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12. ASSESSMENT OF LEAD EXPOSURES AND ABSORPTION IN HUMAN POPULATIONS

12.1 INTRODUCTION

Although epidemiological studies provide the most directly relevant data for setting ambient air quality standards, such investigations are subject to methodological and practical difficulties. Of most interest are studies relating ambient air lead exposures directly to human health effects in various population groups. Unfortunately, few such studies exist. Standards setting, then, must rely on constructing (1) the linkage between exposures to environmental sources of lead and the incorporation of lead from those sources in various segments of the population as measured by blood lead levels and (2) the relationship between levels of lead in the blood and associated health effects.

This chapter will examine the details of studying blood lead levels in human populations. Included will be an examination of the statistical considerations of such investigations as well as a discussion of the characteristics of the frequency distribution of blood lead values and of how these may be used as tools in setting environmental standards. In addition, the effects of geographic and demographic variables on lead burdens will be considered. Finally, the epidemiological and clinical studies on the relationships between environmental lead exposures and human absorption will be described, and, where available, quantitative estimates of those relationships will be presented.

12.2 LEAD IN HUMAN POPULATIONS

In this section, the statistical approaches for assessing blood lead levels in human populations will be discussed, as will their applications and implications. This discussion will be followed by a description of findings relating to the geographic and demographic distributions of blood lead levels.

12.2.1 Statistical Descriptions and Implications

Many surveys have described blood lead values in human populations. Not unexpectedly, the investigators' choices of statistics to describe central tendencies and dispersion patterns are not uniform. This lack of uniformity makes comparison of the various studies quite difficult. For example, central tendencies are expressed as either arithmetic or geometric means, and the measures of dispersion also vary. Often the arithmetic mean of the distribution is much larger than the geometric mean.

12.2.1.1 FORM OF THE DISTRIBUTION OF BLOOD LEAD LEVELS

Several authors have either suggested or implied that the distribution of blood lead levels for any relatively homogeneous population closely follows a lognormal distribution.[1-3] Lognormality has also been noted for other metals, such as ^{90}Sr in bones of human populations.[4] Snee has suggested that the Pearson system of curves provides a slightly better fit for the data of Azar et al. than the lognormal,[5] but the improvement derived from this system does not seem sufficient to warrant the use of this little-known technique. Yankel et al.[1] and Tepper and Levin[2] both found their lead data to be lognormally distributed. Further analysis of the Houston study of Johnson et al.,[6] the Southern California study of Johnson et al.,[7] and the study of Azar et al.[3] also confirmed that a lognormal distribution provided a good fit to the data. For these reasons, much of what is presented in this chapter is based on the acceptance that homogeneous populations have a lognormal distribution of blood lead values.

The lognormal distribution and its application to biological measurements are discussed by several authors.[4,8,9] A variable is said to have a lognormal distribution if the logarithm of the variable is normally distributed. Because of the skewed nature of the lognormal distribution, the median (50th percentile) is a more meaningful estimate of central tendency than the arithmetic mean. For the normal distribution, the best estimate of the median is $\bar{X}$, the simple arithmetic mean. For the lognormal distribution, the best estimate of the median is the geometric mean (GM):

$$GM = \text{Exp}[\sum_{i=1}^{n} (\ln(X_i))/n]. \quad (12\text{-}1)$$

The standard deviation of the logarithms is:

$$S = [\sum_{i=1}^{n} (\ln(X_i) - \ln(GM))^2/n-1]^{1/2}. \quad (12\text{-}2)$$

The geometric standard deviation, also known as the standard geometric deviation, is given by:

$$GSD = \text{Exp}(S).$$

If only the arithmetic mean, $\bar{X}$, and arithmetic standard deviation, SD, are given, then the geometric mean and the geometric standard deviation can be estimated by:[10]

$$\hat{GM} = \bar{X}/(1 + SD^2/\bar{X}^2)^{1/2} \quad (12\text{-}3)$$

and

$$\hat{GSD} = \text{Exp}[(\ln(SD^2/\bar{X}^2 + 1))^{1/2}]. \quad (12\text{-}4)$$

The geometric standard deviation must be interpreted differently than the arithmetic standard deviation. Using the SD, approximately 68 percent of the population will fall between (mean - SD) and (mean + SD). These same limits for the lognormal distribution become GM/GSD and (GM)(GSD). For example, if a population has a geometric mean blood lead level of 20 with a GSD of 1.3, then 95 percent of the population will have blood lead levels between $20/(1.3)^{1.96}$ and $(20)(1.3)^{1.96}$ or 11.96 and 33.45.

12.2.1.2 PERCENTILE ESTIMATES OF THE LOGNORMAL DISTRIBUTION

From the GM and GSD, estimates of percentiles of the lognormal distribution can easily be obtained either numerically or graphically. Numerically, the pth percentile, X_p, is estimated by

$$\hat{X}_p = (\hat{GM})\,(\hat{GSD})^{z_p} \quad (12\text{-}5)$$

where z_p is the z value from a standard normal table. The following values are often used:

Percent	z_p	Percent	z_p	Percent	z_p
1	-2.326	25	-.674	95	1.645
2.5	-1.960	50	0.000	97.5	1.960
5	-1.645	75	0.674	99	2.326
10	-1.282	90	1.282	99.9	3.090

Another method of obtaining percentile estimates is a graphical one using lognormal probability paper. One point is placed where the geometric mean intersects the 50th percentile. A second point is placed where $(\hat{GM})\,(\hat{GSD})^{2.326}$ intersects the 99th percentile. A line drawn through these two points gives the estimated cumulative frequency distribution. Figure 12-1, for example, is drawn with an assumed geometric standard deviation of 1.3.

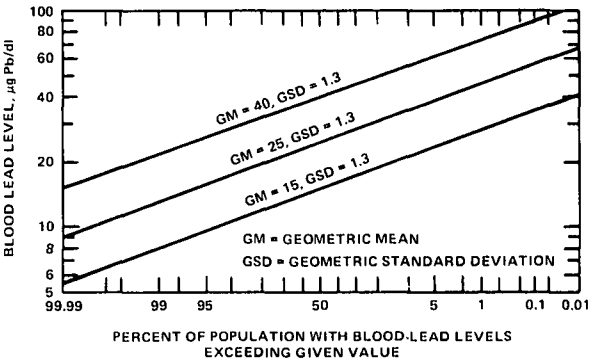

Figure 12-1. Estimated cumulative distribution of blood lead levels for populations in which the geometric mean level is 15, 25, or 40 μg/dl.

From this description of the distribution, estimates can be obtained of the percentage of blood lead values expected to exceed any given level for any given geometric mean blood lead level. For example, (Figure 12-1) in the populations with geometric mean blood lead levels of 15, 25, and 40 μg/dl whole blood, 0.1, 10, and 68 percent, respectively, will have blood lead levels exceeding 35 μg/dl.

As stated above, Figure 12-1 was drawn with a GSD of 1.3. The effect of varying the geometric standard deviations on the percentage exceeding a specified blood lead value is shown in Figure 12-2 because the value of the GSD has been shown to vary across studies (Table 12-1). A marked effect can be noted. It is very important, therefore, to be sure of

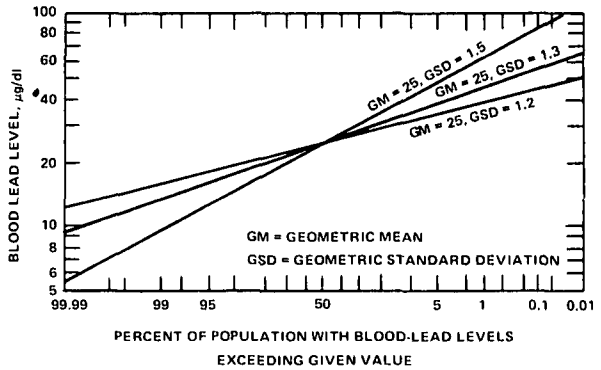

Figure 12-2. Estimated cumulative distribution of blood lead levels for populations having a geometric mean blood lead level of 25 μg/dl, but geometric standard deviations of 1.2, 1.3, or 1.5.

the value used for the geometric standard deviation if the lognormal distribution is to be used in setting environmental standards.

Because most blood lead data have been reported as arithmetic means and standard deviations, and because the raw data are not generally available, this chapter will use the term "mean" for arithmetic mean. The arithmetic standard deviations, when available, will be identified. If the geometric means are available, they will be reported as geometric means with the geometric standard deviation provided.

TABLE 12-1. ANALYSIS OF VARIANCE FOR THE LOGARITHMS OF BLOOD LEAD VALUES FOR SELECTED STUDIES (Geometric standard deviations given in parentheses)

Study	Population size	Replicates per observation	Number of duplicates	Population variance[a]	Within group variance[a]	Measurement variance
Idaho[1]	879	3	16[b]	0.190 (1.55)	0.072 (1.31)	0.012[b] (1.12)
Seven City Study[2]	1908	1	171	0.090 (1.35)	0.082 (1.33)	0.063 (1.28)
Southern California-Males[7]	64	2	64	0.224 (1.60)	0.181 (1.53)	0.216 (1.59)
Southern California-Females[7]	107	2	107	0.183 (1.53)	0.167 (1.51)	0.141 (1.45)
Houston[6]	189	2	189	0.182 (1.53)	0.069 (1.30)	0.094 (1.36)
Azar[3]	149	2-8	NA[c]	0.148 (1.47)	0.099 (1.37)	0.049 (1.25)

[a] Includes measurement variation.

[b] Based on a separate Center for Disease Control versus Idaho comparison of 16 samples of 1975 data, which are different from the 1974 data for the Idaho study.[1] The estimates of population and within group variance come from the original study.

[c] Not available.

12.2.1.3 VARIATION IN BLOOD LEAD VALUES

The total variation in blood lead values for any study is composed of three variance components: (1) between group, (2) within group or individual, and (3) method variation. The method variance results from both sampling and analytical measurement variations. The within group variance results from the difference in biological response among individuals with the same exposure as well as demographic differences in age, sex, race, socioeconomic status, and environmental background of the individuals in a group. The within group variance is a measure of the homogeneity of people in a group, but also includes method variance. The between group variance results from the differences in the composition of people in a group, such as police officers or housewives. In studying the effect of lead exposure on blood lead levels, it is necessary to separate these sources of variation to know whether the study results are meaningful. If the blood lead sampling and analysis errors are large, any effects of different lead exposure may not be seen. In a similar manner, if the group chosen for a study is not homogeneous, the within group variance may be so large that the differences in blood lead values cannot be interpreted as resulting from exposure. The sources of variation are estimated in Table 12-1 for several studies for which the raw data were available. The variation is expressed in terms of the natural logarithms of the blood lead values, and the calculations were made using standard analysis of variance techniques. The variances are converted to geometric standard deviations and these values are shown in parentheses.

