low flow rate. This method first was used in mine atmospheres to determine the amount of radon progeny activity present in contaminated air. In this method, samples are collected for 5 minutes and the filter is then counted by an alpha scintillation system at three separate time intervals (5, 15, and 30 minutes after the termination of sampling). The individual air concentrations of the three short-lived radon daughters, RaA, RaB, and RaC, can be estimated from the total activity on the filter at the three measurement times by solving a set of differential equations. Three measurements are required because three differential equations are used in this technique, one for each radon progeny, with three unknowns. One subset of equations accounts for the buildup and decay of activity on the filter during the sampling period, while another accounts for the time period after the termination of sampling (when the progeny are decaying but not being collected). The rate of buildup of the three radon progeny on the filter depends upon their concentrations in air, the flow through the filter, and the radiological decay constants of the three progeny. The activity of each of the radon progeny is described by the sets of differential equations incorporating these factors. From these differential equations and the above factors, it is possible to solve for the activity of each of the progeny on a filter at any time, given the concentration in the air. This situation could be reversed and the concentration of the progeny in the air may be inferred from the activity on the filter (gross alpha counts). Therefore, measurements of the activity on the filter may be used to calculate the concentrations of the three radon progeny. The solutions to these differential equations are quite long and cumbersome and are presented in a paper by D. E. Martz (Martz et al,1969). These equations allow for a variation in counting and sampling times and include a theoretical development of the associated standard errors. However, these equations assume that measurements are available of the instantaneous count rates during each of the three 1-minute counting intervals. To improve the accuracy of the counting method by accounting for the finite length of the measurement intervals, the equations describing count rate must be integrated over the three different time intervals (personal communication, Crawford-Brown). With this modification, total alpha counts over three specified time intervals are used instead of count rates.

Several studies of different time intervals were reviewed to determine the simplest intervals to use with the available equipment without sacrificing accuracy. J. W. Thomas found that the post-sampling time intervals of 2 to 5 minutes, 6 to 20 minutes, and 21 to 30 minutes with a sampling period of 5 minutes yield the highest accuracy (Thomas,1972). However, for simplicity, time intervals suggested by A. G. Scott were chosen (Scott,1981). The time intervals suggested by Thomas involved irregular counting times which would have required manual control of the counting equipment. Errors might be introduced due to manually controlling the scaler. Therefore, to reduce possible error and still retain high accuracy, the Scott method of 5-minute counts was used. This procedure involved taking an air sample for 5 minutes, then counting the filter with an alpha scintillation system from 1 to 6 and 6.25 to 11.25 minutes after the termination of sampling. The third 5-minute count is made on the filter at any time between 40 and 85 minutes post-sampling. The last counting interval was chosen here to be 40 to 45 minutes to reduce total counting and waiting times. Using these intervals, the filter must be transported from the holder to the counters within 1 minute after the end of sampling. In addition, the scaler reading must be noted and the second interval started within 15 seconds. This requires a careful account of time since the scaler must be started manually. However, by using the 5-minute intervals the scaler will stop automatically since 5-minute counting times can be preset on the scalers, thus removing some possible counting errors. This technique was practiced using an early 1900's radium "drinking water" source placed in a wooden box with drilled sampling ports. This "radon box" was used to practice sampling and counting techniques before home measurements were made.

A computer code designed to relate the activity on the filter (gross alpha counts) to the concentrations of the three radon progeny in air has been written based on the Tsivoglou technique. This program uses simplified equations derived by Y. Fu-Chia and T. Chia-Yong (Fu-Chia and Chia-Yong, 1978) and can be found in Appendix C with a brief explanation of the major steps involved. This program yields the RaA, RaB, and RaC concentrations in pCi/l and their standard errors along with working level computations. Table 5 illustrates the quantities required to be input into this computer code. To test this computer program, time intervals given by Thomas (2-5, 6-20, 21-30) and Scott (1-6, 6.25-11.25, 70-75) were entered into the program along with the 5-minute sampling time used by both authors. A comparison then was made between the results calculated by the code and those published by Thomas and Scott. An exact match was obtained and the computer code was assumed correct.

The theoretical development of the standard errors corresponding to the radon progeny concentrations can be found in the Martz paper. Errors associated with background subtraction were not included in the Martz paper but were included in this program since fewer sample counts were expected than in the mine atmospheres that Martz was considering. The standard errors were determined by error propagation formulas as shown in Appendix D. These standard errors were determined to demonstrate that errors that could be quantified were at an acceptable level. All radon progeny concentration standard errors were less than 10%. Error was not propagated throughout the dose equations since many uncertainties are present which are difficult to quantify, although the lung model itself should be accurate to a factor of two (personal communication, Crawford-Brown).

Table 5 Inputs for Computer Code

INPUT	SOURCE
Sampling time (minutes)	Preset (5 minutes)
Sampling flow rate (lpm) *	Flowmeter/Pump (12.2 lpm)
Sampling flow rate std. error *	Manufacturer
Detector efficiency *	Detector/Source
Detector efficiency std. error *	Source Cert./Error Prop.
Total alpha counts (3 intervals)	Detector
Duration of 3 intervals (minutes)	Preset (5 minutes)
Total bkg. counts (3 intervals)	Detector (5-minute counts)
Post-sampling start times	Preset (1,6.25,40 minutes)

* See Appendix D for measurements and calculations

3.2 EQUIPMENT AND CALIBRATIONS

3.2.1 Filters

Membrane filters were used because of their ability to trap particles on the filter surface rather than within the filter matrix. This is important when sampling alpha particles due to self-absorption. Membrane filters also have a high retention efficiency for respirable particles and are commonly used for radioactive aerosol sampling (Cember,1987). Millipore 0.8 micron, 37-millimeter diameter filters were used along with backing pads to support the filters against vacuum pressure. Plastic 37-millimeter aerosol analysis monitors were used to hold the filters in place. These holders have a center section between the top and bottom portions which serves as a retaining ring to hold the filter in place. This filter apparatus is shown in Figure 6. When the top section is removed, open aerosol sampling can be accomplished with a vacuum pump connected to the monitor outlet by tygon tubing. However, air leaks were observed on these monitors during vacuum testing and black electrical tape was wrapped securely around the retaining ring seals while sampling to eliminate this problem.

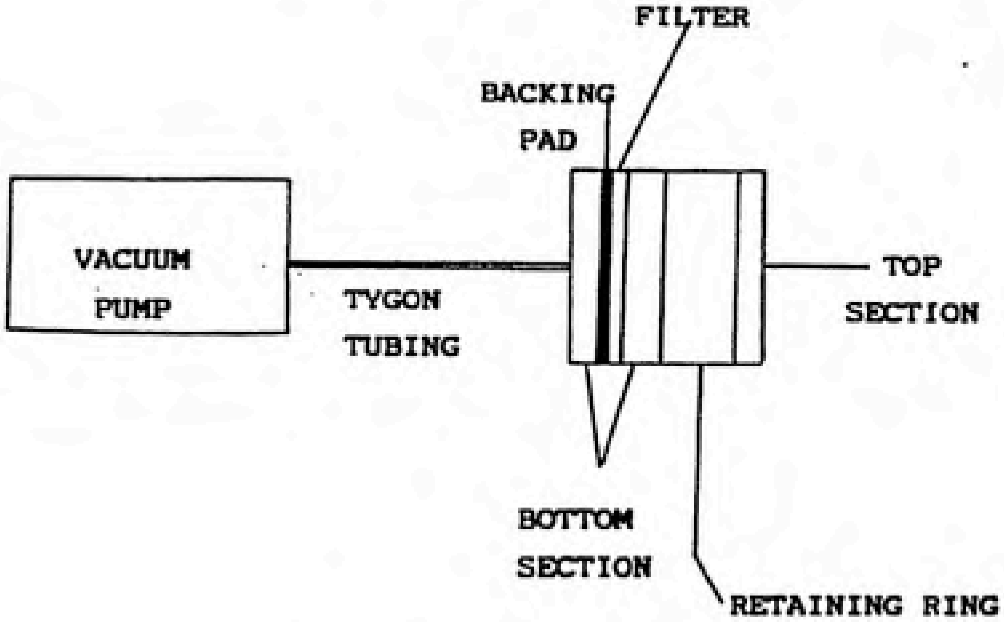


Figure 6 Filter Apparatus

3.2.2 Screens

Two 60-mesh screens with 3.9 centimeter diameters were used to determine the unattached radon progeny. One screen fitted into a metal monitoring device with a top retaining ring to hold the screen in place, similar to the apparatus shown in Figure 6. A paper filter followed and prevented the progeny from contaminating the vacuum pump. Tygon tubing was then tightly connected to the monitoring apparatus and to the vacuum pump. This equipment and method was developed by A. George at the Environmental Measurements Laboratory in New York (personal communication, George). While other methods are available, wire screens are inexpensive and simple to use. However, the unattached radon progeny must be collected with high efficiency and minimal collection of the attached radon progeny. The wire screen has an inherently negative charge which attracts the positively charged unattached radon progeny, especially RaA. With the proper combination of air velocity and mesh size, experimental evidence has shown that a reasonable collection efficiency for unattached radon progeny can be obtained (George, 1972). In George's experiment, wire screen mesh sizes from 60 to 325 per inch were tested and only the 60-mesh screen demonstrated "zero collection efficiency" for attached radon daughters. George determined efficiencies for unattached radon progeny of 0.60 and 0.50 for 60-mesh screens at linear velocities of 12 and 17 centimeters per second respectively. A linear velocity of 17 cm/s was used for these measurements which corresponds to a sampling rate of 12.2 liters per minute and 50% screen efficiency. This sampling rate was determined from the following calculation:

$$Q = A \times V$$

$$Q = 11.95 \text{ cm}^2 \times 17 \text{ cm/s} \times 60 \text{ s/min} \times 1 \text{ l}/1000 \text{ cc}$$

$$Q = 12.2 \text{ lpm}$$

where Q = sampling rate in liters per minute, A = area of the screen in cm^2, V = linear velocity in cm per second, and conversion factors are included to obtain the units of lpm.

3.2.3 Condensation Nuclei Monitor

An inverse relationship exists between the unattached fraction of radon progeny and particle concentration as shown in Figure 7. As the number of particles in the air increases, more unattached atoms have particles they can attach to, and hence a smaller unattached fraction results. This explains why unattached fractions are larger in the home than in a mining atmosphere where more aerosol particles are present. Therefore, particle concentration measurements were made in order to confirm or explain the unattached fraction results.

An Environment One Rich 100 Condensation Nuclei Monitor was used to measure the concentration of aerosol particles. According to the equipment manual, this monitor measures particles 0.0025 micron and larger with a range of 300 to 10^7

particles per cubic centimeter. This instrument operates on the principle of a cloud chamber which produces droplets from condensation of submicroscopic particles. A light beam is attenuated by the cloud proportional to the concentration of aerosol particles. The humidifier was filled with distilled water which was removed and replaced each time the instrument was moved to prevent flooding of the cloud chamber. Ideally this monitor is tested with a known concentration of particles. This monitor had been calibrated when it was purchased several years ago and a new calibration could not be obtained. As a rough check of the ability of the detector to respond to different particle concentrations, the detector was exposed to two atmospheres of very different particle concentration. First, cigarette smoke was used to produce a high concentration of particles to determine if the monitor needle would rise rapidly. Then, the vacuum pump intake was filtered to check if the needle would drop rapidly. The detector readily responded to the difference in particle concentration. It is assumed, therefore, that the detector can detect the difference between two atmospheres of very different particle concentration. Since a new calibration was not available, only relative values of particle concentration can be obtained.

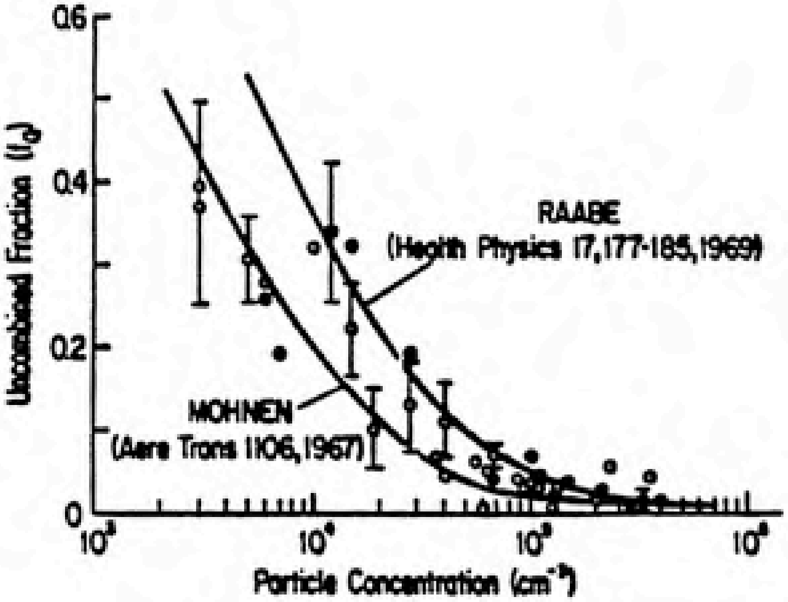


Figure 7 Variation of unattached fraction of RaA with aerosol concentration (NCRP-78,1984).

3.2.4 Alpha Scintillation Detectors

Two alpha scintillation detectors were used since simultaneous measurements of the wire screen and filter were necessary. Both detectors contained a thin sheet of zinc-sulfide scintillation material. This scintillation material produces light photons when alpha particles strike the surface. A photomultiplier tube then detects this light and converts it into an electrical signal. Figure 8 shows a diagram of the detector and associated electronics.

An Americium-241 small circular plane source was used for all voltage and efficiency determinations, as well as for the standard error computations. This National Bureau of Standards

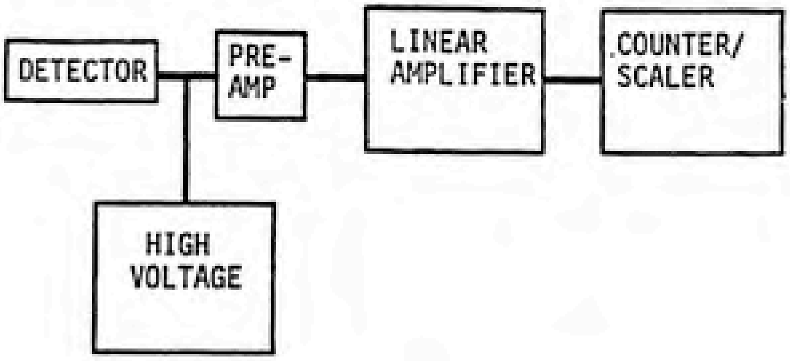


Figure 8 Alpha scintillation detector and associated electronics

source was chosen from the available sources because the alpha energy emitted most closely resembled that of the radon daughters. The two alphas emitted by Am-241 have energies of 5.29 MeV (85%) and 5.44 MeV (13%) (Radiological Health Handbook, 1970). The alpha energy of RaA is 6.00 MeV (100%) and that of RaC' is 7.69 MeV (100%). Operating voltages were determined by voltage plateaus such as the one shown in Figure 9. This plateau was generated by increasing the voltage on the detector by small increments and then noting the corresponding 5-minute source counts. An operating voltage then was chosen from the flat region (plateau) of the graph. Efficiency determinations were performed by obtaining a 10-minute background count and five 10-minute source counts. Background counts were then subtracted from each count and an average of the five counts was calculated. After correcting for decay, efficiencies then were calculated from detector counts per minute divided by source disintegrations per minute. These calculations are shown in Appendix D.

The first detector used was an Eberline SAC-4 alpha scintillation counter. This detector was used to count the thick screens because it had a sample holder which adjusted to various depths. A voltage plateau was obtained using a Sensitive Research electrostatic voltmeter and resulted in an operating voltage of 575 volts. An efficiency of 42.22% was determined by the calculations shown in Appendix D. Since the source was much thinner than the wire screen, this efficiency was determined by placing pads under the source until the same thickness as the wire screen was obtained.

The other detector used was fabricated at Brookhaven National Laboratory and was not self-contained. Therefore, the associated electronics were placed in a BNC Portanim. These electronics consisted of a Canberra Dual Counter/Timer, a Bertan Associates High Voltage Module, and a Canberra Preamplifier/Amplifier Module. The preamplifier/amplifier module was adjusted to the following settings: coarse gain = 4, fine gain = 1, and discrimination = 0.8 as per Laboratory personnel suggestions. The voltage plateau was obtained by adjusting the potentiometer on the high voltage module and the operating voltage was set at 1300 volts. The efficiency calculations resulted in 35.69%, as shown in Appendix D. An additional Brookhaven scintillation detector was kept for use as a spare in case problems with this one arose.

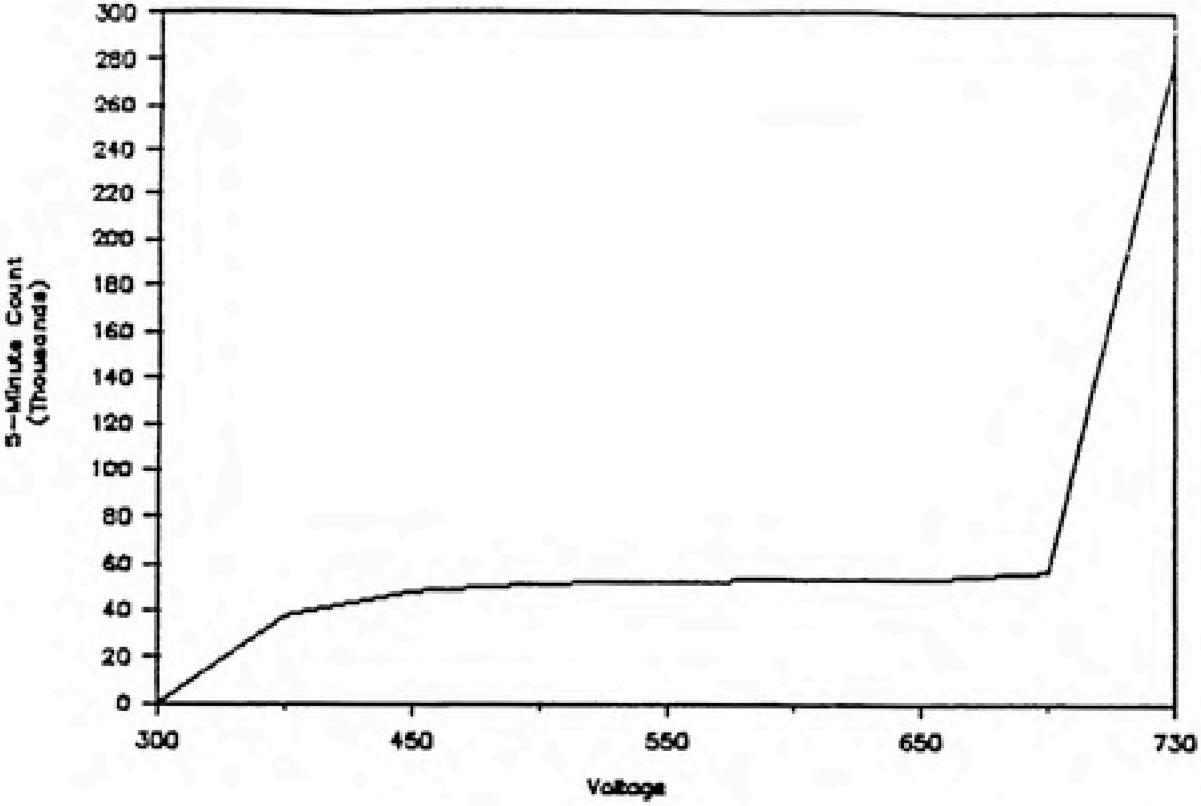


Figure 9 Voltage plateau for Eberline detector

3.2.5 Vacuum Pumps and Flowmeter

Air sampling equipment consisted of three Gast diaphragm vacuum pumps and a Cole-Parmer precision variable area flowmeter. Two of these pumps were used for the screen and filter and the remaining pump was used to purge the screen and as a spare. The flowmeter was calibrated by comparing the flowmeter reading with a known air source from a Brooks air flow calibrator on the 0-100 liters per minute scale. Different flowrates were obtained by adjusting the valves on the air samplers. This calibration plot is shown in Figure 10.

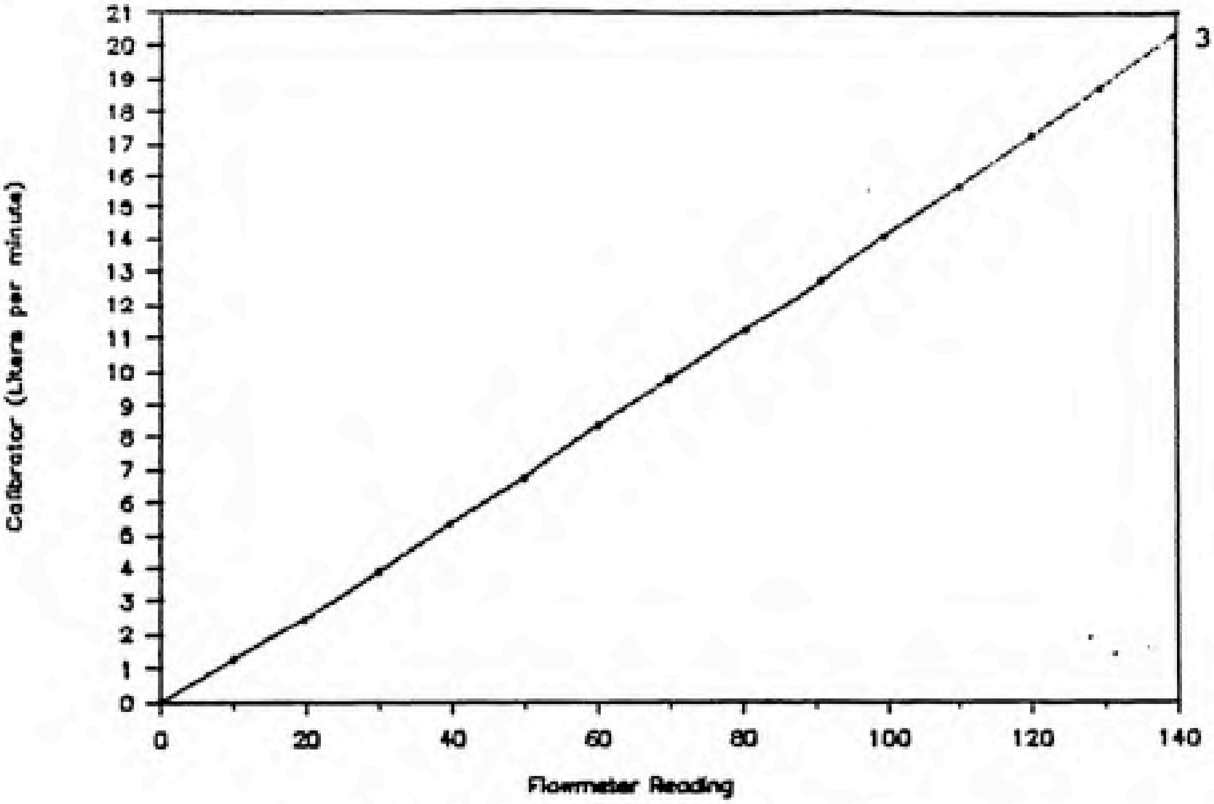


Figure 10 Flowmeter calibration plot.

3.2.6 Pylon AB-5 Radon Gas Monitor

A Pylon AB-5 radon gas monitor was used to make comparative radon gas measurements using an alpha scintillation cell (Lucas cell size 300). This instrument operates on the same principle as the alpha scintillation detector except that air is pumped directly into a cell coated inside with scintillation material. This instrument was calibrated in the Environmental Measurements Laboratory radon chamber at a humidity of 44% and a temperature of 22.4 degrees Celcius. An alpha scintillation cell adapter was used to secure the cell next to the photomultiplier tube. The detector was programmed to continuously take 10-minute counts in the chamber. A length of tygon tubing was connected from the pump intake on the rear panel to the alpha scintillation cell. Another length of tygon was connected to the alpha scintillation cell, and to an open-faced (top section removed) 0.8 micron Millipore filter apparatus which was placed in the chamber sampling port. Figure 11 demonstrates this calibration set-up. The filter was attached to prevent radon progeny from entering the alpha scintillation cell so that only radon gas entered the cell. In this calibration, 25 radon gas measurements were made corresponding to a radon chamber concentration of approximately 20 pCi/l. A calibration factor of 1.1 cpm / pCi/l was determined by the plot shown in Figure 12. The first counts were disregarded until the gas had equilibrated, then subsequent counts were used as true measurements. These 10-minute counts and corresponding concentrations were averaged to determine the above calibration factor.

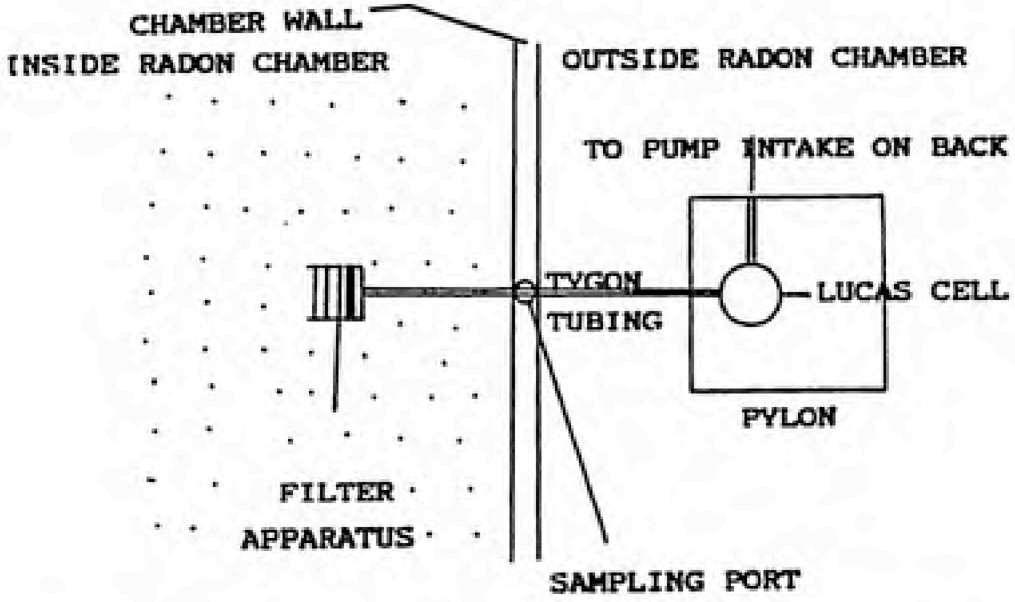


Figure 11 Pylon AB-5 calibration set-up

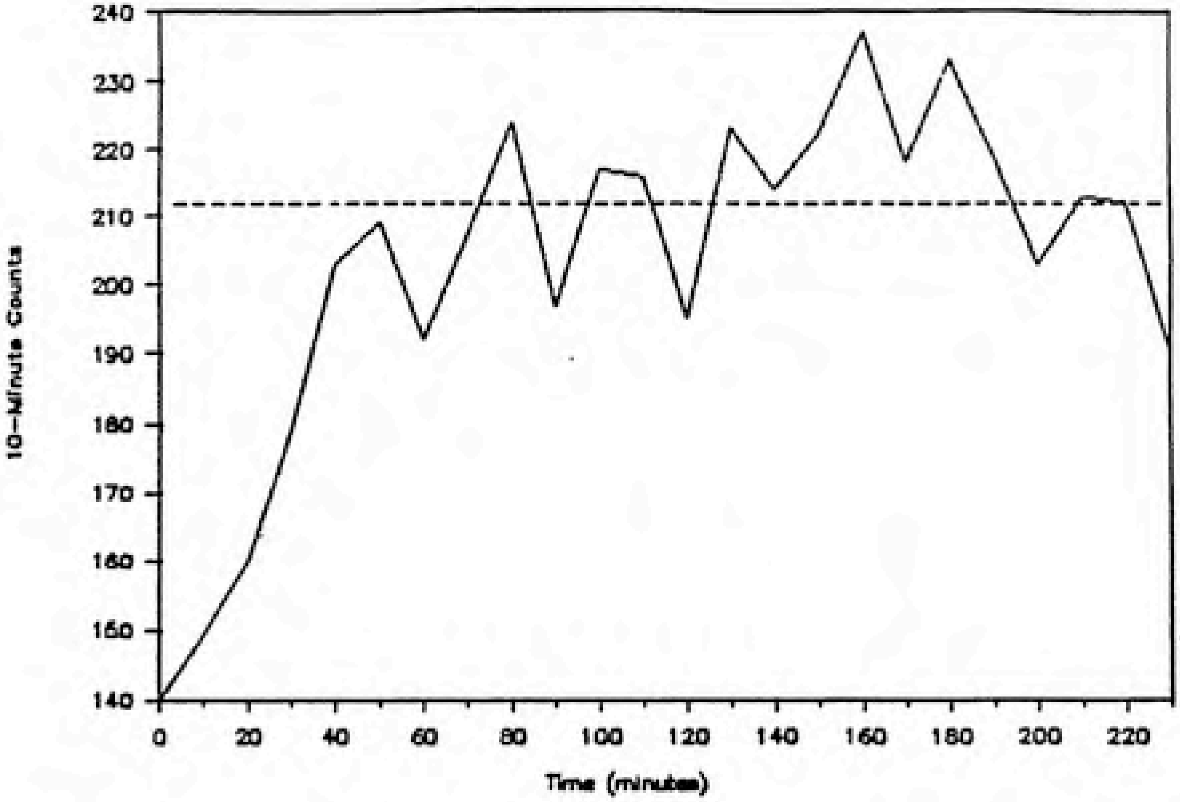


Figure 12 Pylon AB-5 calibration plot. The dotted line represents the average 10-minute counts obtained in the period following equilibration.