Table 12-1 shows that a large portion of the total variation is caused by measurement variation, except possibly for the Idaho[1] study. The measurement variation was unusually large for the Southern California study,[7] suggesting that results from this study should be viewed with caution. Except for the Southern California study, the GSD for within group variation was consistently near 1.3. This number includes both biologic and measurement variation. It is possible for the measurement variation to exceed

the within group variation if there is more than one reading per individual, however, as was the case in both the Southern California and Houston studies.

12.2.1.4 PROBLEM OF FALSE EXCEEDENCES

Lucas[11] has described a problem that he terms "false exceedences." For example, a lognormal distribution with a geometric mean of 25 and a geometric standard deviation of 1.3 will have 3.7 percent of the distribution above 40. As a hypothetical example, if half of the variation is caused by measurement variation, then the "true" distribution would have a geometric standard deviation of 1.2 and would have only 0.6 percent of the distribution above 40.

False exceedences become a real problem if a threshold value, such as 40, is determined from sources of data lacking a large measurement variation. In such cases, the estimated percentage of the distribution above a fixed level will be an overestimate as shown in the previous paragraph. It is extremely difficult to obtain more accurate estimates because the appropriate variance can only be estimated indirectly and only in cases where there are replicate measurements on the same individual. If, however, the threshold itself is estimated from data having this same measurement variation, then the problem is more difficult. In such cases, the observed variances including measurement variation may be more appropriate. As the technology of measurement improves, the problem will become much less significant.

12.2.2 Geographic Variability in Human Blood Lead Levels

Numerous studies have been conducted throughout the world establishing mean blood lead concentrations for various remote, rural, suburban, and urban populations. By examining the differences among the observed levels across these populations, inferences can be drawn concerning the ubiquity of lead exposures as well as their relative magnitudes. A word of caution, however, must be inserted here. Many of these data have been collected over a period of time in which measurement technology for blood lead determinations has changed and improved. Also, sometimes neither the methods of analysis nor the sampling scheme used have been reported.

Studies of remote populations have been used to estimate the natural background blood lead level for humans.[12-15] Likewise, studies comparing either rural or suburban populations have been used to establish the effect of urban living on blood lead levels. All these studies, however, can be used to demonstrate the broad variety of populations in which lead from all environmental sources has been found in people.

Only a few studies[12-15] have focused on remote populations. Goldwater and Hoover[12] conducted an international study of urban and rural populations in which investigators from 14 countries participated; only non-occupationally exposed adults were studied. One laboratory did all the chemical analyses. Some of these populations — New Guinea aborigines, for example — were thought to be remote from the effects of industrialization. The mean and standard deviations of blood lead for the aborigines, however, were 22 and 5 μg/dl, respectively. Examination of their living habits could shed no light on the sources of this lead. In contrast to this, urban residents from Peru in the same study had a mean of 7 μg/dl and a standard deviation of 5 μg/dl.

Stopps[13,14] reported data on remote populations. Table 12-2 presents the blood lead means as ranging from 23 to 12 μg/100 g.

In contrast to the findings of Goldwater and Hoover[12] and Stopps,[13,14] Hecker et al.[15] in a more recent study of Amazon River Basin Indians, using anodic stripping voltammetry, found a mean blood lead of 0.83 μg/dl with a standard deviation of 0.59 in 90 subjects. The urinary levels were not quite as low as the blood leads (mean, 7.9 μg/dl; SD, 5.7), but still are low in comparison with the values reported in Goldwater and Hoover.[12]

TABLE 12-2. BLOOD LEAD LEVELS OF REMOTE POPULATIONS[13,14]

Populations	Sample size	Blood lead, μg/100 g
Brazilian Indians	11	23
Marshall Islanders	33	23
Peruvian Indians	39	18
Islanders off Australia	28	17.5
Bushmen	68	16
New Guinea natives	67	13
East Africans	63	12

A number of studies have specifically contrasted blood lead results between rural, suburban, and urban populations.[2,16-21] Two of the methodologically better studies are those of Tepper and Levin,[2] and Nordman.[16] Tepper and Levin[2] conducted a study of the blood lead levels of 11 groups of housewives from 8 U.S. metropolitan areas. Three of these, Chicago, New York, and Philadelphia, had urban-

suburan comparison groups. Table 12-3 displays the results of the contrasts between those groups as calculated by Hasselblad and Nelson.[22] In every case, a significant difference was obtained.

TABLE 12-3. AGE AND SMOKING-ADJUSTED GEOMETRIC MEAN BLOOD LEADS IN URBAN VERSUS SUBURBAN AREAS OF THREE CITIES

City	Blood Lead, μg %			
	Urban	Suburban	Urban excess	Significant
Chicago, IL	17.55	14.02	3.53	>0.01
Philadelphia, PA	20.12	17.88	2.24	>0.01
New York, NY	16.47	15.24	1.23	>0.01
Three cities together	18.05	15.71	2.34	>0.01

Nordman[16] studied a series of populations in Finland including downtown urban, suburban, and rural populations. No statistically significant differences were observed between urban and rural or suburban residents. But, interestingly, none of the populations studied, which included traffic policemen, streetsweepers, downtown Helsinki residents, and rural controls, had a mean blood lead level that exceeded 13.5 μg/dl.

Other studies permitting urban rural comparisons include those of Hofreuter et al.,[17] Creason et al.,[18] Scanlon,[19] Gershanik et al.,[20] and Cohen et al.[21] Hofreuter et al.,[17] in 1960, collected blood samples from about 120 people in each of 6 cities and from 162 people in a rural area (central Ohio). Table 12-4 displays the results of these comparisons. In all urban survey sites, the mean blood lead level was significantly higher than in the rural survey sites.

TABLE 12-4. BLOOD LEAD CONCENTRATIONS IN SIX URBAN AND ONE RURAL POPULATION

Survey site	No. of samples	Mean blood lead, μg/100 g	Urban excess
New Orleans, LA	130	22	8
Chicago, IL	97	20	6
New York, NY	112	20	6
Cincinnati, OH	137	20	6
Dallas, TX	128	18	4
Denver, CO	131	19	5
Rural	162	14	

Creason et al.[18] studied military recruits in the Chicago area at the time of their induction. By the very nature of the sample, only young male adults were included. Further, analysis was restricted to those having lived at the same home address for two or more years. The population was broken down by race and three residential locations, namely urban, suburban, and outstate. Median blood levels for whites were 22, 20, and 36 μg/dl for the urban, suburban, and outstate populations, respectively.

Scanlon[19] reported on umbilical cord blood lead levels for infants born to Boston area women. Mean blood lead levels for urban infants were 22.1 μg/dl compared with 18.3 μg/dl for the suburban newborn. This difference was not statistically significant.

Gershanik et al.[20] studying a larger sample of cord bloods in Shreveport, Louisiana, however, found a statistically significant difference between urban and suburban infant cord blood lead levels, 9.7 ± 3.9 versus 8.3 ± 2.4 μg/dl, respectively.

Cohen et al.[21] reported on a rural-urban comparison for children, aged 1 to 5 years, living in 2 rural counties and in Hartford, Connecticut. Although the 2 samples were adequately matched on age, there was a major racial/ethnic difference — the urban population being either black or Puerto Rican and the rural primarily white. The mean and standard deviation of the blood lead concentrations were 32.7 ± 14.8 and 22.8 ± 11.0 for the urban and rural populations, respectively.

Some of these same studies, as well as others, can be used to discern a wider picture of the variability of blood lead levels.[12-14,17] In the Goldwater and Hoover study,[12] urban population mean blood lead levels were found to range from 7 to 25 μg/dl, whereas the mean for rural areas ranged from 9 to 32 μg/dl. The wide range of means in both population types suggests that lead can be found in many locations.

Nordman[16] reviewed the available literature on blood lead levels and concluded that "the Pb-B mean values for occupationally unexposed rural and urban populations range from 10 to 26 μg/dl." Exceptions to this general range are found, however. Lower-than-usual blood lead levels have been reported from some parts of Sweden and Finland. There, levels in women were found to be 10 μg/dl.[16,23] On the other hand, higher-than-usual blood lead values have been reported from sections of Italy and France.[24-27] Zurlo et al.,[24] in particular, reported very high blood lead levels for adults in the Milan area, urban mean of 30 μg/dl for males and 23.7 μg/dl for females.

Data obtained from adults within the United States follow a similar pattern.[2,17,28] In data from Tepper and Levin,[2] differences were noted in the geometric mean blood lead among the 11 populations of housewives studied. The lowest blood lead values were found in Houston, Texas, with a GM and a GSD of 12.5 and 1.31, respectively, whereas the highest were found in Rittenhouse, a section of

Philadelphia — GM and GSD of 20.6 and 1.33, respectively.

In the 1960 Hofreuter et al. study,[17] blood samples were collected from people in six metropolitan areas and one rural control site. The mean blood lead values varied from 14 to 22 μg/100 g. The maximum observed values ranged from 38 to 60 μg/100 g.

Kubota et al.[28] studied blood lead levels in male residents of 19 intermediate-sized cities across the United States. Mean blood levels were found to vary from 7.25 μg/dl in Lafayette, Louisiana, to 20.34 μg/dl in Jacksonville, Florida. The highest reported value, 109.27 μg/dl, occurred in Fargo, North Dakota. A wide range in values was reported for each city, the largest being 5.91 to 109.27 μg/dl in Fargo. Further, the authors report three cities with mean blood lead levels below 8.00 μg/dl, namely Lubbock, Texas, 7.95; Geneva, New York, 7.65; and Lafayette, Louisiana, 7.25 μg/dl. These low values approximate those found in parts of Scandinavia.[16]

Workers at 23 DuPont Company plants were studied over a 5-year period, 1967 through 1971.[29] No time trend was noted for blood lead levels, and the samples were pooled per plant for the 5 years. The geometric mean values varied from a low of 15.5 μg/100 g for the Ashland, Wisconsin, plant to a high of 21.6 μg/100 g at the Los Angeles, California, plant. The overall geometric mean for the 23 locations was 18.2 μg/100 g.

Data addressing geographic variation of blood lead values in children are not as extensive. For the United States, Fine et al.,[30] Baker et al.,[31] and Joselow et al.[32] provided the best available information. Fine et al.[30] studied 6151 children aged 1 to 6 years in 14 intermediate-sized cities in Illinois in 1971. Blood lead values (Table 12-5) were determined by an atomic absorption technique. Mean values for cities ranged from 19.8 to 32.9 μg/dl; the mean for all 14 cities was 25.5 μg/dl. These values are indicative of sources of lead in the children's environment.

Baker et al.[31] determined blood lead values for 1672 children aged 1 to 5 living in 19 towns containing smelters and 3 control towns. The smelter communities were selected for study because they had not previously been subject to thorough investigation. Blood lead values were determined by an atomic absorption technique.

The mean blood lead levels for the lead and copper smelter towns did not differ from those control towns, as shown in Table 12-6. The children living in zinc smelter towns, however, showed significantly higher blood lead values than the other three groups. The lowest mean blood lead value, 9.15 μg/dl, was found in children for McGill, Nevada, whereas the highest mean value was found for Bartlesville, Oklahoma, with 28.60 μg/dl.

TABLE 12-5. MEAN BLOOD LEAD VALUES FOR CHILDREN IN 14 INTERMEDIATE-SIZED CITIES IN ILLINOIS, 1971[30]

City	No. of children screened	% of city's children ages 1-6 yr screened	Mean blood lead value, μg/dl
Aurora	449	5.09	28.2
Springfield	670	7.28	31.5
Peoria	387	2.97	32.9
East St. Louis	376	4.09	28.6
Decatur	793	5.84	21.5
Joliet	383	4.54	27.8
Rock Island	285	5.60	25.0
East Moline	298	12.32	23.5
Harvey and Phoenix	226	4.90	22.6
East Chicago Heights	172	17.13	27.3
Chicago Heights	537	10.36	25.2
Robbins	103	6.78	22.2
Carbondale	264	17.46	28.5
Rockford	1,208	7.31	19.8
Total	6,151	6.14	25.5

Joselow et al.[32] compared the blood lead levels of children aged 3 to 5 years in Newark, New Jersey, and Honolulu, Hawaii, in 1973. The study included 152 children who were matched for age and sex into 2 groups of 76 from each city. The mean blood lead value for the Newark children was 28 μg/dl, considerably higher than that found in Honolulu children, 17 μg/dl.

12.2.3 **Demographic Variables and Human Blood Lead Levels**

Fewer data are available to evaluate the effects of age, sex, and race on blood lead levels.

Children consistently develop higher blood lead levels than do adults in the same environmental setting. In El Paso, Texas,[33] in 1972, 70 percent of children 1 to 4 years old living near a primary lead, copper, and zinc smelter had blood lead levels >40 μg/dl, and 14 percent exceeded 60 μg/dl. In children 5 to 9 years old, 45 percent exceeded 40 μg/dl, as did 31 percent of measurements in individuals 10 to 19 years old and 16 percent of those over 19.

In the vicinity of a primary lead smelter in Idaho in 1974, the geometric mean blood lead levels shown in Table 12-2 were obtained.[1] As can be seen from Table 12-7, children under 10 years of age consistently had higher blood lead values than older children and adults within the same environment.

TABLE 12-6. BLOOD LEAD LEVELS (WHOLE BLOOD) IN CHILDREN IN U.S. SMELTER AND COMPARISON TOWNS, 1975[31]

City	No. of samples	Mean	SE[a]	GM	GSD	Percent exceeding 35 μg/dl
Comparison towns						
Albuquerque, NM	81	17.70	0.63	16.8	1.39	0.0
Perryville, MO	85	16.88	0.74	15.8	1.42	2.4
Safford, AZ	92	15.26	0.71	13.8	1.57	1.1
Total	258	16.56	0.41	15.4	1.57	1.2
Lead smelter towns						
Bixby, MO	48	13.76	0.96	12.4	1.66	0.0
Glover, MO	23	12.05	1.19	11.1	1.58	0.0
Herculaneum, MO	87	18.80	0.94	17.2	1.54	8.0
Total	158	16.34	0.66	14.6	1.64	4.4
Copper smelter towns						
Ajo, AZ	105	12.55	0.46	11.7	1.45	0.0
Anaconda, MT	64	13.38	0.95	11.6	1.77	1.6
Copper Hill, TN	86	16.63	0.74	15.4	1.47	1.2
Douglas, AZ	97	20.47	0.86	18.9	1.49	3.1
Hayden, AZ	100	21.24	0.85	19.9	1.42	5.0
Hurley, MN	42	14.33	1.23	12.8	1.60	4.8
McGill, NV	50	9.15	0.52	8.9	1.45	0.0
Miami, AZ	94	17.00	0.74	15.5	1.59	3.2
Morenci, AZ	100	13.87	0.56	12.9	1.47	0.0
San Manuel, AZ	101	18.01	0.55	17.2	1.37	1.0
White Pine, MI	70	18.62	0.74	17.8	1.34	2.9
Total	909	16.36	0.25	14.8	1.58	2.0
Zinc smelter towns						
Amarillo, TX	84	22.34	1.16	20.9	1.41	4.8
Bartlesville, OK	87	28.60	1.91	23.6	1.92	31.0
Corpus Christi, TX	12	19.02	1.42	18.4	1.32	0.0
Monaco, PA	62	14.84	0.82	13.7	1.49	1.6
Palmerton, PA	102	17.51	0.60	16.5	1.42	1.0
Total	347	21.04	0.66	18.6	1.63	9.5

[a]SE = standard error.

TABLE 12-7. GEOMETRIC MEAN AND GEOMETRIC STANDARD DEVIATIONS (IN PARENTHESES) OF BLOOD LEAD LEVELS BY AGE AND STUDY SECTOR (μg/dl)

Study sector	Age, years		
	<10	10-19	>20
I	66 (1.33)	39 (1.26)	38 (1.32)
II	47 (1.30)	33 (1.23)	33 (1.33)
III	34 (1.26)	28 (1.40)	30 (1.35)

Likewise, a study of traffic exposure in Dallas, Texas,[34] found mean blood lead concentrations of 12 to 18 μg/dl in children as contrasted with 9 to 14 μg/dl in adults, when exposure levels are controlled.

Simpson et al.[35] summarized the results of 27 neighborhood screening programs conducted throughout the United States in the spring and summer of 1971. They found that children less than 3 years of age had a lower rate of elevated blood lead than children older than 3 years. Of those under 3 years, 25.8 percent had values of ≥ 40.0 μg/dl, whereas 31.4 percent of those 3 years of age or older had values ≥40.0 μg/dl.

Elam et al.[36] studied pediatric patients in a Chicago outpatient service. The proportion of children (Table 12-8) with blood lead values ≥ 50 μg/dl varied with age; the proportion over 50 μg/dl peaked at 18 to 30 months of age.

TABLE 12-8. PROPORTION OF CHILDREN WITH BLOOD LEAD VALUES BETWEEN 50 AND 99 μg/dl, BY AGE, CHICAGO 1971-1975[36]

Age, months	% Blood lead 50 to 99 μg/dl
6-17	24
18-30	40
31-42	16
43-52	12
55-66	7

A study of Philadelphia ghetto children[37] conducted in 1972 through 1973 provides data relevant to the relationship between age and blood lead level. The study population consisted of 1559 black children aged 6 months to 18 years of age. Table 12-9 presents the blood lead levels by age. In both

G6PD normal and deficient children, the blood lead pattern of increase and decrease by advancing age pertains. The only increase, but a substantial one, is observed between children less than 1 year of age and those 1 to 3 years old. Blood lead levels decrease in all succeeding age groups.

Billick et al,[38] analyzed data from New York City lead screening programs from 1970 through 1976. The data include age in months, sex, race, residence expressed as health district, screening information,

TABLE 12-9. MEAN BLOOD LEAD (μg%) BY AGE, SEX, AND G6PD STATUS IN 1559 URBAN BLACK CHILDREN[37]

Age, years	Sex	Number	G6PD normal	Number	G6PD deficient
<1	Both	61	19.1 ± 9.5	9	18.3 ± 8.2
	Males	32	19.5 ± 9.0	6	18.8 ± 8.2
	Females	29	19.2 ± 9.2	3	17.3 ± 8.4
1-3	Both	289	29.1 ± 14.6	40	33.2 ± 15.5
	Males	133	30.5 ± 15.1	30	33.1 ± 15.5
	Females	156	28.8 ± 11.0	10	33.6 ± 13.5
4-8	Both	404	25.0 ± 12.6	55	25.7 ± 13.4
	Males	177	24.6 ± 13.2	38	25.2 ± 12.9
	Females	227	25.1 ± 11.1	17	26.1 ± 13.5
9-13	Both	394	21.3 ± 10.4	44	23.0 ± 12.5
	Males	189	20.4 ± 10.9	29	22.1 ± 11.8
	Females	205	21.7 ± 9.7	15	24.8 ± 13.9
14-18	Both	242	18.7 ± 9.7	21	19.1 ± 9.9
	Males	94	18.5 ± 10.1	13	18.9 ± 9.3
	Females	148	18.8 ± 8.9	8	19.5 ± 10.1

and blood lead values expressed in decades. Only the first screening data for individual children were included based on the analysis of venous blood. Only the data (178,588 values) clearly identified as coming from the first screening of a given child were used. All blood lead determinations were done by the same laboratory. The data presented are preliminary and an exhaustive analysis has not been completed. Table 12-10 presents the geometric means for the children's blood lead levels by age and

TABLE 12-10. GEOMETRIC MEAN BLOOD LEAD LEVELS IN NEW YORK CITY LEAD SCREENING PROGRAM (Calculated on the basis of the Billick et al.[38] data)

Group and year	Age, months						
	1-12	13-24	25-36	37-48	49-60	61-72	73+
Blacks							
1970	27.2	31.2	31.2	28.4	31.4	22.9	25.7
1971	25.2	29.7	30.4	29.8	28.7	27.7	27.0
1972	22.3	26.3	26.7	25.8	25.0	24.3	23.8
1973	22.6	26.9	26.3	25.6	24.5	24.1	23.1
1974	22.2	25.7	25.5	24.4	23.7	22.2	22.1
1975	20.5	22.9	22.9	22.3	21.7	21.8	19.6
1976	18.1	20.7	21.2	20.9	20.3	19.2	19.3
Hispanic							
1970	21.5	24.9	25.5	23.9	24.1	24.5	24.0
1971	19.9	22.9	25.0	24.9	24.4	23.9	23.9
1972	18.7	20.6	22.1	22.6	22.1	22.0	21.3
1973	20.1	21.8	22.5	23.1	22.2	21.6	21.7
1974	19.7	21.4	23.0	22.6	22.1	20.1	20.3
1975	17.4	19.6	20.6	20.9	20.6	20.0	18.5
1976	17.9	18.6	19.2	19.3	19.2	18.2	18.4
Whites							
1970	21.0	23.9	24.7	25.0	23.7	24.9	22.5
1971	19.9	22.8	22.9	23.0	23.9	21.9	21.7
1972	17.1	20.2	22.0	21.1	21.2	21.4	20.6
1973	20.3	21.5	21.9	22.1	20.6	21.6	21.1
1974	18.6	20.5	20.0	21.1	21.4	21.3	19.6
1975	19.1	20.0	19.0	18.2	19.8	18.0	17.3
1976	20.7	17.2	19.1	18.7	18.4	17.7	17.5

race for the 7 years. It should be mentioned that the means presented were derived by EPA from the raw data provided by Billick et al.[38] Because the blood lead levels were available to the nearest 10 μg/dl, the midpoints of each interval were used to calculate the geometric means. These means were calculated for each 2-month interval for each age and ethnic group and were then combined across the six 2-month intervals using an unweighted geometric mean so as to minimize any seasonal effects.