3.3 HOME SAMPLING PROCEDURES

Before sampling in the homes, 5-minute background and source counts were taken on the two scintillation detectors. The source checks were taken to determine if moving the detectors had caused any damage which would result in a poor response. The Pylon was then programmed to take continuous grab samples and store counts in 15-minute intervals. The condensation nuclei monitor was next started and allowed to warm up. Since only one flowmeter was available for both pumps, flow rates were set up outside where the radon progeny concentration was assumed to be negligible.

The screen and filter to be used were placed in their respective holders, which were attached to the vacuum pumps by tightly fitting tygon tubing. The flow was then quickly adjusted on each pump to the specified amount. Using the graph in Figure 10 and conducting experiments with the calibrator, this amount was 87.5 on the flowmeter which corresponds to 12.2 liters per minute. Figure 13 demonstrates the flowmeter, filter, and pump set-up. The filter and screen mechanisms were set up at the desired location in the home and the scintillation detectors were placed in a "low background" area. The filter and screen apparati were placed side by side a few feet off the floor and the pumps were turned on simultaneously. Exactly 5 minutes later, the pumps were turned off together. Within 1 minute, the screen and filter were disassembled from their holders and transported to the scintillation detectors. At precisely 1 minute after sample termination, the two detectors simultaneously were started to count the samples. Five-minute counting intervals were preset on the detectors. The detectors were restarted after 15 seconds for a second count and after 40 minutes post-sampling for a third count. A new set of measurements using the screen/filter samples were obtained during the delay before the last count was made on the first set of samples. These times were carefully calculated and documented to insure that no errors were made. In addition, the same pump and detector combination was used each time for consistency. The particle concentration was noted each time a new sample was started and flow rates and background counts were taken before each set of samples.

Since only two wire screens were available for sampling, the residual radon progeny had to be removed from them before reuse. An alcohol rinse was applied to these screens with little success. This was a significant problem since radon progeny in the home atmosphere were attracted to the screens even without being suctioned. After making several attempts to decontaminate these screens, two methods proved to be the most effective in removing the progeny. Following the first two counts, the screens then were placed in small plastic bags and sealed tightly. After the third count was completed, the screens were purged outside with the spare vacuum pump at a high flow rate and again placed in a clean, sealed plastic bag until reuse. This procedure was repeated for every two filter/screen measurements.

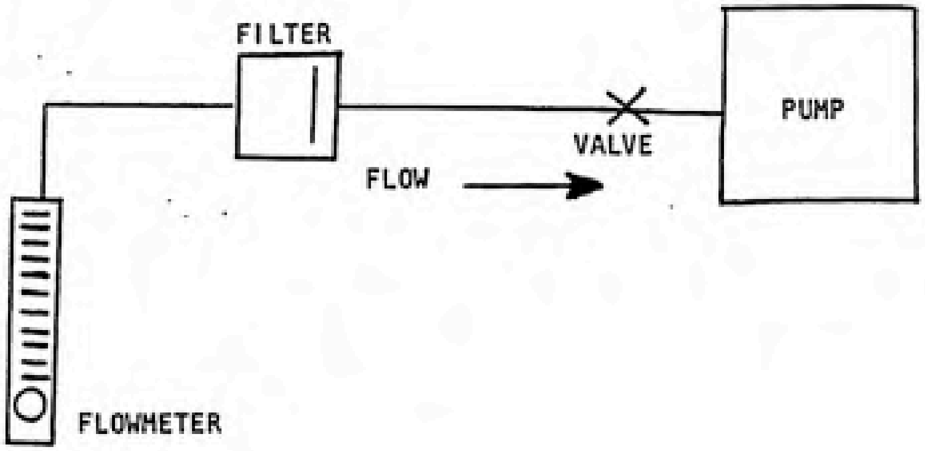


Figure 13 Flowmeter set-up

4 RESULTS FOR TWO NEW YORK HOMES

4.1 RADON PROGENY MEASUREMENTS

The first home sampled, Home A, had a finished basement that was only partially underground. The basement consisted of a living area, play area, workroom, and a bathroom. Four filter/screen measurements were taken in the living/play area outside the workroom which was assumed to be the source of radon from cracks in the block wall and concrete floor. Table 6 displays these measurement results along with measurements of the unattached fractions. The unattached fractions were calculated by the following equation:

$$\frac{C_s / E_s}{C_f}$$

where C_s = the concentration of radon progeny on the screen, E_s = the collection efficiency of the screen for unattached radon progeny (0.50), and C_f = the concentration of radon progeny on the filter (personal communication, George). The values found in Home A generally were higher than the standard unattached fraction of 0.07. The particle concentration in Home A varied from 2,000 to 12,000 particles per cubic centimeter. George has conducted condensation nuclei concentration studies in homes and buildings with a range of 15,000 to 100,000 particles per cubic centimeter, as shown in Figure 14. Figure 7 displays an inverse relationship between particle concentration and unattached fraction. This helps to explain why the unattached fractions in

Home A were higher than average, since the particle concentration was generally lower than the average given by NCRP-78.

TABLE 6 HOME A MEASUREMENT RESULTS

Sample Number	Filter WL	Screen WL	Unattached Fraction	Location	Average Radon WL
1	2.72 E-2	1.02 E-3	0.0752	BASEMENT	------
2	2.73 E-2	1.56 E-3	0.1143	BASEMENT	------
3	2.37 E-2	3.01 E-3	0.2548	BASEMENT	------
4	2.15 E-2	1.03 E-3	0.1210	BASEMENT	------
AVG	2.49 E-2	1.72 E-3	0.1382	BASEMENT	2.5 E-2

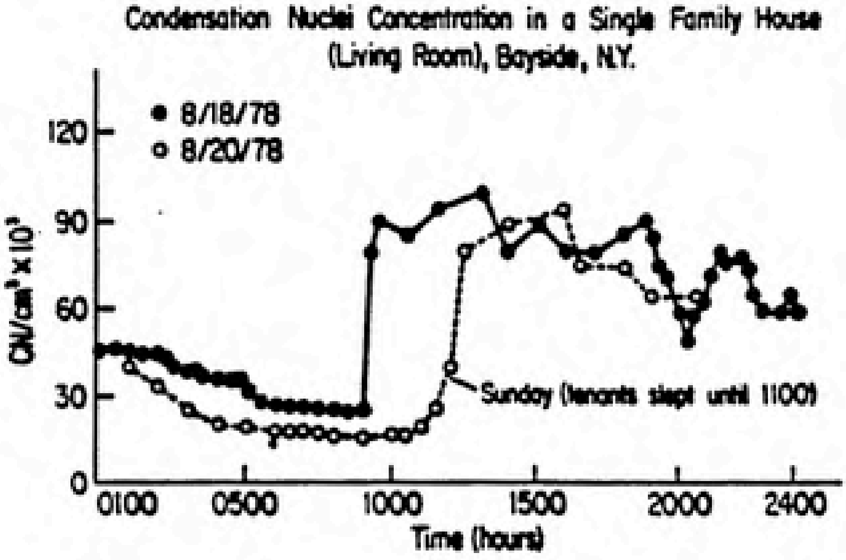


Figure 14 Condensation nuclei concentrations in a single family home (NCRP-78,1984).

As a rough check of the filter method, 13 radon gas measurements were made with an average measurement of 5 pCi/l. Assuming 50% equilibrium (1 WL = 200 pCi/l), this average corresponds to 0.025 WL, approximately the average obtained by the filter measurements. If the radon gas and radon progeny measurements had been grossly different, the sampling techniques could have been incorrect since the equilibrium ratio does not vary greatly from home to home (personal communication, Crawford-Brown). These measurements were all made at the same location from about 9:00 A.M. to noon in August of 1988. It was perceived that the windows and doors would be closed in upstate New York for the majority of the year. Therefore, the windows and doors were closed for these measurements in an attempt to approximate a year-round average. The alpha counts and other necessary parameters were input into the computer program to result in the calculated concentrations found in Table 6. These sample runs can be found in Appendix E. Measurements were also made in the upstairs living area but were disregarded due to counting fluctuations and screen problems.

The second home, Home B, also had a finished, partially underground basement. This basement consisted of a living area and a laundry/storage room. The radon was determined to be entering into the laundry/storage room. In this section, there was poured concrete over the existing rock and the block wall foundation was visible. This home did not have central air conditioning and the windows were usually left open in the summer. The windows in the upstairs bedrooms had been left open on the day the following measurements were taken, but the basement windows were closed. Again, all measurements were taken in August of 1988.

Four filter/screen measurements and 11 radon gas measurements were taken in the basement laundry room during the morning hours. The pylon, condensation nuclei monitor, and both vacuum pumps were set up near the area where clothing would be handled with the detectors placed in a lower background area. The filter and gas averages are shown in Table 7. Four filter/screen measurements and eight radon gas measurements were taken in the basement living area in the afternoon. In these samples, with the assumed 50% equilibrium, the WL computed from the radon gas average was larger than the radon progeny average. The equilibrium ratio can vary slightly and result in less accurate working level calculations from the radon gas measurements. Therefore, the radon progeny measurements were used for the lung dose calculations.

Four filter/screen measurements and 10 radon gas measurements were also taken in the upstairs living area which adjoins the kitchen. Again, the bedroom windows had been left open previous to and during sampling. The results of the radon gas average and radon progeny average are comparable. As shown in Table 7, the averages of the unattached fractions are approximately that of a typical home as defined by the NCRP. In addition, the particle concentrations in Home B were generally

TABLE 7 HOME B MEASUREMENT RESULTS

Sample Number	Filter WL	Screen WL	Unattached Fraction	Location	Average Radon WL
1	3.47 E-2	1.20 E-3	0.0689	LAUNDRY	------
2	3.07 E-2	8.67 E-4	0.0566	LAUNDRY	------
3	2.28 E-2	7.87 E-4	0.0689	LAUNDRY	------
4	1.97 E-2	9.06 E-4	0.0920	LAUNDRY	------
AVG	2.70 E-2	9.40 E-4	0.0696	LAUNDRY	2.50 E-2
5	1.19 E-2	6.78 E-4	0.1143	LIVING	------
6	1.16 E-2	4.90 E-4	0.0846	LIVING	------
7	1.06 E-2	4.48 E-4	0.0849	LIVING	------
8	9.36 E-3	2.33 E-4	0.0497	LIVING	------
AVG	1.09 E-2	4.62 E-4	0.0848	LIVING	2.31 E-2
9	2.14 E-2	6.94 E-4	0.0649	UPSTAIRS	------
10	1.77 E-2	3.09 E-4	0.0349	UPSTAIRS	------
11	6.10 E-3	4.06 E-4	0.1332	UPSTAIRS	------
12	8.39 E-3	4.91 E-4	0.1171	UPSTAIRS	------
AVG	1.34 E-2	4.75 E-4	0.0709	UPSTAIRS	1.25 E-2

higher than in Home A, explaining the lower unattached fractions. The majority of these measurements were in the range specified by Figure 14. Only one measurement was atypical due to cooking activities using a gas burner which resulted in a particle concentration of 250,000 particles per cc. The computer runs for the Home B measurements can be found in Appendix E.

As shown in Tables 6 and 7, the measurement results for both homes generally decrease as time progresses. The highest measurements were found in the morning hours, indicating that still higher measurements can be obtained in the very early morning hours. A few of the measurements were taken in the afternoon when levels were generally the lowest. Therefore, it is possible that these measurements are lower than the average levels found in this home.

4.2 LUNG DOSE CALCULATIONS

In calculating the lung dose equivalents for the two New York families, the present recommended quality factor for alphas, 20, was used (NCRP-93,1987). These lung dose equivalents are shown in Table 8. They were calculated using the radon progeny concentrations and corresponding unattached fractions shown in Tables 6 and 7 and the equations found in Table 4.

As shown in Table 8, Home A consists of two adults and a two-year-old child. Only basement data were used and a typical particle size distribution of 0.1 micron median diameter with a geometric standard deviation of 2 was assumed since the particle distribution was not measured. The age-dependency of these lung doses is especially obvious in the average lung dose equivalent of 44 rem per year for the two-year-old. This value is approximately twice that of an adult in Home A (22 rem per year). The dose equivalents presented for Home A would have been more representative of an annual average if upstairs and winter measurements were available.

Also shown in Table 8, Home B consists of two adults and two preteen children. Again, a typical particle size distribution was assumed and the age-dependency of these lung doses is demonstrated in the table. The average lung dose for an adult in Home B is 9 rem per year as compared to a value of 12 rem per year for a twelve-year-old and almost 14 rem per year for an eight-year-old in Home B.

TABLE 8   AGE-DEPENDENT LUNG DOSES IN TWO NEW YORK HOMES

Home	Age	Dose 1	Dose 2	Dose 3	Dose 4	Avg. Dose
A	Adult	14.87	20.33	34.51	16.74	21.61
A	2	31.94	42.20	68.27	34.60	44.26
B	Adult-L	17.87	13.85	11.74	12.45	13.98
B	Adult-B	8.86	6.90	6.32	3.91	6.50
B	Adult-U	10.59	6.07	5.13	6.36	7.04
B	Adult-A	12.44	8.94	7.73	7.57	9.17
B	12-L	23.54	18.35	15.47	16.27	18.41
B	12-B	11.52	9.03	8.27	5.20	8.51
B	12-U	13.97	8.16	6.64	8.27	9.26
B	12-A	16.34	11.80	10.13	9.91	12.06
B	8-L	27.12	21.24	17.82	18.63	21.20
B	8-B	13.14	10.36	9.49	6.04	9.76
B	8-U	16.12	9.56	7.55	9.42	10.66
B	8-A	18.79	13.72	11.62	11.36	13.87

Note: All doses equivalents are in rem per year. For Home B results; L = laundry room, B = basement living area, U = upstairs living area, and A = average of all areas.