It should be noted that all racial/ethnic groups show an increase in geometric mean levels from < 1 to 1 to 2 years of age. Figure 12-3 shows the trends for 1970. Similar patterns hold for other years. The

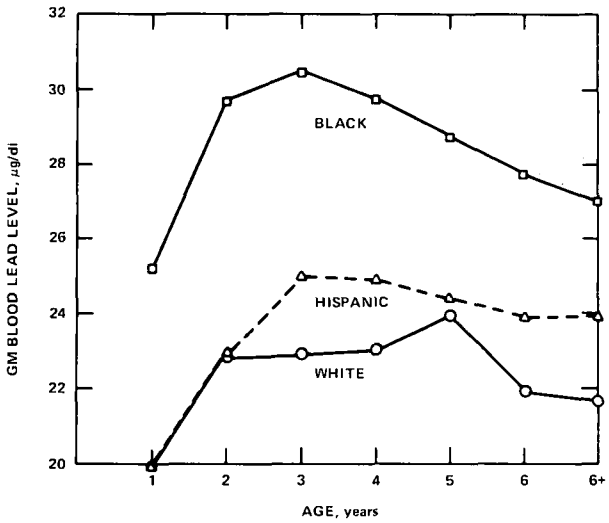

Figure 12-3. Geometric means for blood lead values by race and age, New York City, 1971.

differences in age-associated patterns for the three racial/ethnic groups may be influenced by the substantial differences in population sizes for the groups: whites were the smallest group, Hispanics were next, and blacks the largest. Table 12-11 shows the size of the groups for the 7 years.

TABLE 12-11. NUMBER OF CHILDREN'S INITIAL SCREENS IN NEW YORK CITY PROGRAMS BY RACE/ETHNICITY AND YEAR, 1970-1977[38]

Year	White	Black	Hispanic
1970	1,282	8,839	8,251
1971	2,796	23,174	18,740
1972	1,350	16,730	10,153
1973	823	9,722	6,875
1974	601	4,139	2,498
1975	656	4,585	2,620
1976	491	3,755	2,178

It is of interest to note that the age-associated pattern observed in the United States was not seen in a West German[39] study. In that study, 363 children of ages 8 days to 8 years showed increasing mean blood lead levels with age: 3.3 ± 2.6 μg/dl in the first year of life, increasing with each year to a mean of 11.5 ± 4.9 μg/dl at age 6 to 8.

In contrast to studies of children, most studies of adult populations do not show any marked effect of aging on blood lead levels.[17,40,41] Nordman found that males and females over the age of 65 years had lower blood lead values than the rest of the adult population in his study.[16]

Effects of sex on blood lead levels appear to be age dependent. Adult females are commonly found to have lower levels than males.[2,16,17,23,24] Among children, however, sex does not appear to be a differentiating factor.[42,43] Tepper and Levin[2] have suggested that the differences found in blood lead levels of adult men and women are not the result of either differences in lead intake from food or from differences in hematocrit levels between them.

Data for the assessment of race as a factor in blood lead levels are relatively scarce.[18,25,38,44,45] The earlier studies[18,44] report only the number of cases above a specified blood lead level. One study[18] shows higher lead levels for blacks than Puerto Ricans, but the other[44] reports that blacks had higher levels than nonblacks.

In their study of military recruits, Creason et al.[18] compared white and black subjects. Data in Table 12-12 show higher mean values for all black groups than for the whites.

TABLE 12-12. BLOOD LEAD LEVELS (μg/dl)[18] IN MILITARY RECRUITS, BY RACE AND PLACE

	Black			White		
Place	Number	Mean	90th percentile	Number	Mean	90th percentile
Urban	58	38	85	203	31	69
Suburban	4	80	124	218	27	54
Outstate	15	59	105	406	39	71

The Billick et al.[38] data show higher geometric mean blood lead values for blacks than for Hispanics or for whites. Table 12-13 presents these geometric means for the three racial/ethnic groups for 7 years. The consistency of the association is remarkable.

Numerous data have been published showing the effect of various occupations on blood lead levels.[16,25,40,46] In general, these data support the conclusion that workers exposed to automobile exhaust, lead fumes, or dust in manufacturing carry higher lead burdens than those who do not.

TABLE 12-13. GEOMETRIC MEAN BLOOD LEAD LEVELS (μg/dl) IN NEW YORK LEAD SCREENING PROGRAM, 1970-1976, FOR CHILDREN UP TO 72 MONTHS OF AGE, BY RACE AND YEAR[38]

Year	Black	Hispanic	White
1970	28.6	24.0	23.8
1971	28.5	23.4	22.4
1972	25.0	21.3	20.4
1973	25.0	21.9	21.3
1974	23.9	21.6	20.8
1975	22.0	19.8	19.0
1976	20.0	18.7	18.6

12.3 RELATIONSHIPS BETWEEN EXTERNAL EXPOSURES AND BLOOD LEAD LEVELS

In previous chapters, it has been shown that lead:

1. Is emitted from various sources, primarily automobiles and industrial operations.
2. Is distributed across the environment.
3. Is capable of being absorbed into the human body.

This section will describe the relationships observed between the different environmental exposures and the resulting absorption as measured by blood lead levels.

Lead that is emitted from mobile sources, e.g. automobile exhausts, and from stationary sources, e.g. industrial operations, either remains in the air or falls out, as discussed in Chapter 6. Studies have shown a buildup of lead in soil and dust as a result of emissions from these two sources. Further, the lead in soil and dust does not derive only from these sources but, in addition, from the deterioration and erosion of lead based paint. Therefore, although soil and dust are direct sources of human exposure to lead, they must also be viewed in terms of the primary mobile and stationary sources of the lead. Consequently, studies that examine only ambient air lead exposures may, in fact, underestimate the total contribution of airborne lead to the population's lead burden.

Efforts to estimate experimentally the relative importance of combustion of leaded gasoline to total lead burden in humans have only recently been initiated. Manton has presented evidence from a preliminary study using lead isotope ratios.[47] His findings suggest that automobiles supplied between 7 ± 3 and 41 ± 3 percent of the lead in blood of Dallas residents during 1972 to 1973. Garibaldi et al.,[48] in a major study being conducted in Italy, are attempting such allocations on a much larger scale. It is hoped that these data will be available shortly.

Because multiple sources of lead do exist and because each can contribute to the total lead burden of man, an important question to be addressed is the contribution of each source to the total body burden. In this section, individual studies examining the contribution from the major environmental sources of lead, that is, air, soil-dust, paint, food, and water, will be discussed.

12.3.1 Air Exposures

Studies of the relationship of air exposures to blood lead levels may be separated into two main categories: epidemiological and clinical.

Epidemiological studies in turn may be grouped into three types: those pertaining to populations exposed to mobile sources of emission, those of populations exposed to stationary sources, and those in which only the amount of airborne lead is taken into account with no effort made to identify the source.

Studies dealing with mobile sources of lead will be discussed first, followed by a presentation of stationary sources studies. Studies concerned with air lead levels regardless of sources will then follow, and clinical studies will complete the presentation. From this array, the studies that permit the calculation of the quantitative relationship between lead in air and lead in blood will be selectively analyzed and discussed.

Clinical studies have the advantage of permitting precise control over the levels of exposure but have the disadvantages of studying people under somewhat artifical conditions and of dealing, by necessity, with very few subjects. All clinical studies to be presented were limited to adults. Epidemiological studies have the advantage of studying people in their natural state, but frequently have the disadvantage of rather imprecise estimates of the exposures encountered. These studies allow estimates of the relationship to be made for both adults and children.

12.3.1.1 MOBILE SOURCE STUDIES

12.3.1.1.1 Studies in the United States. A 1973 Houston study examined the blood lead levels of parking garage attendants, traffic policemen, and adult females living near freeways.[6] A control group for each of the three exposed populations was selected by matching for age, education, and race. Unfortunately, the matching was not altogether successful; traffic policemen had less education than their controls and the garage employees were younger than their controls. Females were matched

adequately, however. The findings for the six groups studied are presented in Table 12-14. It should be noted that the mean blood lead values for traffic policemen and parking garage attendants, two groups regularly exposed to higher concentrations of automotive exhausts, were significantly higher than the means for their relevant control groups. Statistically significant differences in mean values were not found, however, between women living near a freeway and control women living at greater distances from the freeway.

TABLE 12-14. MEAN BLOOD LEAD LEVELS FOR STUDY AND CONTROL GROUPS, HOUSTON[6]

Group	Mean, μg/dl	SD	Sample size	
Policemen	23.1	9.21	141	$P = 0.05$
Controls	18.4	7.38	150	
Garage attendants	28.3	10.33	119	$P = 0.05$
Controls	21.3	9.70	95	
Women living near freeway	12.9	4.47	120	$P > 0.05$
Controls	11.9	4.28	117	

A California study[7,49] examined blood lead levels in relation to exposure from automotive lead in two communities, Los Angeles and Lancaster (a city representative of the high desert). Los Angeles residents studied were individuals living in the vicinity of heavily traveled freeways within the city. They included males and females, aged 1 through 16, 17 through 34, and 35 and over. The persons selected from Lancaster represented similar age and sex distributions. On two consecutive days, blood, urine, and feces samples were collected. Air samples were collected from one Hi-Vol sampler in Los Angeles, located near a freeway, and two such samplers in Lancaster. The Los Angeles sampler collected for 7 days; the 2 in Lancaster were utilized for 14 days. On the first day of air sampling, soil samples were collected in each area in the vicinity of study subjects.

Lead in ambient air along the Los Angeles freeway averaged 6.3 ± 0.71 μg/m³, and in the Lancaster area the average was 0.6 ± 0.21 μg/m³. The mean soil lead in Los Angeles was 3633 μg/g, whereas that found in Lancaster was 66.9 μg/g. Higher concentrations of lead were found in the blood of children, as well as younger and older adults living near the freeway, than in individuals living in the control area. Table 12-15 shows the mean blood lead values for the six groups. Differences between Los Angeles and Lancaster groups were significant with the sole exception of the older males.

TABLE 12-15. ARITHMETIC AND GEOMETRIC MEAN BLOOD LEAD LEVELS (μg/dl) FOR LOS ANGELES AND LANCASTER, CA, BY SEX AND AGE[7]

	Los Angeles				Lancaster				
Groups by sex and age, years	N	Mean	SE[a]	Geometric mean	N	Mean	SE	Geometric mean	Significance of difference P[b]
Total	126	16.4	0.7	14.6	119	10.5	0.4	9.6	<<.001
Males	56	19.3	1.1	17.2	50	11.8	0.6	10.8	<<.001
1-16	20	23.5	2.5	20.8	21	11.1	0.8	10.4	<<.001
17-34	29	16.6	1.1	15.1	18	11.8	0.9	10.9	.003
35-	7	18.5	2.0	17.1	11	13.0	2.0	11.1	.09
Females	70	14.2	0.7	12.8	69	9.6	0.4	8.8	<<.001
1-16	18	16.7	1.8	14.9	25	10.2	0.7	9.6	<.001
17-34	41	12.9	0.6	11.8	16	9.1	1.2	8.0	<.001
35-	11	14.7	1.5	13.4	28	9.3	0.5	8.7	<.001

[a] Standard error.
[b] t test.