5 DISCUSSION AND RECOMMENDATIONS

A specific method has been presented to assess the radon progeny hazards in the home. Lung dose equations for different aged individuals have been formulated using an age-dependent lung model by D. Crawford-Brown. These equations are unique in the respect that no similar equations have been developed which apply to a variety of ages and particle size distributions. These equations have been simplified and require only three parameters: the unattached fraction, the radon progeny concentration in working levels, and the particle size distribution.

A method for measuring the radon progeny concentration and unattached fraction also has been applied to two New York homes. The gross alpha counts detected from a wire screen and a membrane filter were input into a computer program which implements the modified Tsivoglou technique to obtain radon progeny concentrations and working levels. The concentrations found in these homes were approximately at the EPA action level of 4 pCi/l (0.02 WL). Home A had a slightly higher concentration than 4 pCi/l and Home B had a slightly lower concentration. The unattached fraction measurements were determined by a wire screen method from A. George. The majority of the unattached fraction measurements were comparable to 0.07, considered typical by the NCRP. Some unattached fraction measurements were larger due to lower particle concentrations in one home. Using these measurements in the Equation 1 yields estimates of annual lung dose equivalent for the two New York families, under the assumption of a typical particle size distribution. Doses under any other particle size distribution could be calculated using Equation 2 and the values for A and B found in Table 4. The most obvious increase in these lung dose results due to age-dependency was for a two-year-old in Home A receiving 44 rem per year to the lung. This value is approximately twice that of an adult in Home A. This age-dependency also is demonstrated in Home B where the lung doses of the children (ages eight and twelve) are approximately 1.5 and 1.3 times, respectively, that of an adult in this home.

Home A also consists of a smoker, who according to the Committee on the Biological Effects of Ionizing Radiation (BEIR IV, 1988) experiences even higher lung cancer risks. A female adult nonsmoker experiences a lifetime excess risk of lung-cancer mortality of approximately 0.00427 for the annual exposure rate found in Home A, 1.25 WLM per year (0.025 WL for 1 year). By comparison, an adult male smoker at this exposure rate has a corresponding excess risk of 0.073. Home B consists of two nonsmoking adults with lifetime excess risks of lung-cancer mortality of approximately 0.0052 (male) and 0.00292 (female) for the annual exposure rate found in Home B, 0.85 WLM per year (0.017 WL for 1 year). These risks were obtained from Table 2-4 in BEIR IV. This table gives the exposure rate in WLM per year with the corresponding lifetime risk of lung-cancer mortality specific to gender and smoking status. The excess risks were derived by subtracting the lifetime risks at an exposure rate of 0 WLM per year from the lifetime risks corresponding to the exposure rate of interest. Since the table only gave specific exposure rates, interpolation was necessary to obtain the lifetime risks corresponding to the exposure rates of interest.

In summary, lung dose equations were formulated in this report and apply to any radon progeny concentration and unattached fraction for a variety of ages and particle size distributions. A method also has been presented to obtain the radon progeny concentration and unattached fraction measurements in the home. Annual lung doses were calculated for two New York families as an example of this method. Recommendations for improving measurements and dose calculations include:

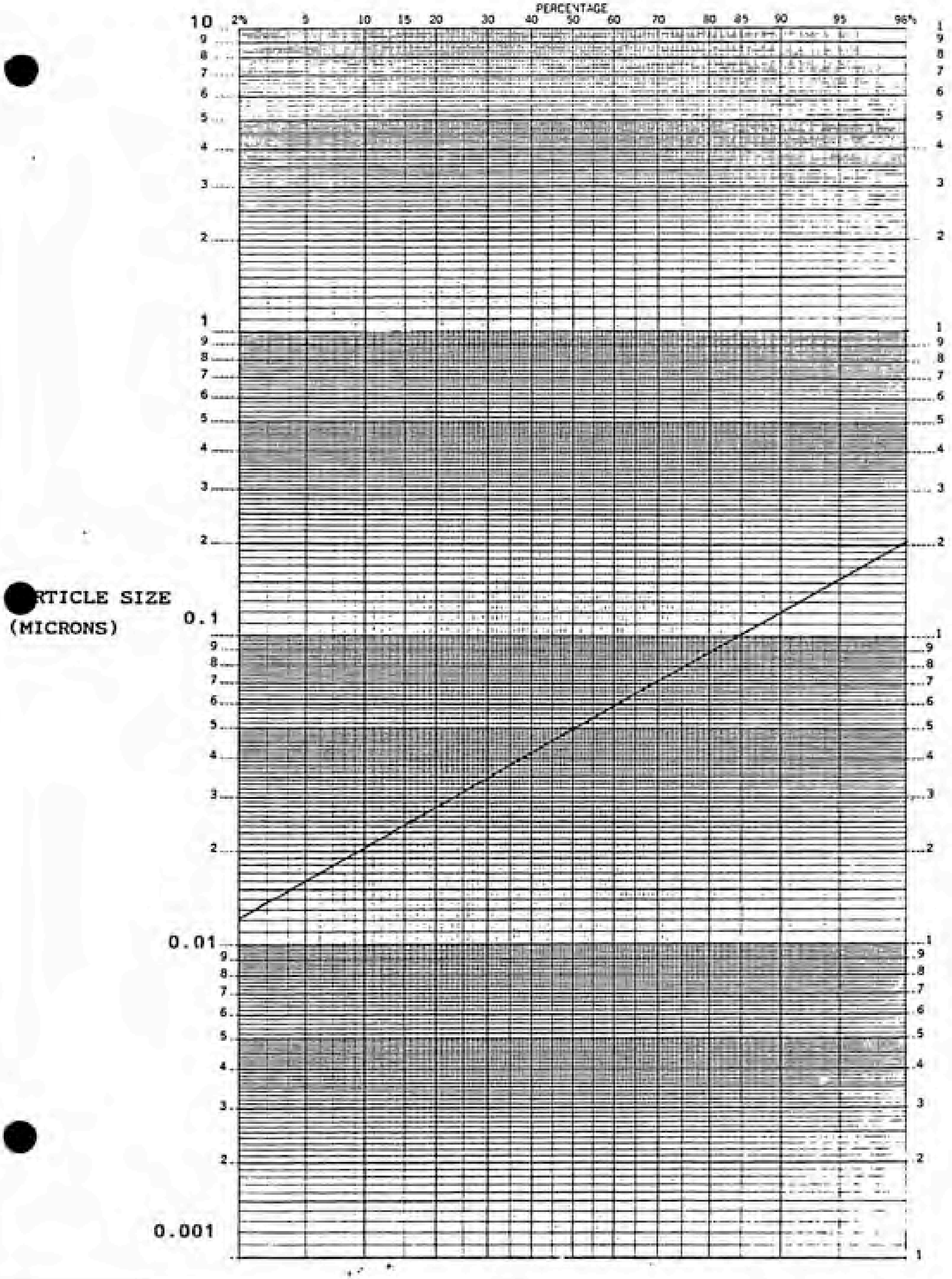
1. Make winter or long-term measurements in addition to summer measurements to determine a more accurate average radon progeny concentration.
2. Use several wire screens for the unattached fraction measurements due to the difficulty in removing the radon progeny from the mesh.
3. Measure the particle size distribution with an instrument such as a cascade impactor or a diffusion battery to determine which of the values for A and B in Table 4 are most representative of the environment sampled. If these measurements are not available, use the equations corresponding to 0.1 micron median diameter and a geometric standard deviation of 2.

4. When the unattached fraction is not measured, use the NCRP recommended value of 0.07 which was also closely approximated in the Home B results.
5. If possible, use easily portable instruments for measuring gross alpha counts to avoid the awkwardness of nimbin electronics.
6. Use alpha spectroscopy instrumentation if available to determine alpha counts, since this gives a separate determination of the rate of decay for RaA and RaC', yielding a more accurate detection of the activity of each progeny.
7. To use the NCRP-78 factors for lung dose per unit radon progeny concentration corresponding to gender-specific environment exposures (see page 17), multiply the lung doses obtained by the equations in this report by 1.2 for women and 1.4 for men.

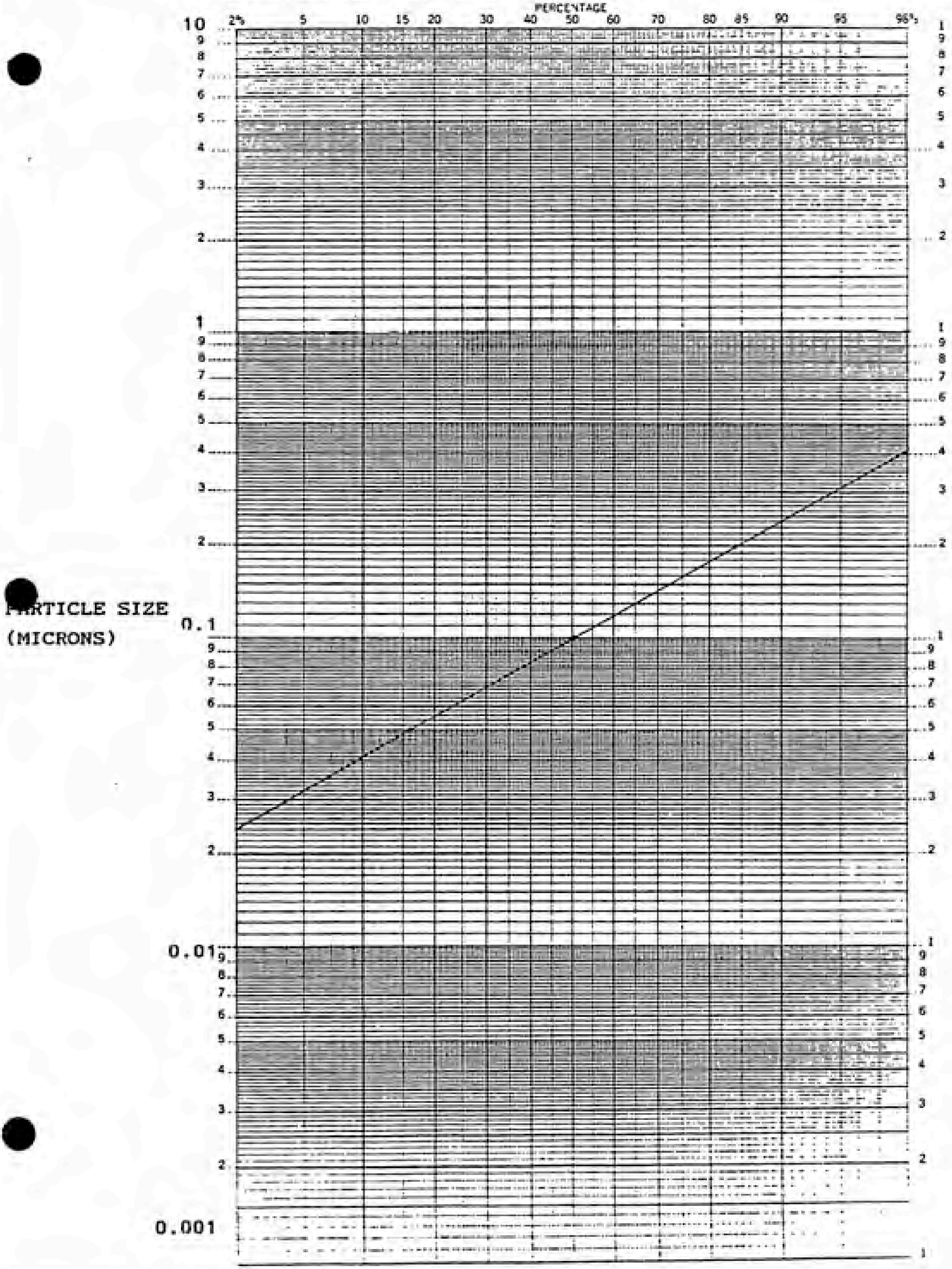
APPENDIX A

CUMULATIVE PLOTS OF PARTICLE SIZE DISTRIBUTIONS

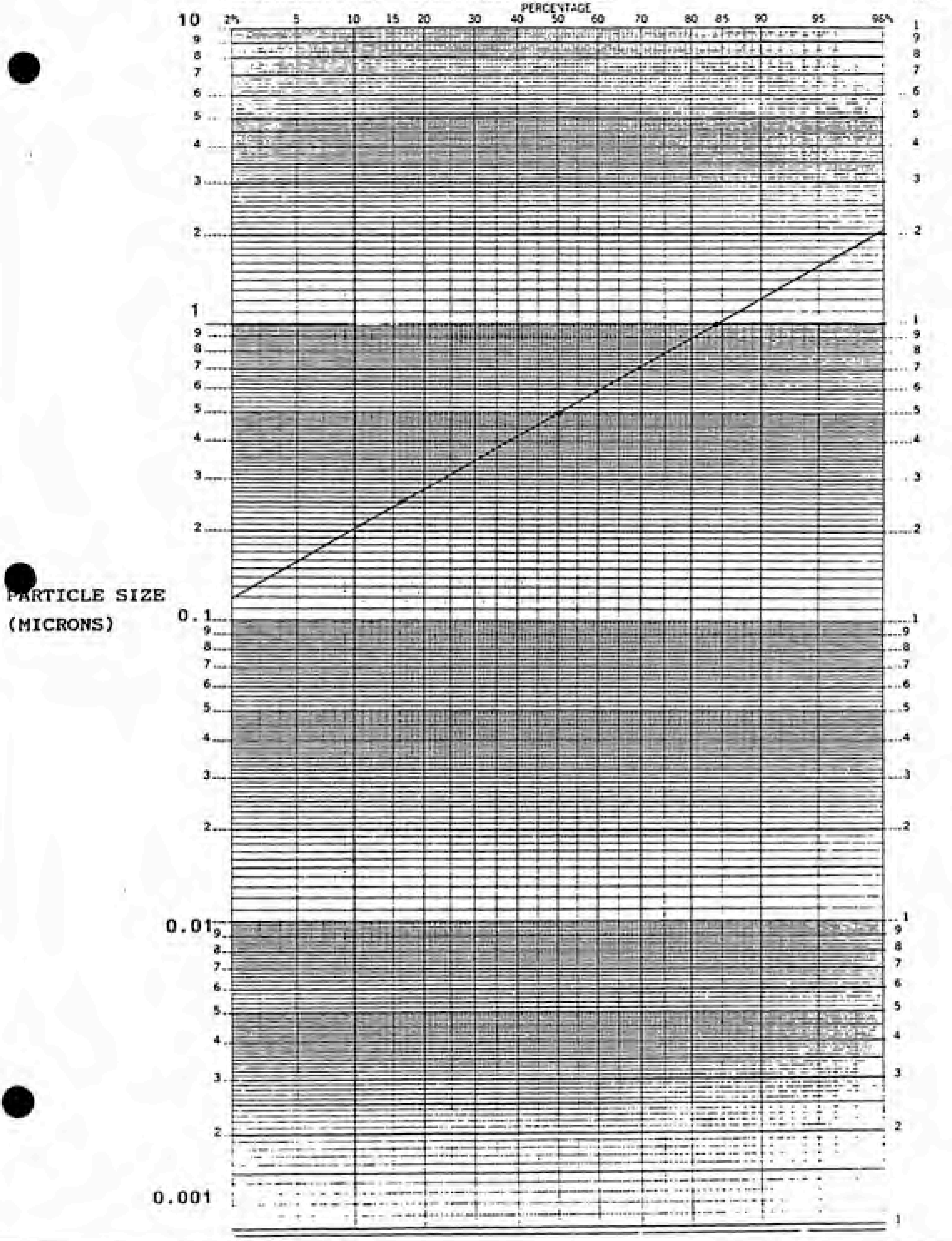
DISTRIBUTION: 0.05 MEDIAN, 2 GSD



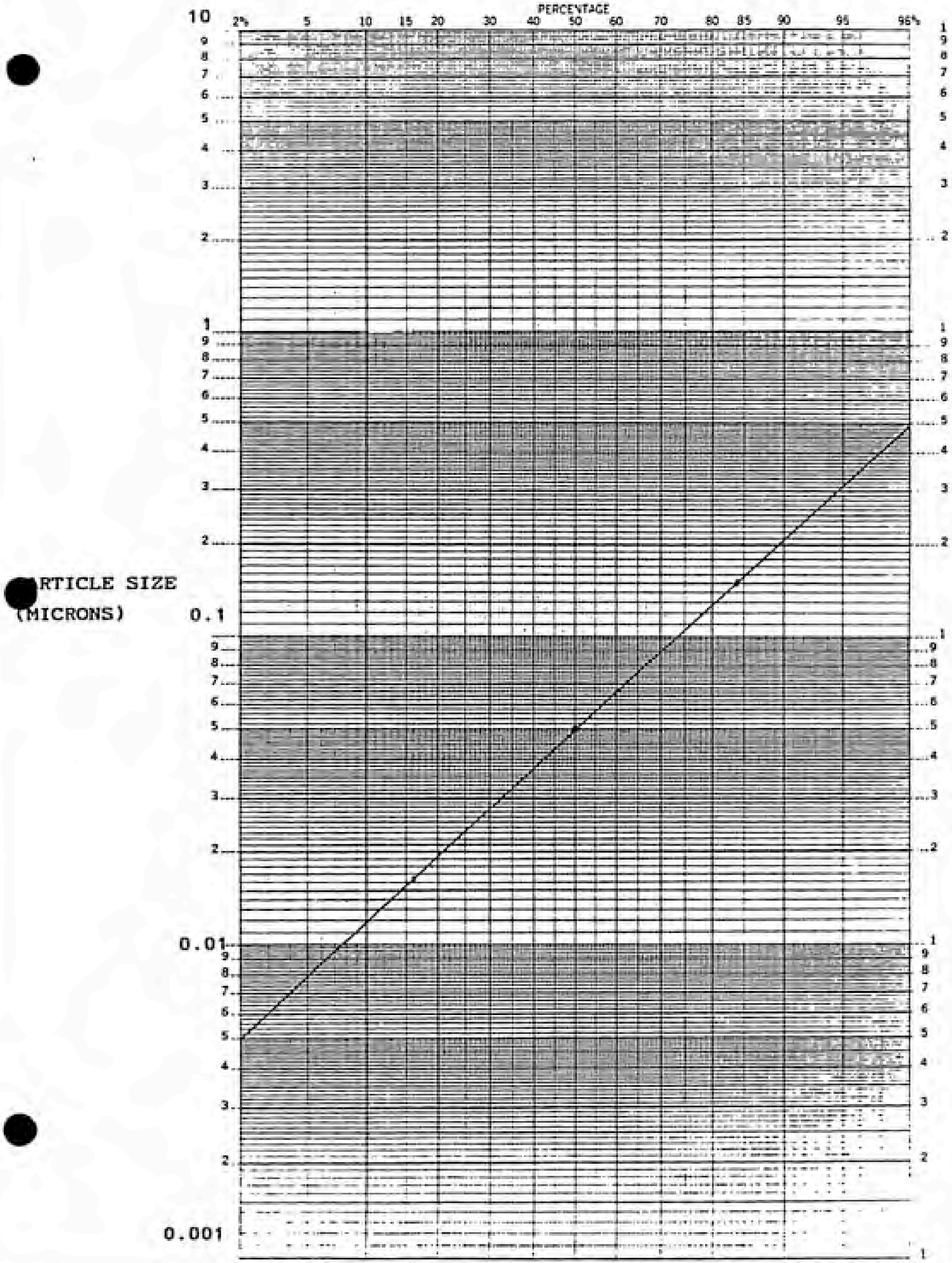
DISTRIBUTION: 0.1 MEDIAN. 2 GSD



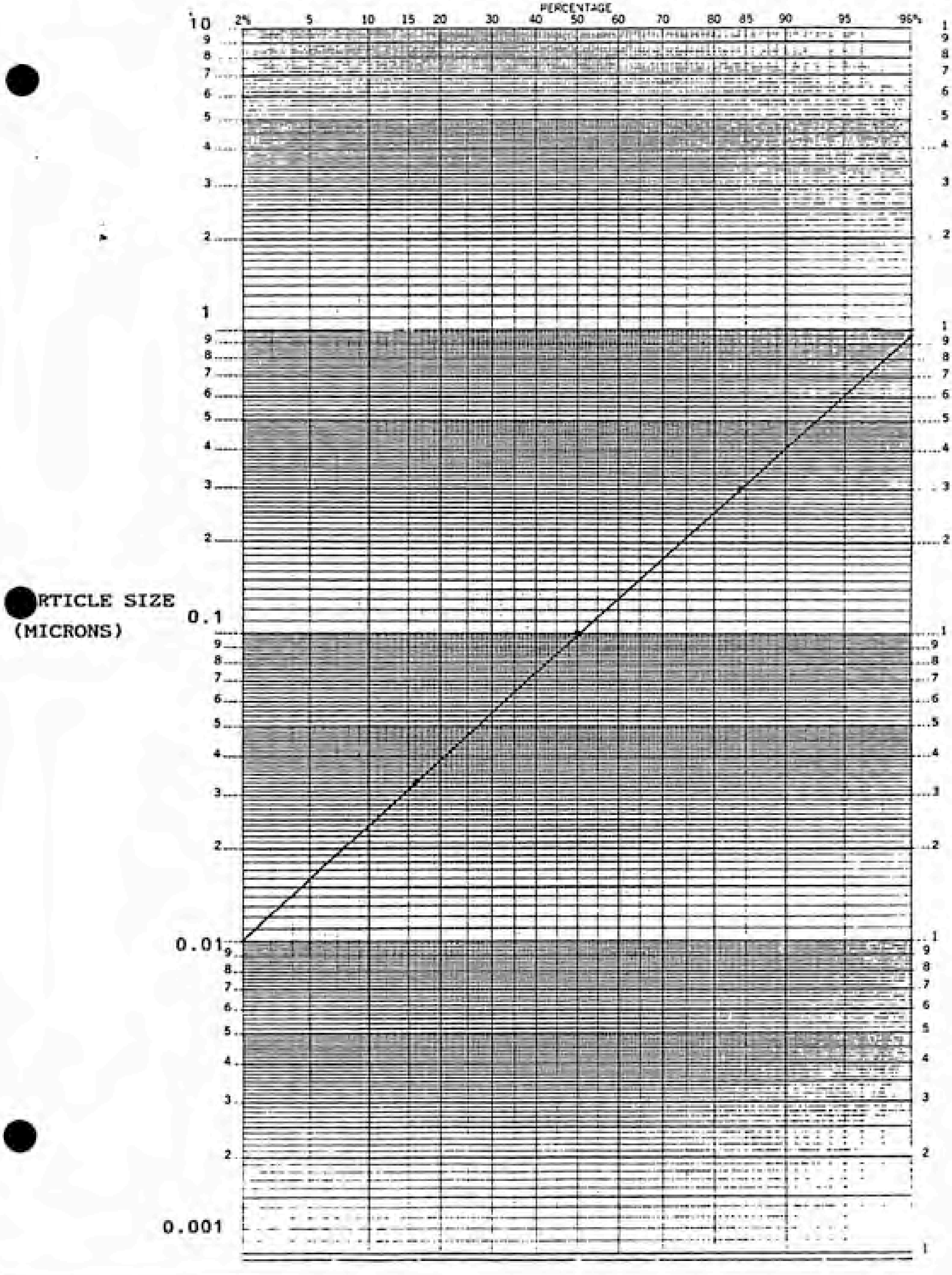
DISTRIBUTION: 0.5 MEDIAN, 2 GSD



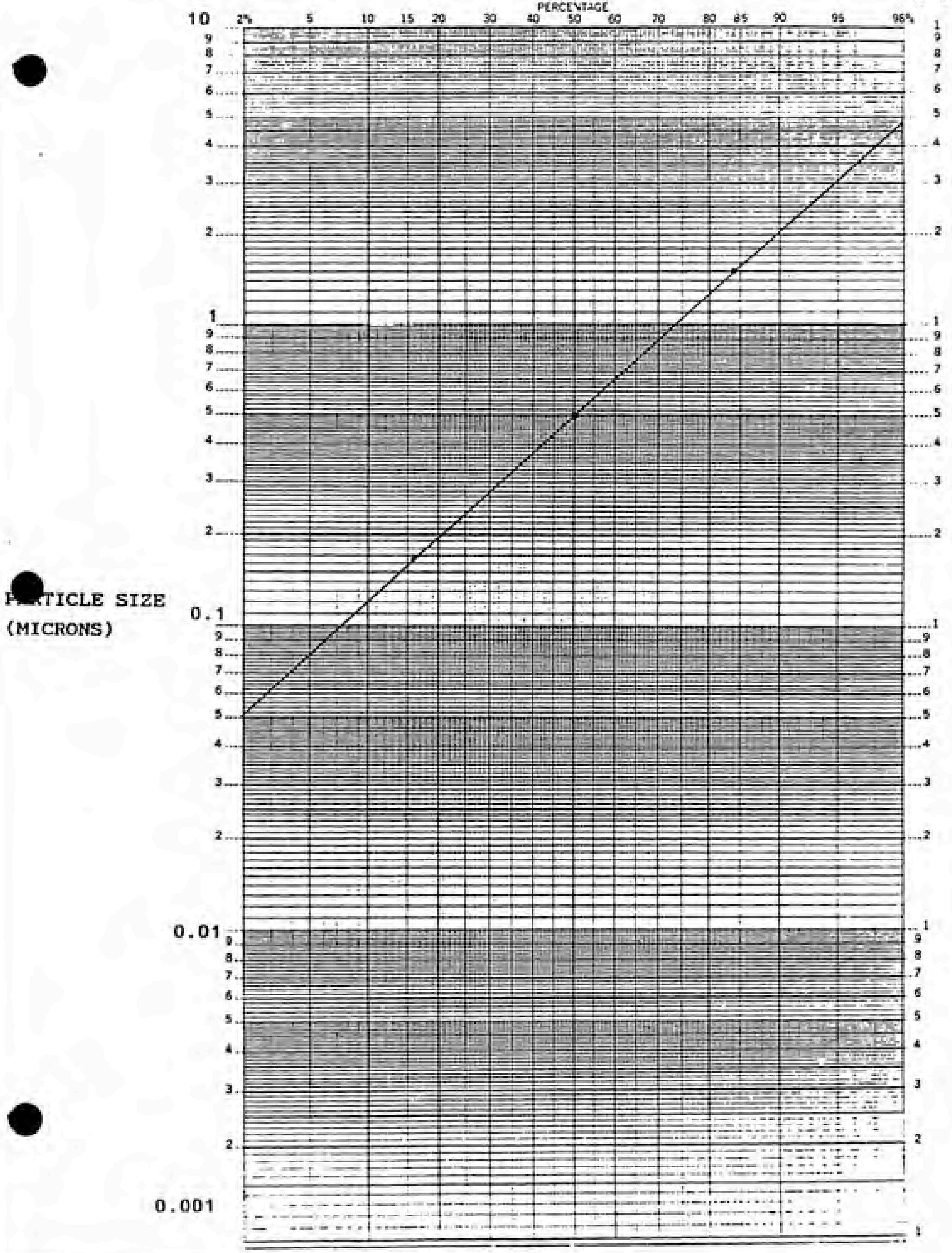
DISTRIBUTION: 0.05 MEDIAN, 3 GSD



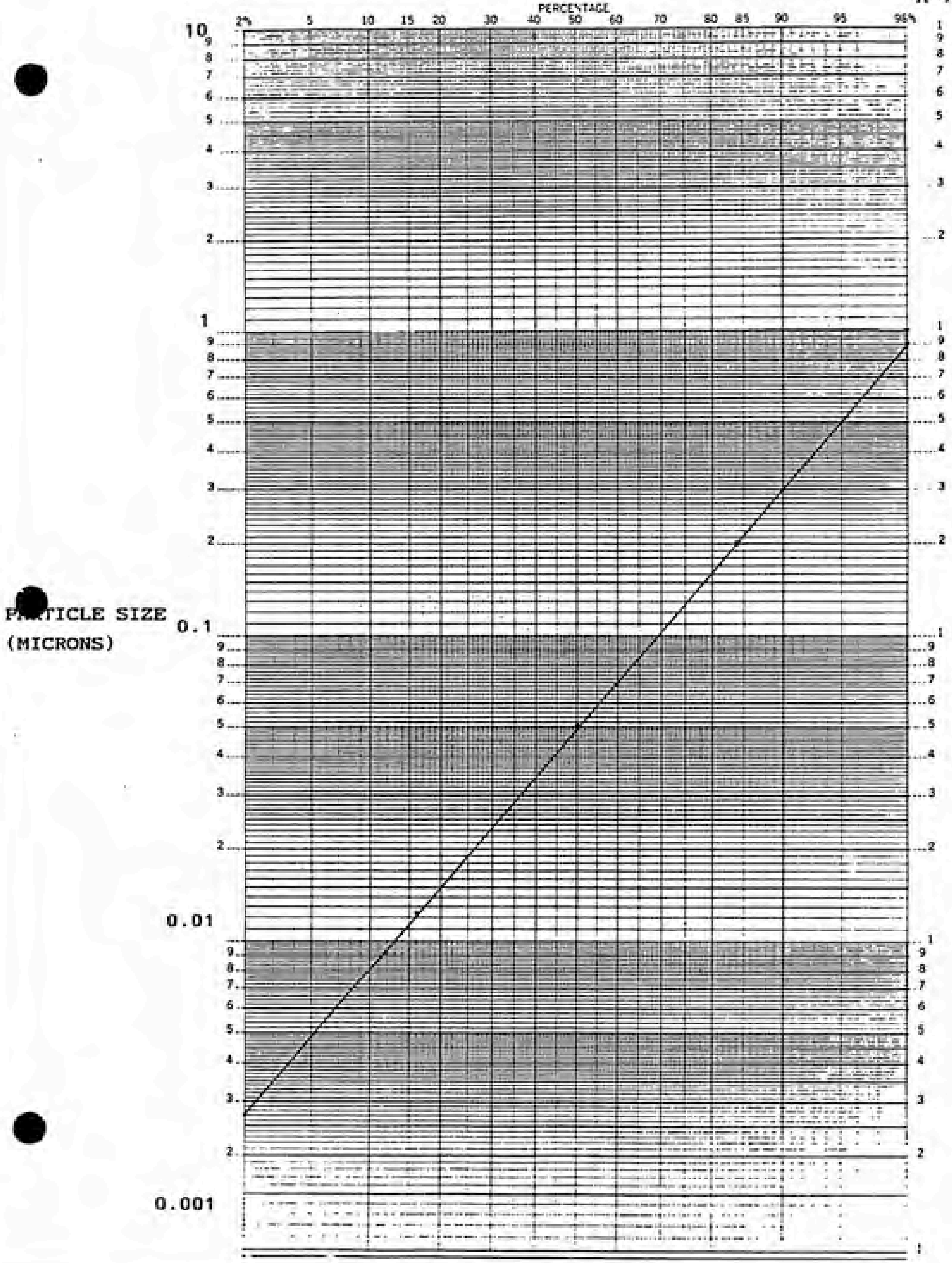
DISTRIBUTION: 0.1 MEDIAN, 3 GSD



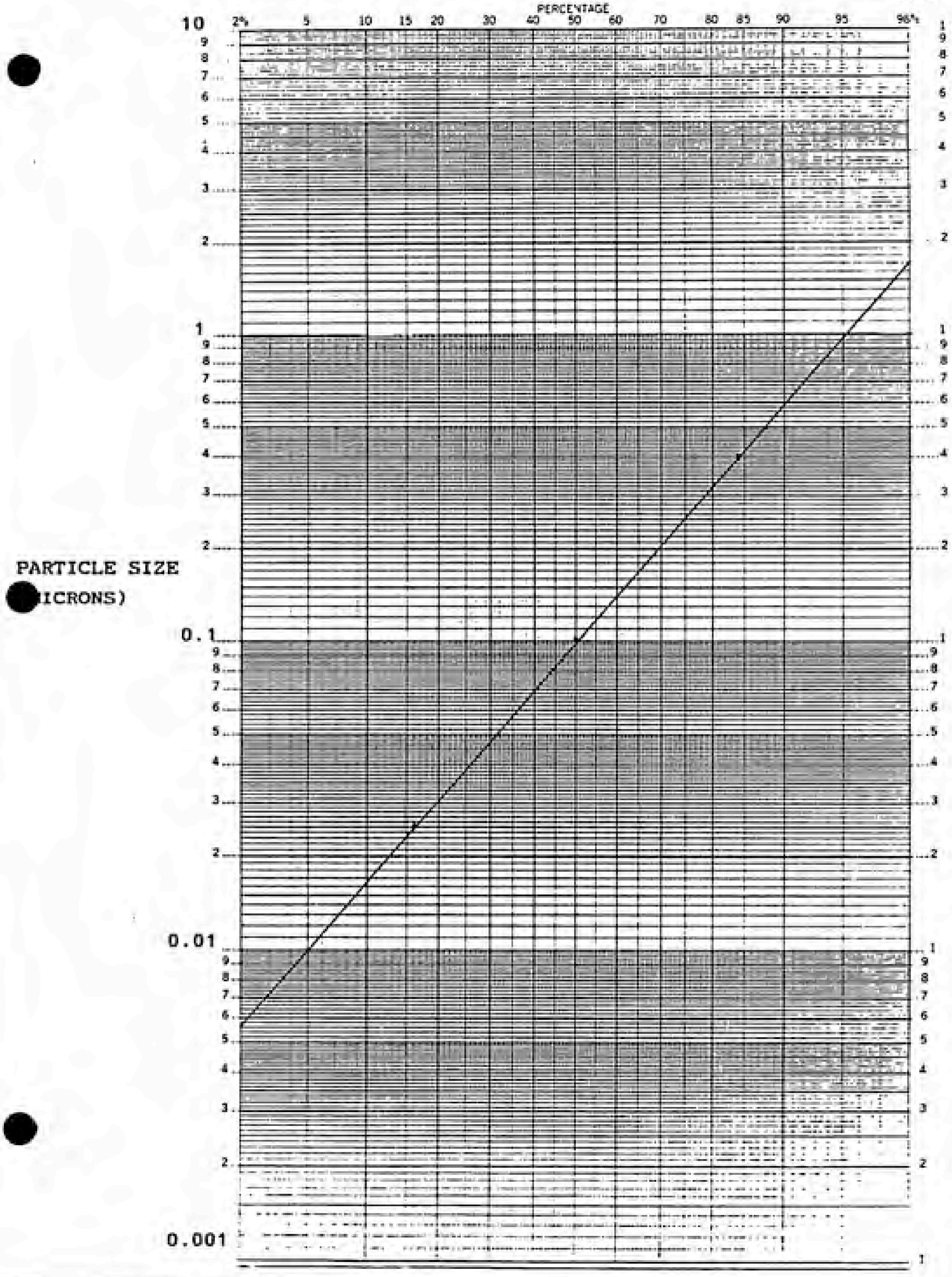
DISTRIBUTION: 0.5 MEDIAN, 3 GSD



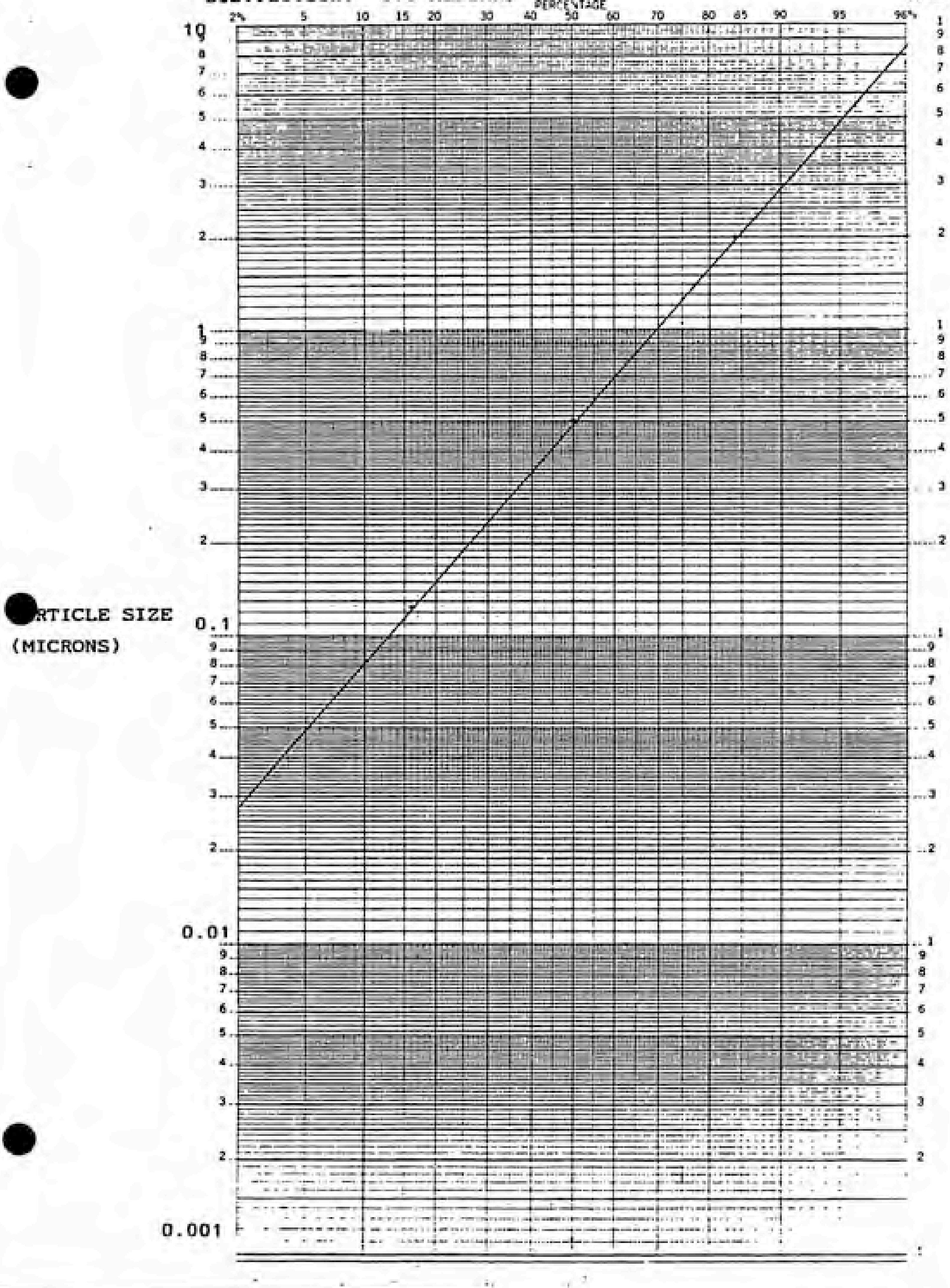
DISTRIBUTION: 0.05 MEDIAN, 4 GSD



DISTRIBUTION: 0.1 MEDIAN, 4 GSD



DISTIBUTION: 0.5 MEDIAN, 4 GSD



6.2 APPENDIX B: FACTORS REQUIRED FOR EQUATION 1

AGE	VALUE FOR $D_{f,a}$
32	3.7271 E 7
16	3.1285 E 7
12	2.6166 E 7
8	2.0937 E 7
2	1.1130 E 7
0	5.2286 E 6

DISTRIBUTION (MEDIAN, GSD)	AGE	VALUE FOR $\sum_i f_i, D_{i,a}$
0.05, 4	32	2.0989 E 6
	16	1.8681 E 6