It has been pointed out by Snee that, in the high-traffic-density area, the reported 29 percent of samples in children 1 through 16 years old exceeding 40 μg/dl represented 5 individuals.[50] For 3 of these a second blood sample showed approximately 20 μg/dl; a second sample was not collected from the other 2. The disparity between blood samples taken on consecutive days from children in the study calls into question the validity of using these values to quantify the air lead to blood lead relationship. The differences between samples for adults, although somewhat larger than those found in other studies, appear acceptable for use in calculations, however.

A study of the effects of lower-level urban traffic densities on blood lead levels was undertaken in Dallas, Tex., in 1976.[34] The study consisted of two phases. One phase measured air-lead values for selected traffic densities and conditions, ranging

from ≤1,000 to about 37,000 cars/day. The second phase consisted of an epidemiological study of traffic density and blood lead levels among residents. Figure 12-4 shows the relationship between arithmetic means of air lead and traffic density. As can be seen from the graph, a reasonable fit is shown.

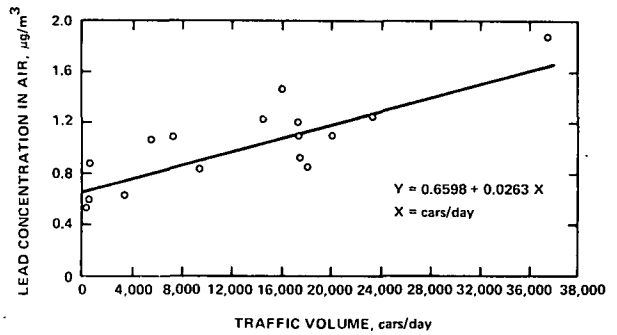

Figure 12-4. Arithmetic mean of air lead levels by traffic count, Dallas, 1976.[34]

In addition, during this phase, data for indoor-outdoor comparisons of air lead levels were collected. In two areas, with traffic densities of 10,000 and 20,000 cars/day, high volume samplers measured air lead outside of selected houses. At the same time, indoor air lead values for these houses were also collected. Table 12-16 shows the findings. Approximately a tenfold difference was found between indoor-outdoor values in both locations. It has been postulated that at least part of this difference is the result of using air conditioners.

TABLE 12-16. MEAN AIR LEAD LEVELS (μg/m³) INDOORS AND OUTDOORS AT TWO TRAFFIC DENSITIES, DALLAS, TEX. 1976[34]

	10,000 cars/day		20,000 cars/day	
	Indoor	Outdoor	Indoor	Outdoor
Mean	0.182	0.918	0.199	2.105
N	9	9	5	5

In addition, for all distances measured (5 to 100 ft from the road), air lead concentrations declined rapidly with distance from the street. At 50 ft concentrations were about 55 percent of the street concentration; at 100 ft concentrations were less than 40 percent of the street concentrations. In air lead collections from 5 to 100 ft from the street, approximately 50 percent of the airborne lead was in the respirable range (< 1 μm) and the proportions in each size class remained approximately the same as the distance from the street increased.

Soil lead concentrations were higher in areas with greater traffic density (Table 12-17). The maximum soil level obtained was 730 μg/g.

TABLE 12-17. SOIL LEAD LEVELS BY TRAFFIC DENSITY[34]

Traffic density, vehicles/day	Soil lead levels, μg/g
<1,000	73.6
1,000-13,499	92.2
13,500-19,499	110.9
>19,500	105.9

Dustfall samples for 28 days from 9 locations showed no relationship to traffic densities, but outdoor levels were at least 10 times the indoor concentration in nearby residences.

In the second phase, three groups of subjects, 1 to 6 years old, 18 to 49 years old, and 50 years and older, were selected in each of 4 study areas. Traffic densities selected were: < 1,000, 8,000 to 14,000, 14,000 to 20,000, and 20,000 to 25,000 cars/day. The study groups averaged about 35 subjects, although the number varied from 21 to 50. The smallest groups were from the highest traffic density area. No relationship between traffic density and blood lead levels in any age groups was found (Figure 12-5). Blood lead levels were significantly higher in children, 12 to 18 μg/dl, than in adults, 9 to 14 μg/dl.

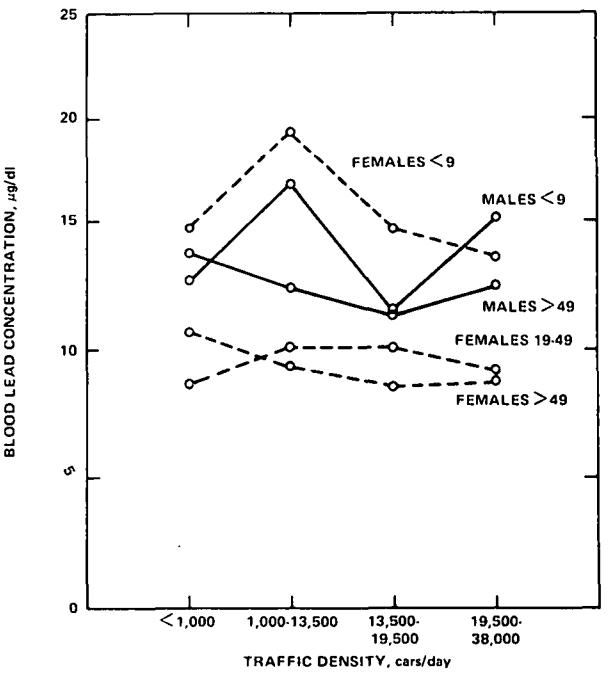

Figure 12-5. Blood lead concentration and traffic density by sex and age, Dallas, 1976.[34]

Galke et al.[43] studied blood lead levels in 187 South Carolina children 1 to 5 years old in relation to lead in soil and to automobile traffic. The arithmetic mean blood lead level was related to both factors, as shown in Table 12-18.

TABLE 12-18. BLOOD LEAD CONCENTRATIONS IN RELATION TO SOIL LEAD CONCENTRATIONS AND TRAFFIC DENSITY[43] (μg/dl)

Soil lead concentrations, μg/g	Automobile traffic density: Low mean (951-1677 cars/day)	High mean (2446-9637 cars/day)	All densities
<585	32 (7)[a]	41 (8)	35 (8)
>585	36 (10)	43 (11)	41 (11)
Total	34 (9)	42 (10)	38 (10)

[a] Standard deviation of a single observation.

Caprio et al.[51] compared blood lead levels and proximity to major traffic arteries in a study, reported in 1971, that included 5226 children in Newark, New Jersey. Over 57 percent of the children living within 100 ft of roadways had blood lead levels greater than 40 μg/dl. For those living between 100 and 200 ft from the roadways, more than 27 percent had such levels; and at distances greater than 200 ft, 31 percent exceeded 40 μg/dl. Table 12-19 indicates that the effect of automobile traffic was seen only in the group that lived within 100 ft of the road.

TABLE 12-19. BLOOD LEAD LEVELS IN CHILDREN AGED 1 TO 5 IN NEWARK, NJ, IN RELATION TO DISTANCE OF RESIDENCE FROM A MAJOR ROADWAY, 1971[51] (μg/dl)

Distance of residence from roadway, ft	Percent blood lead levels: <40	40-59	>60	Number
<100	42.6	49.3	8.1	758
100-200	72.4	24.2	3.4	507
>200	68.4	26.9	4.7	3961
number	3401	1562	263	5226

No other sources of lead were considered in this study. Data from other studies on mobile sources indicate, however, that it is unlikely that the blood lead levels observed in this study resulted entirely from automotive exhaust emissions.

Daines et al. studied black women living near a heavily traveled highway in New Jersey.[52] The subjects lived in houses on streets paralleling the highway at 3 distances, 3.7, 38.1, and 121.9 m. Air lead as well as levels for blood lead were measured. Mean annual air lead concentrations were 4.60, 2.41, and 2.24 μg/m^3, respectively, for the 3 distances. The mean air lead concentration for the area closest to the highway was significantly different from that in both the second and third, but the mean air lead concentration of the third area was not significantly different from that of the second. The results of the blood lead determinations paralleled those of the air lead. Mean blood lead levels of the 3 groups of women, in order of increasing distance, were 23.1, 17.4, and 17.6 μg/100 g, respectively. Again, the first group showed a significantly higher mean that the other two, but the second and third groups' blood lead levels were similar to each other. Daines et al.,[52] in the same publication, reported a second study in which the distances from the highway were 33.5 and 457 meters and where the subjects were white upper middle class women. Although the air lead levels were trivially different at these two distances, the blood lead levels did not differ. Because the residents nearest the road were already 33 m (+100 ft) from it and because other studies had shown an exponential decline in air lead levels with increasing distance from the road, reaching background air lead levels at 250 ft, the explanation may lie in the fact the air lead levels, although statistically different, were insufficient to be reflected in the blood lead levels. It is not possible to substantiate this possibility because the observed air lead values for the two distances were not reported.

In 1964, Thomas et al.[53] investigated blood lead levels in 50 adults who had lived for at least 3 years within 250 ft of a freeway (Los Angeles) and those of 50 others who had lived for a like period near the ocean or at least 1 mile from a freeway. Mean blood lead levels for those near the freeway were 22.7 ± 5.6 for men and 16.7 ± 7.0 μg/dl for women. These concentrations were higher than for control subjects living near the ocean: 16.0 ± 8.4 μg/dl for men and 9.9 ± 4.9 μg/dl for women. The higher values, however, were similar to those of other Los Angeles populations. Measured mean air concentrations of lead in Los Angeles for October 1964 were 12.25 ± 2.70 μg/m^3 at a location 30 ft from the San Bernardino freeway; 13.25 ± 1.90 μg/m^3 at another location 40 ft from the same freeway; 6.40 ± 2.15 μg/m^3 at a fourth floor location 300 ft from the freeway; and 4.60 ± 1.92 μg/m^3 1 mile from the nearest freeway. The investigators concluded that the differences observed were consistent with coastal-inland atmospheric and blood lead gradients in the Los Angeles basin and that the effect of residential proximity to a freeway (25 to 250 ft) was not demonstrated.