	12	1.6202 E 6
	8	1.3930 E 6
	2	8.3733 E 5
	0	2.8997 E 5
0.10, 4	32	2.7312 E 6
	16	2.6340 E 6
	12	2.3441 E 6
	8	2.1393 E 6
	2	1.3627 E 6
	0	3.5340 E 5
0.50, 4	32	1.3504 E 7
	16	1.3305 E 7
	12	1.1308 E 7
	8	9.7379 E 6
	2	5.1621 E 6
	0	1.2428 E 6

DISTRIBUTION (MEDIAN, GSD)	AGE	VALUE FOR $\sum_i f_i, D_{i,a}$
0.05, 3	32	1.5394 E 6
	16	1.3423 E 6
	12	1.1539 E 6
	8	9.6875 E 5
	2	5.6126 E 5
	0	2.1536 E 5
0.10, 3	32	1.7396 E 6
	16	1.6269 E 6
	12	1.4570 E 6
	8	1.3190 E 6
	2	8.5605 E 5
	0	2.3875 E 5
0.50, 3	32	1.0262 E 7
	16	1.0383 E 7
	12	9.0974 E 6
	8	8.2145 E 6
	2	4.7960 E 6
	0	1.0867 E 6

DISTRIBUTION (MEDIAN, GSD)	AGE	VALUE FOR $\sum_{i} f_{i}, D_{i,a}$
(0.05, 2)	32	1.3168 E 6
	16	1.1394 E 6
	12	9.5703 E 5
	8	7.8267 E 5
	2	4.3242 E 5
	0	1.8579 E 5
(0.10, 2)	32	1.1792 E 6
	16	1.0783 E 6
	12	9.4193 E 5
	8	8.2570 E 5
	2	5.1472 E 5
	0	1.6647 E 5
(0.50, 2)	32	6.6555 E 6
	16	6.7293 E 6
	12	6.1395 E 6
	8	5.8039 E 6
	2	3.8081 E 6
	0	8.0456 E 5