12.3.1.1.2 British studies. In a Birmingham, England, study, mean blood lead levels in 41 males and 58 females living within 800 m of a highway interchange were 14.41 and 10.93 μg/dl, respectively, just prior to the opening of the interchange in May 1972.[54] From October 1972 to February 1973 the respective values for the same individuals were 18.95 and 14.93 μg/dl. In October 1973 they were

23.73 and 19.21 μg/dl. The investigators noted difficulties in the blood collection method during the baseline period and changed from capillary to venous blood collection for the remaining two samples. To interpret the significance of the change in blood collection method, some individuals gave both capillary and venous blood at the second collection. The means for both capillary and venous bloods were calculated for the 18 males and 23 females who gave both types of blood.[55] The venous blood mean values for both these males and females were lower, 0.8 and 0.7 μg/dl, respectively. If these differences in means were applied to the means of the third series, the means for males would be reduced to 24.8 μg/dl and that for the females to 18.7 μg/dl. These adjusted means still show an increase over the means obtained for the first series. On the other hand, discarding the means calculated for the first series and comparing only the means for venous bloods, namely series two and three, again shows an increase for both groups. The increase in blood lead values was larger than expected following the model of Knelson et al.[56] because air lead values near the road were approximately 1 μg/m^3. The investigators concluded that either the lead aerosol of very small particles behaved more like a gas so that considerably more than 37 percent of inhaled material was absorbed or that ingestion of lead-contaminated dust might be responsible.

Studies of taxicab drivers have employed different variables to represent the drivers' lead exposure,[57,58] one being night- versus day-shift drivers;[51] the other, mileage driven.[58] In neither case was any difference observed.

The studies reviewed show that automobiles produce sufficient emissions to increase air and nearby soil concentrations of lead as well as increase blood lead concentrations in children and adults. The problem is of greater importance when houses are located within 100 ft (30 m) of the roadway.

12.3.1.2 STATIONARY SOURCE STUDIES

12.3.1.2.1 Primary smelters. Most studies of nonindustry-employed populations living in the vicinity of industrial sources of lead pollution were triggered because evidence of severe health impairment had been found. Subsequently, extremely high exposures and high blood lead concentrations were found. The following studies document the health problems that can develop as well as some of the relationships between environmental exposure and human response.

12.3.1.2.1.1 *El Paso, Texas.* In 1972, the Center for Disease Control, formerly the Communicable Disease Center, studied the relationships between blood lead levels and environmental factors in the vicinity of a primary smelter emitting lead, copper, and zinc located in El Paso, Texas, that had been in operation since the late 1800's.[33,59] Estimated lead emissions from this smelter were 297 metric tons in 1969, 519 metric tons in 1970, and 317 metric tons in 1971.[33] These figures, however, include only stack emissions; the quantities in fugitive emissions via ventilation, windows, etc., are unknown. Daily high-volume samples collected on 86 days between February and June 1972 averaged 6.6 μg/m^3 of lead. Concentrations ranged from 0.49 to 75 μg/m^3. These air lead levels fell off rapidly with distance, reaching, as would be expected, background values approximately 5 km from the smelter. Levels were higher downwind, however. High concentrations of lead in soil and housedust were found, with the highest levels occurring near the smelter. The geometric means of 82 soil and 106 dust samples from the sector closest to the smelter were 1791 and 4022 μg/g, respectively. Geometric means of both soil and dust lead levels near the smelter were significantly higher than those in study sectors 2 or 3 km farther away.

Sixty-nine percent of children 1 to 4 years old living near the smelter had blood lead levels > 40 μg/dl, and 14 percent had blood lead levels that exceeded 60 μg/dl. Concentrations in older individuals were lower; nevertheless, 45 percent of the children 5 to 9 years old, 31 percent of the individuals 10 to 19 years old, and 16 percent of the individuals above 19 had blood lead levels all exceeding 40 μg/dl. The data presented preclude calculations of means and standard deviations.

Data for people aged 1 to 19 years living near the smelter showed a relationship between blood lead levels and concentrations of lead in soil and dust. For individuals with blood lead levels >40 μg/dl, the geometric mean concentration of lead in soil at their homes was 2587 μg/g, whereas for those with a blood lead concentration <40 μg/dl, home soils had a geometric mean of 1419 μg/g. For housedust, the respective geometric means were 6447 and 2067 μg/g.

Analysis found the effect of length of residence to be important only in the sector nearest the smelter. Forty-three percent of the 1- to 19-year-olds who had lived there 2 or more years had blood lead values ≥40 μg/dl, whereas only 18 percent of the 1- to 19-year-olds who had lived there less than 2 years had similar levels.

Additional sources of lead were also investigated. A relationship was found between blood lead con-

centrations and lead release from pottery, but the number of individuals involved was very small. No relationships were found between blood lead levels and hours spent out of doors each day, school attendance, or employment of a parent at the smelter. The reported prevalence of pica also was minimal.

It was concluded that the primary factor associated with elevated blood lead levels in the children was ingestion or inhalation of dust containing lead. Data on dietary intake of lead were not obtained because the climate and proximity to the smelter prevented any farming in the area. It was unlikely that the dietary lead intakes of the children from near the smelter and farther away were significantly different.

12.3.1.2.1.2 *Kellogg, Idaho.* In 1970, EPA carried out a study of a lead smelter in Kellogg, Idaho.[60,61] The study was part of a national effort to determine the effects of sulfur dioxide, total suspended particulate, and suspended sulfates, singly and in combination with other pollutants, on human health. It focused on mixtures of the sulfur compounds and metals. Although it was demonstrated that children had evidence of lead absorption, insufficient environmental data were reported to allow further quantitative analyses.

In 1974, following the hospitalization of two children with suspected acute lead poisoning, CDC joined the State of Idaho in a comprehensive study of children in the area.[1,62] The studies conducted in this area unfortunately used a bewildering array of designations in their reports, but all are related to the same industrial complex.

The source of exposure was a smelter whose records showed that emissions of lead into the atmosphere averaged 8.3 metric tons per month from 1955 to 1964, 11.7 metric tons from 1965 to September 1973, and 35.3 metric tons from October 1973 to September 1974.[62] In September 1973, a fire destroyed the main filtration facility for the smelter. The study was initiated in September 1974, after two children were hospitalized with symptoms of lead poisoning. At that time, blood lead levels ≥40 μg/dl were found in 385 (41.9 percent) of 919 children less than 10 years old who were examined. About 99 percent of the 172 children living within 1.6 km of the smelter had blood lead values ≥40 μg/dl. The mean blood concentration declined with distance from the point of emission (Table 12-20). Blood lead levels were consistently higher in children 1 to 4 years old than in those 5 to 9 years old. In addition, higher levels in children were associated with reported active ingestion of lead-containing material (pica), with lower socioeconomic status, and with parental employment at the smelter or at a lead mine. A significant negative relationship between blood lead level and hematocrit value was found. Seven of 41 children (17 percent) with blood lead levels ≥80 μg/dl were diagnosed by the investigators as being anemic on the basis of hematocrit less than 33 percent, whereas only 16 of 1006 children (1.6 percent) with blood lead levels < 80 μg/dl were so diagnosed.

TABLE 12-20. GEOMETRIC MEAN BLOOD LEAD LEVELS BY AREA COMPARED WITH ESTIMATED AIR LEAD LEVELS FOR 1- TO 9-YEAR-OLD CHILDREN LIVING NEAR IDAHO SMELTER (Geometric standard deviations, sample sizes, and distances from smelter are also given)[a]

Area	GM blood lead, μg/dl	GSD	Sample size	Estimated air lead, μg/m³	Distance from smelter, km
1	65.9	1.30	170	18.0	0- 1.6
2	47.7	1.32	192	14.0	1.6- 4.0
3	33.8	1.25	174	6.7	4.0-10.0
4	32.2	1.29	156	3.1	10.0-24.0
5	27.5	1.30	188	1.5	24.0-32.0
6	21.2	1.29	90	1.2	about 75

[a] EPA analysis of data from Yankel et al.[1]

Although no overt neurologic disease was observed in children with higher lead intake, differences were found in nerve conduction velocity. Details of this finding were discussed in a previous chapter.

Beginning in 1971, ambient concentrations of lead in the vicinity of the smelter were determined from particulate matter collected in high-volume air samplers. Data indicated that monthly average levels measured in 1974 (Figure 12-6) were three to four times the levels measured in 1971.[63] Individual exposures to lead were estimated by interpolation from these high-volume data, and a strong correlation was found between the estimates and the measured blood lead levels (r + 0.72).

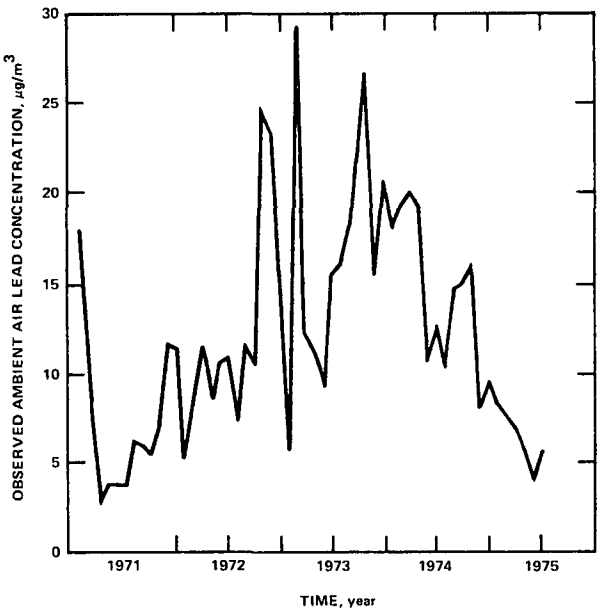

Figure 12-6. Monthly ambient air lead concentrations in Kellogg, Idaho, 1971 through 1975.[63]

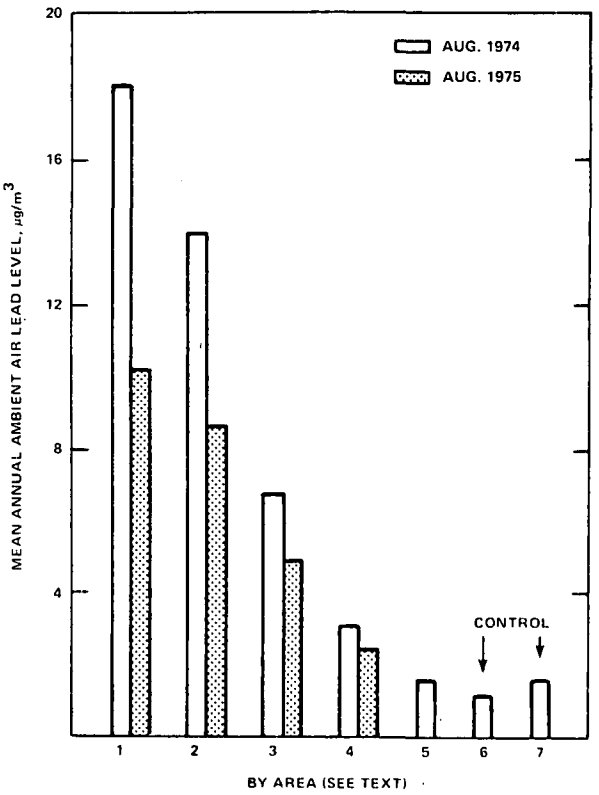

Figure 12-7. Annual ambient air lead concentration, by area, before the August 1974 and August 1975 surveys.[1]

Subsequently, Yankel et al. published additional information concerning the 1974 study as well as the results of a follow-up study conducted in 1975.[1] The follow-up was undertaken to determine the effectiveness of control measures initiated after the 1974 study.

Between August 1974 and August 1975, the mean annual air lead levels decreased at all stations monitored (Figure 12-7). In order of increasing distance from the smelter, the concentrations in the two years were 18.0 to 10.3 $\mu g/m^3$, 14.0 to 8.5 $\mu g/m^3$, 6.7 to 4.9 $\mu g/m^3$, and, finally, 3.1 to 2.5 $\mu g/m^3$ at 10 to 24 km. Similar reductions were noted in the housedust lead concentrations.

In a separate report, von Lindern and Yankel described reductions in blood lead levels of children for whom determinations were made in both years.[60] It was pointed out that the children with the highest blood lead levels in 1974 had been relocated; their removal and subsequent relocation would complicate any analysis in which they were included. To compensate for this, the authors also presented separately the blood lead levels for those children living in the same home both years. This greatly reduced the number of observations reported. The results (Table 12-21) demonstrate that significant reductions in blood lead concentration can be effected, and that they were observed in each study area. In areas III, IV, and V, all mean blood lead levels were <40 $\mu g/dl$.

The report of Yankel et al.[1] showed that there were reductions in environmental lead contamination between 1974 and 1975, and that the correlations between blood lead levels and environmental or demographic factors were consistent from one year to the next. Five factors influenced, in a statistically significant manner, the probability of a child developing an excessive blood lead level:

1. Concentrations of lead in ambient air ($\mu g/m^3$).
2. Concentration of lead in soil (ppm).
3. Age (years).
4. Cleanliness of the home (subjective evaluation coded 0, 1, and 2, with 2 signifying dirtiest).
5. General classification of the parents' occupation (dimensionless).

Although the strongest correlation found was between blood lead level and air lead level, the authors concluded that it was unlikely that inhalation of contaminated air alone could explain the elevated blood lead levels observed.

Yankel and von Lindern reasoned that even though air lead was the principal source, a major route of exposure was the ingestion of lead in soil and dust.[1] They proposed that to protect the health

TABLE 12-21. MEAN BLOOD LEAD LEVELS IN CHILDREN LIVING IN VICINITY OF A PRIMARY LEAD SMELTER, 1974 and 1975

	Study area and data set									
	I		II		III		IV		V	
Group	N	$\bar{X}$	N	$\bar{X}$	N	$\bar{X}$	N	$\bar{X}$	N	$\bar{X}$
Blood levels >80 μg/dl[a] in 1974 test	—	90.2	—	80.0	—	—	—	—	—	—
Retested in 1975	7	52.3	1	61.0	—	—	—	—	—	—
Difference	—	-38.0	—	-19.0	—	—	—	—	—	—
Blood levels >60 but <80 μg/dl in 1974 test	—	64.5	—	69.6	—	—	—	—	—	61.0
Retested in 1975	18	47.4	8	50.3	—	—	—	—	3	51.0
Difference	—	-17.2	—	-19.3	—	—	—	—	—	-10.0
Blood levels <60 μg/dl in 1974 test	—	52.3	—	47.0	—	45.6	—	43.7	—	43.4
Retested in 1975	9	37.4	23	36.0	20	39.8	14	37.4	8	33.5
Difference	—	-14.9	—	-11.0	—	- 5.8	—	- 6.3	—	- 9.9

[a] Adapted from von Lindern and Yankel.[63]

of the children in this area the regulation of environmental standards must take into account all of these routes of exposure.

These investigators developed a mathematical model based on the 1974 data that included each of the five factors that had been shown to be correlated with increased blood lead levels. The model, shown below, can be used to estimate the effect of variations in the environmental factors on mean blood lead levels in children:

$$\ln(\text{Pb-B}) = 3.1 + 0.041\,(\text{Air}) + 2.1 \times 10^{-5}\,(\text{Soil}) + 0.087\,(\text{Dust}) + 0.018\,(\text{Age}) + 0.024\,(\text{Occupation}).$$

(See above for definition of units). (12-6)

12.3.1.2.1.3 *CDC-EPA study.* Baker et al.,[31] in 1975, surveyed 1774 children 1 to 5 years old, most of whom lived within 4 miles of 19 lead, copper, or zinc smelters located in various parts of the United States. Blood lead levels were modestly elevated near two of the 11 copper and two of the five zinc smelters. Although blood lead levels in children were not elevated in the vicinity of three lead smelters, their FEP levels were somewhat higher than those found in controls. Increased levels of lead and cadmium in hair samples were found near lead and zinc smelters; this was considered evidence of external exposure. No environmental determinations were made for this study.

12.3.1.2.1.4 *Meza Valley, Yugoslavia.* A Yugoslavian study in the Meza Valley investigated exposures to lead from a mine and a smelter over a period of years.[64-69] The mine and smelter are located near a river flowing in the valley. The smelter produces about 23,000 metric tons annually. After control equipment was installed on 1 of 2 lead-emitting stacks, emissions were calculated to be 203.2 metric tons/year. In 1967, 24-hr lead concentrations measured from 4 different days varied from 13 to 84 $\mu g/m^3$ in the village nearest the smelter, and concentrations of up to 60 $\mu g/m^3$ were found as far as 5 km from the source. Mean particle size in 1968 was $<0.8\ \mu m$. The lead levels were about 25,000 ppm in the most contaminated area. Analysis of some common foodstuffs showed concentrations that were 10 to 100 times higher than corresponding foodstuff from the least exposed area (Mezica).[64]

After January 1969 when partial control of emissions was established at the smelter, weighted average weekly exposure was calculated to be 27 $\mu g/m^3$ in the village near the smelter. In contrast to this, the city of Zagreb,[65] which has no large station-

ary source of lead, had an average weekly air lead level of 1.1 $\mu g/m^3$.

In 1968, the average concentration of ALA in urine samples from 912 inhabitants of six villages varied by village from 9.8 to 13 mg/liter. A control group had a mean ALA of 5.2 mg/liter. Data on lead in blood and the age and sex distribution of the villagers were not given.[64]

Of the 912 examined, 559 had an ALA level >10 mg/liter of urine. In 1969, a more extensive study of 286 individuals with ALA >10 mg/liter was undertaken.[66] ALA-U decreased significantly from the previous year. When the published data were examined closely, there appeared to be some discrepancies in interpretation. The exposure from dust and from food might have been affected by the control devices, but no data were collected to establish this. In one village, Zerjau, ALA-U dropped from 21.7 to 9.4 mg/liter in children 2 to 7 years of age. Corresponding ALA-U values for 8- to 15-year-olds and for adult men and women were reduced from 18.7 to 12.1, from 23.9 to 9.9, and from 18.5 to 9.0 mg/liter, respectively. Because lead concentrations in air[65] even after 1969 indicated an average exposure of 25 $\mu g/m^3$, it is possible that some other explanation should be sought. The author indicated in the report that the decrease in ALA-U showed "the dependence on meteorologic, topographic, and technologic factors."[66] Lead in blood was determined, but according to the report "determination of lead in blood could not be used for exposure evaluation because all obtained values were in the normal limits" (under 80 μg/dl blood as defined by the author).[66] In light of current knowledge, this definition of normal levels is excessively high.

The excretion of nonchelated lead in urine in 8.5 percent of 209 individuals was above 0.1 mg/liter. The highest value recorded was 0.19 mg/liter. When treated with Ca EDTA, the mobilized lead in the urine of these individuals ranged from 0.5 to 4.2 mg/liter, indicating the presence of total body burdens ranging from normal to ten times normal.[66,68]

Another finding of this project was a significant increase in reticulocytes, especially in children.[66] Forty-seven percent of exposed adults complained of pain in their bones compared with only 3 percent of the controls.

Fugas et al.[69] in a later report estimated the time-weighted average exposure of several populations studied during the course of this project. Stationary samplers as well as personal monitors were used to estimate the exposure to airborne lead for various parts of the day. These values were then coupled with estimated proportions of time at which these exposures held. In Table 12-22, the estimated time-weighted blood lead values as well as the observed mean blood lead levels for these studied populations are presented. An increase in blood lead values occurs with increasing air lead exposure.

TABLE 12-22. MEAN BLOOD LEAD LEVELS IN SELECTED YUGOSLAVIAN POPULATIONS, BY ESTIMATED WEEKLY TIME-WEIGHTED AIR LEAD EXPOSURE[69]

Population	N	Time-weighted air lead $\mu g/m^3$	Mean blood lead level, μg/dl	SD
Rural I	49	0.079	7.9	4.4
Rural II	47	0.094	11.4	4.8
Rural III	45	0.146	10.5	4.0
Postmen	44	1.6	18.3	9.3
Customs officers	75	1.8	10.4	3.3
Street car drivers	43	2.1	24.3	10.5
Traffic policemen	27	3.0	12.2	5.1

12.3.1.2.1.5 *East Helena, Montana.* EPA in 1972 investigated a lead-emitting smelter complex in East Helena, Montana.[60] The quantities of lead emissions were not known. Air lead concentration, measured in 1969, yielded averages from several stations that varied from 0.4 to 4 $\mu g/m^3$; the maximum 24-hr value was found to be 15 $\mu g/m^3$. In the city of Helena, the average concentration was 0.1 $\mu g/m^3$. Lead in soil was found to be 4000, 600, and 100 $\mu g/g$ at distances of 1.6, 3.2, and 6.4 km (1, 2, and 4 miles), respectively, from the smelting complex. Uncontaminated soil near the Helena Valley showed a mean of 16 $\mu g/g$. Deposited lead (dustfall) was found to vary from 3 to 108 mg/m^2-month in East Helena and from 1 to 7 mg/m^2-month in Helena.

Studies on humans by Hammer et al.[61] were limited to children; lead values in hair and blood were found to be higher in East Helena than in Helena, the respective averages being 15.6 ± 5.1 and 11.6 ± 4.0 μg/dl in blood and about 40 and 13 ppm in hair. The hair values indicated differential exposure to lead. However, in the opinion of the investigators, although the blood lead values indicated an elevated exposure, it had not been excessive. No adverse health effects had been noted in these children.

12.3.1.2.1.6 *Other smelter studies.* Other reports in the literature have also shown that people living near smelters have increased burdens of lead in their bodies.[70-72] It is clear, therefore, that emissions from primary lead smelters can cause elevated blood lead levels and other indicators of increased lead burdens in populations living near these stationary emission sources.