APPENDIX C: COMPUTER CODE FOR MODIFIED TSIVOGLOU TECHNIQUE

```
2 REM       ****************************************
3 REM       *                                      *
4 REM       *       POPE\YANG.BAS                  *
5 REM       *                                      *
6 REM       *                                      *
7 REM       *                                      *
8 REM       ****************************************
9 REM
10 DIM F(12),FF(9),K(9)
15 PRINT "Enter sampling time in minutes"
20 INPUT ST
25 PRINT
75 PRINT "Enter sampling flow rate in liters per minute"
80 INPUT V
85 PRINT
90 PRINT "Enter sampling flow rate standard deviation"
95 INPUT U
100 PRINT
102 PRINT "Enter detector efficiency"
104 INPUT Y
106 PRINT
108 PRINT "Enter detector efficiency standard deviation"
110 INPUT E
111 REM THIS PART DETERMINES ERROR DUE TO BKG. SUBTRACTION
112 PRINT
114 FOR I=1 TO 3
116 PRINT "Enter total counts ";I
118 INPUT TC(I)
120 PRINT
122 PRINT "Enter duration of count in minutes"
124 INPUT D(I)
126 CE(I) = SQR(TC(I))/D(I)
132 PRINT  "Enter total background counts ";I
134 INPUT BC(I)
136 BE(I) = SQR(BC(I))/D(I)
140 B(I) = SQR(BE(I)^2+CE(I)^2)
142 C(I) = TC(I) - BC(I)
146 NEXT I
147 REM
148 REM  THIS PART DETERMINES THE START AND STOP TIMES FOR
149 REM  DIFFERENT COUNTING INTERVALS.
150 PRINT "Enter count start time (min. after end of
sampling)"
152 PRINT "for counts 1, 2, and 3"
154 INPUT T1,T3,T5
160 T2 = T1 + D(1)
162 T4 = T3 + D(2)
164 T6 = T5 + D(3)
168 REM
169 REM
170 REM  THIS PART OF THE PROGRAM DEFINES THE PARAMETERS FOR
171 REM  THE CONCENTRATION FORMULAS.
172 REM
173 REM
```

```
200 L1 = LOG(2)/3.05
210 L2 = LOG(2)/26.8
220 L3 = LOG(2)/19.7
230 H1 = 1/L1
240 H2 = 1/L2
250 H3 = 1/L3
270 G1 = EXP(-ST/H1)
280 G2 = EXP(-ST/H2)
290 G3 = EXP(-ST/H3)
300 G4 = EXP(-T1/H1)
310 G5 = EXP(-T1/H2)
320 G6 = EXP(-T1/H3)
330 G7 = EXP(-T2/H1)
340 G8 = EXP(-T2/H2)
350 G9 = EXP(-T2/H3)
360 G10 = EXP(-T3/H1)
370 G11 = EXP(-T3/H2)
380 G12 = EXP(-T3/H3)
381 G13 = EXP(-T4/H1)
382 G14 = EXP(-T4/H2)
383 G15 = EXP(-T4/H3)
384 G16 = EXP(-T5/H1)
385 G17 = EXP(-T5/H2)
386 G18 = EXP(-T5/H3)
387 G19 = EXP(-T6/H1)
388 G20 = EXP(-T6/H2)
389 G21 = EXP(-T6/H3)
390 F(1) = 1 - G1
400 F(2) = 1 - G2
410 F(3) = 1 - G3
420 F(4) = G4 - G7
430 F(5) = G5 - G8
440 F(6) = G6 - G9
450 F(7) = G10 - G13
460 F(8) = G11 - G14
470 F(9) = G12 - G15
480 F(10) = G16 - G19
490 F(11) = G17 - G20
500 F(12) = G18 - G21
550 FF(1) = F(1)*F(4)
630 FF(2) = F(1)*F(7)
640 FF(3) = F(1)*F(10)
650 FF(4) = F(2)*F(5)
660 FF(5) = F(2)*F(8)
670 FF(6) = F(2)*F(11)
680 FF(7) = F(3)*F(6)
690 FF(8) = F(3)*F(9)
700 FF(9) = F(3)*F(12)
702 K(1) = 44*FF(1)+1610*FF(4)-911*FF(7)
704 K(2) = 12500*FF(4)-6770*FF(7)
706 K(3) = 1790*FF(7)
708 K(4) = 44*FF(2)+1610*FF(5)-911*FF(8)
710 K(5) = 12500*FF(5)-6770*FF(8)
712 K(6) = 1790*FF(8)
```

```
714 K(7) = 44*FF(3)+1610*FF(6)-911*FF(9)
716 K(8) = 12500*FF(6)-6770*FF(9)
718 K(9) = 1790*FF(9)
719 REM
720 REM  THE K VARIABLES ARE MATRIX INVERTED AND MULTIPLIED
721 REM  IN A LATTER PART OF THE PROGRAM.  THE DD VARIABLES
722 REM  ARE PART OF THE ERROR PROPAGATION FORMULA AND THE
723 REM  SS VARIABLES ARE THE ERROR FORMULAS FOR THE
CONCENTRATION
724 REM  STANDARD DEVIATIONS.
725 REM
726 REM
750 DD(1) = C(1)^2*(B(1)^2/(C(1)^2)+E^2/(Y^2)+U^2/(V^2))
760 DD(2) = C(2)^2*(B(2)^2/(C(2)^2)+E^2/(Y^2)+U^2/(V^2))
770 DD(3) = C(3)^2*(B(3)^2/(C(3)^2)+E^2/(Y^2)+U^2/(V^2))
790 GOSUB 4000
810 SS(1) =
SQR(INV(1,1)^2*DD(1)+INV(1,2)^2*DD(2)+INV(1,3)^2*DD(3))/(Y*V)

820 SS(2) =
SQR(INV(2,1)^2*DD(1)+INV(2,2)^2*DD(2)+INV(2,3)^2*DD(3))/(Y*V)

830 SS(3) =
SQR(INV(3,1)^2*DD(1)+INV(3,2)^2*DD(2)+INV(3,3)^2*DD(3))/(Y*V)

848 REM
849 REM
850 REM  THE CN VARIABLES USE THE INVERTED MATRIX SOLUTIONS
851 REM  AND DIVIDES THEM BY THE EFFICIENCY AND FLOW RATE.
852 REM  WORKING LEVELS ARE THEN CALCULATED FROM THESE
CONCENTRATIONS.
853 REM
854 REM
1570 CN(1) = Q3(1,1)/(V*Y)
1580 CN(2) = Q3(2,1)/(V*Y)
1590 CN(3) = Q3(3,1)/(V*Y)
1600 WL = .00103*CN(1) + .00507*CN(2) + .00373*CN(3)
2000 LPRINT "Sampling time in minutes = ";ST;""
2010 LPRINT
2020 LPRINT "Count duration in minutes for count 1 =
";D(1);""
2030 LPRINT
2040 LPRINT "Count duration in minutes for count 2 =
";D(2);""
2050 LPRINT
2060 LPRINT "Count duration in minutes for count 3 =
";D(3);""
2070 LPRINT
2080 LPRINT "Sampling flow rate in liters per minute and its
standard"
2090 LPRINT "deviation = ";V;" +- ";U;""
2100 LPRINT
2130 LPRINT
```

```
3010 LPRINT "Detector efficiency and its standard deviation
="
3020 LPRINT " ";Y;" +- ";E;""
3030 LPRINT
3040 FOR I=1 TO 3
3050 LPRINT "Total counts = ";TC(I);""
3060 LPRINT
3130 NEXT I
3220 LPRINT
3230 LPRINT "RaA concentration in pCi/l and its standard
deviation ="
3240 LPRINT " ";CN(1);" +- ";SS(1);""
3250 LPRINT
3260 LPRINT "RaB concentration in pCi/l and its standard
deviation="
3270 LPRINT " ";CN(2);" +- "SS(2);""
3280 LPRINT
3290 LPRINT "RaC concentration in pCi/l and its standard
deviation="
3300 LPRINT " ";CN(3);" +- "SS(3);""
3310 LPRINT
3320 LPRINT "Working levels of radon = ";WL;""
3500 GOTO 9900
3690 REM
3695 REM
3700 REM  THE K VARIABLES ARE INVERTED AND ARE CALLED THE
"AA" MATRIX.
4000  AA(1,1) = K(1)
4010  AA(1,2) = K(2)
4020  AA(1,3) = K(3)
4030  AA(2,1) = K(4)
4040  AA(2,2) = K(5)
4050  AA(2,3) = K(6)
4060  AA(3,1) = K(7)
4070  AA(3,2) = K(8)
4080  AA(3,3) = K(9)
4090  M = 3
8000  REM
8002  REM
8004  REM
8006  REM  This subroutine inverts AA(M,M) to
8008  REM  yield the inverted matrix, INV(M,M)
8009  REM
8010  FOR I = 1 TO M
8015  INV(I,I) = 1
8020  NEXT I
8025  FOR I = 1 TO M
8030  TT1 = AA(I,I)
8035  FOR J = 1 TO M
8040  AA(I,J) = AA(I,J) / TT1
8045  INV(I,J) = INV(I,J) / TT1
8050  NEXT J
8055  FOR J = 1 TO M
8060  IF J = I THEN GOTO 8090
```

```
8065  TT2 = AA(J,I)
8070  FOR K = 1 TO M
8075  AA(J,K) = AA(J,K) - (AA(I,K) * TT2)
8080  INV(J,K) = INV(J,K) - (INV(I,K) * TT2)
8085  NEXT K
8090  NEXT J
8095  NEXT I
9000  REM
9005  REM  This portion of the program multiplies the
matricies
9010  REM  Q3(M,W) = Q2(M,N) x Q1(N,W)
9015  REM  which equals CONCENTRATIONS = K VARIABLES * NET
COUNTS
9020  M = 3
9030  W = 1
9040  N = 3
9050  FOR I = 1 TO M
9060  FOR J = 1 TO N
9070  Q2(I,J) = INV(I,J)
9080  NEXT J
9090  NEXT I
9100  Q1(1,1) = C(1)
9110  Q1(2,1) = C(2)
9120  Q1(3,1) = C(3)
9500  FOR I = 1 TO M
9502  FOR J = 1 TO M
9503 Q3(I,J) = 0
9504  NEXT J
9505  NEXT I
9510  FOR K = 1 TO M
9520  FOR I = 1 TO W
9540  FOR J = 1 TO N
9560 Q3(K,I) = Q3(K,I) + Q2(K,J) * Q1(J,I)
9580  NEXT J
9600  NEXT I
9620  NEXT K
9640  RETURN
9700  REM    THIS PROGRAM USES SIMPLIFIED EQUATIONS FROM YANG
9702  REM    FU--CHIA AND TANG CHIA--YONG WHICH CAN BE USED FOR
9704  REM    ANY SAMPLING AND COUNTING TIME COMBINATIONS.  THE
9706  REM    COEFFICIENTS FROM THE INVERTED MATRIX EQUATIONS
9708  REM    HAVE BEEN VERIFIED WITH THE COEFFICIENTS FROM J.
9710  REM    THOMAS AND A. SCOTT, BOTH OF WHICH USE A MODIFIED
9712  REM    TSIVOGLOU METHOD.  THIS APPROACH IS THE SAME EXCEPT
9714  REM    THE EQUATIONS ARE GENERIC AND SIMPLIFIED SO THAT ANY
9716  REM    CUNTING AND SAMPLING TIMES CAN BE USED.  THE ERROR
9718  REM    PROPAGATION FORMULAS ARE STANDARD AND WERE TAKEN
9720  REM    FROM WORK DONE BY D. MARTZ.
9900  END
```

6.4 APPENDIX D: EFFICIENCY DETERMINATION AND ERROR PROPAGATION

SOURCE INFORMATION

Radionuclide: Am-241
Activity: 4.753 E 2 disintegrations per second (07-01-80)
Half-life: 432.2 years

SOURCE ACTIVITY ON CALIBRATION DATE (07-25-88):
Decay Equation: $A = A_o \, e^{-lt}$
where A = activity at time "t", A_o = original activity, l = decay constant (0.693/radiological half-life), and t = time.

$e^{-lt} = 0.9871478$
A = (4.753 E 2 dps)(0.9871478)
A = (4.6919 E 2 dps)(60 s/min)
A = 28,151 dpm

EFFICIENCY OF EBERLINE DETECTOR:
10-minute background count = 13 counts/10 minutes = 1.3 cpm
10-minute source counts - background counts
(1) 119,157 counts/10 minutes = 11,915.7 - 1.3 = 11,914.4 cpm
(2) 119,272 counts/10 minutes = 11,927.2 - 1.3 = 11,925.9 cpm
(3) 118,230 counts/10 minutes = 11,823.0 - 1.3 = 11,821.7 cpm
(4) 118,371 counts/10 minutes = 11,837.1 - 1.3 = 11,835.8 cpm
(5) 119,342 counts/10 minutes = 11,934.2 - 1.3 = 11,932.9 cpm

Average corrected cpm = 11,886 cpm
Efficiency = 11,886 cpm/28,151 dpm = 42.22%

ERROR PROPAGATION FOR SOURCE:
Uncertainty from source certificate: 1.1%
Using same derivation as above for source activity on calibration date:

Error (source) = (4.753 E 2 dps) (0.011) = 5.2283
(5.2283) (0.9871478) = 5.1611
(5.1611) (60) = 309.66 dpm

ERROR PROPAGATION FOR DETECTOR COUNTS:
(All error propagation formulas derived from Knoll,1979)

E(counts) = $(\text{counts})^{1/2}$ / minutes
E(1) = 34.5191
E(2) = 34.5358
E(3) = 34.3846
E(4) = 34.4051
E(5) = 34.5459
E(background) = 0.3606

ERROR PROPAGATION FOR BACKGROUND SUBTRACTION:

$E(sub) = ((E\ counts)^2 + (E\ background)^2)^{1/2}$
E(sub 1) = 34.5210
E(sub 2) = 34.5377
E(sub 3) = 34.3865
E(sub 4) = 34.4070
E(sub 5) = 34.5478

ERROR PROPAGATION FOR INDEPENDENT COUNTS:

$E(ind)^2 = (E\ sub\ 1)^2 + (E\ sub\ 2)^2 + (E\ sub\ 3)^2 + (E\ sub\ 4)^2 + (E\ sub\ 5)^2$

E(ind) = 77.0997 / 5 trials = 15.4199

ERROR PROPAGATION FOR DIVISION OF TWO ERRORS:

$$\frac{\text{Detector count rate}}{\text{Source Activity}} = \frac{11{,}886 \text{ cpm} +/- 15.42}{28{,}151 \text{ dpm} +/- 309.66} = \frac{X +/- x}{Y +/- y}$$

$E^2 = (1/Y)^2\ (x)^2 + (-X/Y^2)^2\ (y)^2$

E = 0.0047

Therefore, the Eberline detector efficiency and standard error is 0.4222 +/- 0.0047

The efficiency and standard error of the Brookhaven detector were obtained in a similar manner. Only the calculations will be shown here. For a more detailed and clear account of error propagation, the reader is advised to refer to the Knoll textbook.

EFFICIENCY OF BROOKHAVEN DETECTOR:
10-minute background count = 1 count/10 minutes = 0.1 cpm
10-minute source counts - background counts
(1) 100,752 counts/10 minutes = 10,075.2 - 0.1 = 10,075.1 cpm
(2) 101,486 counts/10 minutes = 10,148.6 - 0.1 = 10,148.5 cpm
(3) 99,571 counts/10 minutes = 9,957.1 - 0.1 = 9,957.0 cpm
(4) 100,405 counts/10 minutes = 10,040.5 - 0.1 = 10,040.4 cpm
(5) 100,133 counts/10 minutes = 10,013.3 - 0.1 = 10,013.2 cpm

Average corrected cpm = 10,047 cpm
Efficiency = 10,047 cpm/28,151 dpm = 35.69%

ERROR PROPAGATION FOR SOURCE:
Same as before in Eberline calculations

ERROR PROPAGATION FOR DETECTOR COUNTS:
E(1) = 31.7415
E(2) = 31.8569
E(3) = 31.5549
E(4) = 31.6868
E(5) = 31.6438
E(background) = 0.1

ERROR PROPAGATION FOR BACKGROUND SUBTRACTION:
E(sub 1) = 31.7430
E(sub 2) = 31.8584
E(sub 3) = 31.5565
E(sub 4) = 31.6883
E(sub 5) = 31.6454

ERROR PROPAGATION FOR INDEPENDENT COUNTS:
E(ind) = 70.8800 / 5 trials = 14.1760

ERROR PROPAGATION FOR DIVISION OF 2 ERRORS:
14.1760 / 309.66 = 0.0040

Therefore, the efficiency and standard error of the Brookhaven detector is 0.3569 +/- 0.0040.

STANDARD ERROR OF FLOWMETER (from manufacturer) = 2%
Flow rate: 12.2 lpm
Flow rate standard error: (12.2) (0.02) = 0.244

APPENDIX E

COMPUTER RUNS FOR HOME A AND HOME B MEASUREMENTS

HOME A

FILTER #1

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3369  +-  .004

Total counts =  824

Total counts =  677

Total counts =  442


RaA concentration in pCi/l and its standard deviation =
  3.128895  +-  .6424943

RaB concentration in pCi/l and its standard deviation=
  2.918311  +-  .1278452

RaC concentration in pCi/l and its standard deviation=
  2.470818  +-  .2009811

Working levels of radon =  2.723475E-02
```

HOME A
SCREEN #1

```
Count duration in minutes for count 1 =  3

Count duration in minutes for count 2 =  3

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  66

Total counts =  16

Total counts =  11


RaA concentration in pCi/l and its standard deviation =
  .9938964  +-  5.125109E-02

RaB concentration in pCi/l and its standard deviation=
 -3.777484E-02  +-  9.634751E-03

RaC concentration in pCi/l and its standard deviation=
 -.1034905  +-  1.314254E-02

Working levels of radon =  4.461753E-04
```

HOME A
FILTER #2

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  839

Total counts =  662

Total counts =  441


RaA concentration in pCi/l and its standard deviation =
  3.971271  +-  .6400486

RaB concentration in pCi/l and its standard deviation=
  2.927601  +-  .1274442

RaC concentration in pCi/l and its standard deviation=
  2.239091  +-  .1979405

Working levels of radon =  2.728516E-02
```

HOME A
SCREEN #2

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  60

Total counts =  26

Total counts =  30


RaA concentration in pCi/l and its standard deviation =
  .7916551  +-  5.392004E-02

RaB concentration in pCi/l and its standard deviation=
  .1466674  +-  1.413894E-02

RaC concentration in pCi/l and its standard deviation=
 -9.335188E-02  +-  1.604249E-02

Working levels of radon =  1.210806E-03
```

HOME A
FILTER #3

```
[illegible]
Count duration in minutes for count 1 =  3

Count duration in minutes for count 2 =  3

Count duration in minutes for count 3 =  3

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  724

Total counts =  585

Total counts =  384


RaA concentration in pCi/l and its standard deviation =
  3.014334  +-  .563619

RaB concentration in pCi/l and its standard deviation=
  2.524601  +-  .1123401

RaC concentration in pCi/l and its standard deviation=
  2.076822  +-  .1755834

Working levels of radon =  2.365103E-02
```

HOME A.
SCREEN #3

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  86

Total counts =  33

Total counts =  49


RaA concentration in pCi/l and its standard deviation =
  1.332397  +-  6.573631E-02

RaB concentration in pCi/l and its standard deviation=
  .323626  +-  1.840296E-02

RaC concentration in pCi/l and its standard deviation=
 -.2051967  +-  .0189895

Working levels of radon =  2.247769E-03
```

HOME A
FILTER #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  720

Total counts =  536

Total counts =  342


RaA concentration in pCi/l and its standard deviation =
  4.008715  +-  .5374224

RaB concentration in pCi/l and its standard deviation=
  2.128475  +-  .1017184

RaC concentration in pCi/l and its standard deviation=
  1.775266  +-  .1627236

Working levels of radon =  2.154209E-02
```

HOME A
SCREEN #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  83

Total counts =  60

Total counts =  27


RaA concentration in pCi/l and its standard deviation =
  .2931465  +-  .0743706

RaB concentration in pCi/l and its standard deviation=
 3.689454E-02  +-  1.370902E-02

RaC concentration in pCi/l and its standard deviation=
  .2182554  +-  2.285516E-02

Working levels of radon =  1.303089E-03
```

HOME B LAUNDRY ROOM
FILTER #1

[illegible]

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  985

Total counts =  816

Total counts =  571


RaA concentration in pCi/l and its standard deviation =
  4.04526  +-  .7655856

RaB concentration in pCi/l and its standard deviation=
  4.005107  +-  .1607465

RaC concentration in pCi/l and its standard deviation=
  2.738509  +-  .2411774

Working levels of radon =  3.468715E-02
```

HOME B LAUNDRY ROOM
SCREEN #1

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  71

Total counts =  29

Total counts =  24


RaA concentration in pCi/l and its standard deviation =
  .8675689  +-  5.837614E-02

RaB concentration in pCi/l and its standard deviation=
  5.957803E-02  +-  1.296112E-02

RaC concentration in pCi/l and its standard deviation=
 -6.007717E-02  +-  1.660539E-02

Working levels of radon =  9.715687E-04
```

HOME B LAUNDRY ROOM
FILTER #2

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  3

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  1043

Total counts =  763

Total counts =  482


RaA concentration in pCi/l and its standard deviation =
  6.090313  +-  .755391

RaB concentration in pCi/l and its standard deviation=
  2.966646  +-  .1392143

RaC concentration in pCi/l and its standard deviation=
  2.502063  +-  .226542

Working levels of radon =  3.064661E-02
```

HOME B LAUNDRY ROOM
SCREEN #2

```
Count duration in minutes for count 1 = [illegible]

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2   +-   .2

Detector efficiency and its standard deviation =
  .4222   +-   .0047

Total counts =  69

Total counts =  30

Total counts =  20

RaA concentration in pCi/l and its standard deviation =
  .757352   +-   5.792978E-02

RaB concentration in pCi/l and its standard deviation=
 1.708223E-02   +-   1.207382E-02

RaC concentration in pCi/l and its standard deviation=
-1.996918E-02   +-   1.653422E-02

Working levels of radon =  7.921944E-04
```

HOME B LAUNDRY ROOM
FILTER #3

```
[illegible] = 5

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  713

Total counts =  564

Total counts =  368


RaA concentration in pCi/l and its standard deviation =
  3.244418  +-  .5501163

RaB concentration in pCi/l and its standard deviation=
  2.39858  +-  .1084223

RaC concentration in pCi/l and its standard deviation=
  1.967698  +-  .1701958

Working levels of radon =  2.284207E-02
```

HOME B LAUNDRY ROOM
SCREEN #3

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2

Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  49

Total counts =  34

Total counts =  18

RaA concentration in pCi/l and its standard deviation =
  .2294396  +-  5.272337E-02

RaB concentration in pCi/l and its standard deviation=
  .0355802  +-  1.098142E-02

RaC concentration in pCi/l and its standard deviation=
  9.923946E-02  +-  .016406

Working levels of radon =  7.868776E-04
```

HOME B LAUNDRY ROOM
FILTER #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  664

Total counts =  502

Total counts =  311


RaA concentration in pCi/l and its standard deviation =
  3.393513  +-  .5026256

RaB concentration in pCi/l and its standard deviation=
  1.896185  +-  9.391598E-02

RaC concentration in pCi/l and its standard deviation=
  1.765458  +-  .1527914

Working levels of radon =  1.969413E-02
```

HOME B LAUNDRY ROOM

SCREEN #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2   +-   .2


Detector efficiency and its standard deviation =
  .4222  +-   .0047

Total counts =  40

Total counts =  32

Total counts =  22


RaA concentration in pCi/l and its standard deviation =
  .1427306  +-  4.939764E-02

RaB concentration in pCi/l and its standard deviation=
  9.013743E-02  +-  1.193864E-02

RaC concentration in pCi/l and its standard deviation=
  8.082854E-02  +-  1.603819E-02

Working levels of radon =  9.054998E-04
```

HOME B BASEMENT

FILTER #1

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
   .3569  +-  .004

Total counts =  422

Total counts =  312

Total counts =  187


RaA concentration in pCi/l and its standard deviation =
  2.248037  +-  .3280835

RaB concentration in pCi/l and its standard deviation=
  1.068963  +-  6.063232E-02

RaC concentration in pCi/l and its standard deviation=
  1.104432  +-  9.928502E-02

Working levels of radon =  1.185465E-02
```

HOME B BASEMENT
SCREEN #1

```
Sampling time in minutes = [illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2

Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  35

Total counts =  15

Total counts =  14

RaA concentration in pCi/l and its standard deviation =
  .4289699  +-  3.932599E-02

RaB concentration in pCi/l and its standard deviation=
  4.650654E-02  +-  9.664996E-03

RaC concentration in pCi/l and its standard deviation=
 -3.600583E-02  +-  1.172987E-02

Working levels of radon =  5.433255E-04
```

HOME B BASEMENT
FILTER #2

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  357

Total counts =  291

Total counts =  190


RaA concentration in pCi/l and its standard deviation =
  1.403658  +-  .2973369

RaB concentration in pCi/l and its standard deviation=
  1.228705  +-  6.083541E-02

RaC concentration in pCi/l and its standard deviation=
  1.047154  +-  9.337663E-02

Working levels of radon =  1.158119E-02
```

HOME B BASEMENT
SCREEN #2

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  29

Total counts =  14

Total counts =  12


RaA concentration in pCi/l and its standard deviation =
  .3133527  +-  3.669869E-02

RaB concentration in pCi/l and its standard deviation=
 3.296726E-02  +-  9.088913E-03

RaC concentration in pCi/l and its standard deviation=
-1.709321E-02  +-  1.122162E-02

Working levels of radon =  4.261395E-04
```

HOME B BASEMENT
FILTER #3

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3567  +-  .004

Total counts =  301

Total counts =  267

Total counts =  178


RaA concentration in pCi/l and its standard deviation =
  .6868713  +-  .2671963

RaB concentration in pCi/l and its standard deviation=
  1.190425  +-  5.731588E-02

RaC concentration in pCi/l and its standard deviation=
  1.02461  +-  8.613666E-02

Working levels of radon =  1.056473E-02
```

HOME B BASEMENT
SCREEN #3

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  25

Total counts =  26

Total counts =  11


RaA concentration in pCi/l and its standard deviation =
 -.1240107  +-  4.313782E-02

RaB concentration in pCi/l and its standard deviation=
 -2.955961E-02  +-  9.856606E-03

RaC concentration in pCi/l and its standard deviation=
  .1201983  +-  1.443586E-02

Working levels of radon =  1.707414E-04
```

HOME B BASEMENT
FILTER #4

[illegible]

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  306

Total counts =  222

Total counts =  153


RaA concentration in pCi/l and its standard deviation =
  1.976712  +-  .2458338

RaB concentration in pCi/l and its standard deviation=
  .9866354  +-  .0506972

RaC concentration in pCi/l and its standard deviation=
  .622394  +-  7.501857E-02

Working levels of radon =  9.359784E-03
```

HOME B BASEMENT

SCREEN #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  21

Total counts =  13

Total counts =  12


RaA concentration in pCi/l and its standard deviation =
  .165344  +-  3.602253E-02

RaB concentration in pCi/l and its standard deviation=
  1.227677E-02  +-  9.940174E-03

RaC concentration in pCi/l and its standard deviation=
 -1.084371E-02  +-  1.177448E-02

Working levels of radon =  1.921006E-04
```

HOME B UPSTAIRS
FILTER #1

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  654

Total counts =  445

Total counts =  346


RaA concentration in pCi/l and its standard deviation =
  5.453383  +-  .4749929

RaB concentration in pCi/l and its standard deviation=
  2.486969  +-  .101433

RaC concentration in pCi/l and its standard deviation=
  .8448371  +-  .1419348

Working levels of radon =  2.137716E-02
```

HOME B UPSTAIRS

SCREEN #1

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  35

Total counts =  26

Total counts =  21


RaA concentration in pCi/l and its standard deviation =
  .1873873  +-  4.598176E-02

RaB concentration in pCi/l and its standard deviation=
  7.435271E-02  +-  1.202899E-02

RaC concentration in pCi/l and its standard deviation=
  3.325988E-02  +-  .0150037

Working levels of radon =  6.940365E-04
```

HOME B UPSTAIRS

FILTER #2

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  461

Total counts =  405

Total counts =  297


RaA concentration in pCi/l and its standard deviation =
  1.499747  +-  .3916069

RaB concentration in pCi/l and its standard deviation=
  2.182742  +-  8.863722E-02

RaC concentration in pCi/l and its standard deviation=
  1.359386  +-  .1265211

Working levels of radon =  1.768175E-02
```

HOME B UPSTAIRS
SCREEN #2

```
[illegible]

Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  26

Total counts =  16

Total counts =  13


RaA concentration in pCi/l and its standard deviation =
  .1977354  +-  .0383485

RaB concentration in pCi/l and its standard deviation=
  1.942798E-02  +-  1.000708E-02

RaC concentration in pCi/l and its standard deviation=
  1.819401E-03  +-  1.232028E-02

Working levels of radon =  3.089537E-04
```

HOME B UPSTAIRS

FILTER #3

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  207

Total counts =  149

Total counts =  98


RaA concentration in pCi/l and its standard deviation =
  1.310668  +-  .1771861

RaB concentration in pCi/l and its standard deviation=
  .6080687  +-  3.617166E-02

RaC concentration in pCi/l and its standard deviation=
  .4463624  +-  5.415403E-02

Working levels of radon =  6.097828E-03
```

HOME B UPSTAIRS

SCREEN #3

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .4222  +-  .0047

Total counts =  14

Total counts =  14

Total counts =  10


RaA concentration in pCi/l and its standard deviation =
 -4.558949E-03  +-  2.968741E-02

RaB concentration in pCi/l and its standard deviation=
  4.795726E-02  +-  7.737868E-03

RaC concentration in pCi/l and its standard deviation=
  4.370307E-02  +-  1.004538E-02

Working levels of radon =  4.014601E-04
```

HOME B UPSTAIRS

FILTER #4

```
Count duration in minutes for count 1 =  5

Count duration in minutes for count 2 =  5

Count duration in minutes for count 3 =  5

Sampling flow rate in liters per minute and its standard
deviation =  12.2  +-  .2


Detector efficiency and its standard deviation =
  .3569  +-  .004

Total counts =  284

Total counts =  215

Total counts =  134


RaA concentration in pCi/l and its standard deviation =
  1.448296  +-  .2355189

RaB concentration in pCi/l and its standard deviation=
  .8085674  +-  4.617877E-02

RaC concentration in pCi/l and its standard deviation=
  .7487197  +-  7.238305E-02

Working levels of radon =  8.383906E-03
```

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