The question of the accuracy of the reported analytic results in these studies is difficult to address because they spanned a period of time in which major strides were taken in improving analytical technology. Hence, the more recent studies are likely, but not necessarily, to provide more accurate information.

Although many of the reports specified that the blood lead levels were done in duplicate, this unfortunately does not ensure their accuracy. This problem is discussed in more detail in Chapter 9.

12.3.1.2.2 Other industrial sources. Exposures from both a primary and secondary smelter in the inner-city area of Omaha, Neb. have been reported by Angle et al. in a series of publications.[73-76] Studied from 1970 to 1977 were children from an urban school immediately adjacent to a small battery plant and downwind from two other lead emission sources, schools in a mixed commercial-residential area, and schools in a suburban setting. Children's blood lead levels were obtained by macro technique for 1970 and 1971, but Delves micro assay was used from 1972 on. The difference for the change in techniques was taken into account in the presentation of the data. Air lead values were obtained by Hi-Vol samplers, and dustfall values also were collected. Table 12-23 presents the authors' summary of all the data, showing that as air lead values decrease and then increase, dustfall and blood lead values follow. The authors used regression models, both log-linear and semilog, to calculate air lead/blood lead ratios and obtained values of 10.04 and 0.4, respectively. The 0.4 value is equivalent to a ratio of 10.4 at an air lead level of 1.0 $\mu g/m^3$.

TABLE 12-23. AIR, DUSTFALL, AND BLOOD LEAD CONCENTRATIONS IN OMAHA, NEB., STUDY, 1970-1977[a,75,76]

Group	Air, $\mu g\ m^3$ (N)[b]	Dustfall, $\mu g\ m^3$ - mo (N)[c]	Blood, $\mu g/dl$ (N)[d]
All urban children, site *m*:			
1970-71	1.48 ± 0.14(7;65)	—	31.4 ± 0.7(168)
1972-73	0.43 ± 0.08(8;72)	10.6 ± 0.3(6)	23.3 ± 0.3(211)
1974-75	0.10 ± 0.03(10;72)	6.0 ± 0.1(4)	20.4 ± 0.1(284)
1976-77	0.52 ± 0.07(12;47)	8.8 (7)	22.8 ± 0.7(38)
Children at school c, site *c*:			
1970-71	1.69 ± 0.11(7;67)	—	34.6 ± 1.5(21)
1972-73	0.63 ± 0.15(8;74)	25.9 ± 2.4(5)	21.9 ± 0.6(54)
1974-75	0.10 ± 0.03(10;70)	14.3 ± 4.1(4)	19.2 ± 0.9(17)
1976-77	0.60 ± 0.10(12;42)	33.9 (7)	22.8 ± 0.7(38)
All suburban children, site *r*:			
1970-71	0.79 ± 0.06(7;65)	—	—
1972-73	0.29 ± 0.04(8;73)	4.6 ± 1.1(6)	19.6 ± 0.5(81)
1974-75	0.12 ± 0.05(10;73)	2.9 ± 0.9(4)	14.4 ± 0.6(31)
1976-77	—	—	18.2 ± 0.3(185)

$r_{Pb\text{-}B \bullet Pb\text{-}A} = -0.95$ (N = 10)
Pb-B = 10.04 Pb-A + 17.06

$r_{1n\ Pb\text{-}B \bullet Pb\text{-}A} = 0.91$ (N = 10)
1n Pb-B = 0.4 Pb-A + 2.86

[a]Blood lead 1970-71 is by the macro technique, corrected for an established laboratory bias of 3 $\mu g/dl$, macro-micro; all other values are by Delves micro assay.
[b]N = Number of months; number of 24-hour samples.
[c]N = Number of months.
[d]N = Number of blood samples.

Specific reports present various aspects of the work done. Black children in the two elementary schools closest to the battery plant had higher blood leads (34.1 $\mu g/dl$) than those in elementary and junior high schools farther away (26.3 $\mu g/dl$). Best estimates of the air exposures were 1.65 and 1.48 $\mu g/m^3$, respectively.[73] The later study compared three populations: urban versus suburban high school students, ages 14 to 18; urban black children, ages 10 to 12, versus suburban whites, ages 10 to 12; blacks, ages 10 to 12, with blood lead over 20 μg percent versus schoolmates with blood lead levels below 20 μg percent.[74] The urban versus suburban high school children did not differ significantly, 22.3 ± 1.2 to 20.2 ± 7.0 $\mu g/dl$, respectively, with mean values of air lead concentrations of 0.43 and 0.29 $\mu g/m^3$. For the 15 students who had environmental samples taken from their homes, correlation

coefficients between blood lead levels and soil and housedust lead levels were 0.31 and 0.29 respectively.

Suburban 10-to-12-year-olds had lower blood lead levels than their urban counterparts, 17.1 ± 0.7 and 21.7 ± 0.5 μg/dl, respectively.[74] Air lead exposures were higher in the urban than in the suburban population, although the average exposure remained less than 1 $\mu g/m^3$. Dustfall lead measurements, however, were very much higher: 32.96 mg/m^2-month for urban 10-to-12-year-olds versus 3.02 mg/m^2-month for suburban ones.

Soil lead and housedust lead exposure levels were significantly higher for the urban black high-lead group than for the urban low-lead group. A significant correlation ($r = 0.49$) between blood lead and soil lead levels was found.

In a Dallas, Texas, study of two secondary lead smelters, the average blood lead levels of exposed children was found to be 30 μg/dl versus an average of 22 μg/dl in control children.[77] For the two study populations, the air and soil lead levels were 3.5 and 1.5 $\mu g/m^3$ and 727 and 255 ppm, respectively. Direct automobile traffic exposure was not considered.

In Toronto, Canada, the effects of two secondary lead smelters on the blood and hair lead levels of nearby residents have been extensively studied.[78,79] In a preliminary report, Roberts et al.[78] stated that blood and hair lead levels were higher in children living near the two smelters than in children living in an urban control area. Biologic and environmental lead levels were reported to decrease with increasing distance from the smelter stacks.

A later and more detailed report identified a high rate of lead fallout around the two secondary smelters.[79] Fallout in the vicinity of the smelters was caused primarily by large particulate fugitive emissions rather than stack emissions. Lead emissions from the two smelters were estimated to be 15,000 and 30,000 kg/yr. Lead concentrations in soil were as high as 40,000 and 16,000 ppm, respectively, close to the 2 smelters and dropped off exponentially with distance. They reached urban background levels of 100 to 500 ppm, 200 to 300 m from the smelter. Horn, in a later report, pointed out that the extremely high soil levels were the result of some samples containing scrap battery plate; in his report he states that the soil lead levels, excluding those contaminated samples, approached 8000 ppm in nonresidential areas and exceeded 4000 ppm in several residential yards.[80] He also pointed out several other deficiencies in the data.[80] A general criticism he leveled at the study's interpretation was that the authors concluded that soil lead was the main source of lead, a putative finding in Horn's view, especially considering that few soil samples were taken.

Lead concentrations in dustfall were much higher at 1 of the 2 smelters, exceeding 1500 mg/cm^2-month. These concentrations also exhibited an exponential decrease with distance similar to that observed for soils. Because the lead fallout occurred over a small area and consisted primarily of large particles (in some cases the mass median diameter was as large as 4.6 ± 1.3 μm), it was believed that the emissions originated mainly from dust-producing operations at low height rather than from stack emissions.[78]

Lead concentrations in air ranging from 1.0 to 5.3 $\mu g/m^3$ were only twice those found at other Toronto urban sites away from the smelter (0.8 to 2.4 $\mu g/m^3$). The range of daily concentrations was much greater. At 60 m from the stack, lead in 96 air samples ranged from 0.5 to 725 $\mu g/m^3$, whereas at 220 m 94 samples varied from <0.5 to 14 $\mu g/m^3$. Two groups of children living within 300 m of each of the smelters had geometric mean blood levels of 27 and 28 μg/dl, respectively; the geometric mean for 1231 controls was 17 μg/dl. Twenty-eight percent of the sample children tested near one smelter during the summer and 13 percent of the sample children tested near the second smelter during the winter had blood lead levels >40 μg/dl. Only 1 percent of the controls had blood lead levels >40 μg/dl. For children, blood lead concentrations increased with proximity to both smelters but this trend did not hold for adults generally.

Lead levels in hair samples averaged 41 μg/g in the smelter areas and 13 μg/g in the control area.[78] Blood lead and hair lead levels were found to be related, thus indicating a fairly constant rate of absorption. The authors concluded that for children with excessive lead absorption the major route of lead intake was ingestion of contaminated dirt and dust.[78,79] Increased excretion of δ-aminolevulinic acid and coproporphyrins was observed in most of these cases, and increased density of bone metaphyses was observed in four children.

Blood lead levels in 293 Finnish individuals aged 15 to 80 were significantly correlated with distance of habitation from a secondary lead smelter.[81] The geometric mean blood lead concentration for 121 males was 18.1 μg/dl; that for 172 females was 14.3 μg/dl. In 59 subjects who spent their entire day at home, a positive correlation was found between

m. Only one of these 59 individuals had a blood lead >40 μg/dl, and none exceeded 50 μg/dl.

A weaker correlation was obtained between ALAD activity and distance from the smelter, this being due almost entirely to the female subjects. Examination of ALAD activity for males showed it to be similar regardless of distance from the smelter. The authors speculate that this could be caused by other lead exposures in the male population.

Two reports from the USSR describe effects of lead in an area near a smelter.[82,83] Average concentrations of lead in air were as high as 4.1 μg/m^3 at a distance of 1500 m; peak exposures at this distance reached 9.7 μg/m^3. Neurological disturbances were noted in 50 percent of the subjects from the smelter area, compared with 6 percent in controls. No data were given on age, sex, and type of disturbances.[82] In a later study, children from the area were found to excrete more coproporphyrin than controls and also more lead.[83] The highest lead concentration in urine was reported to be 50 μg/liter.

Studies of the effects of storage battery plants have been reported from France and Italy.[84,85] The French study found that children from an industrialized area containing such a plant excreted more ALA than those living in a different area.[84] Increased urinary excretion of lead and coproporphyrins was found in children living up to 300 ft from a battery plant in Italy.[85] Neither study gave data on plant emissions or lead in air.

These studies demonstrate that stationary sources within urban areas do contribute to increases in air lead levels. They show not only that mean exposure levels are higher but that the range of exposures encountered in their vicinities is much larger for daily or longer averaging times than in the vicinity of mobile sources. Increases of 2 to 3 μg/m^3 in air lead concentrations have been associated with higher blood lead levels in exposed populations.

Although the significantly higher air lead concentrations decrease rapidly with distance from the point of emission, they contribute, together with mobile emissions, to the generally higher air levels found in urban areas and thus to the higher blood lead levels found in urban populations.

12.3.1.3 URBAN POPULATION STUDIES

Another group of studies dealing with urban populations examined air lead and blood lead values without considering the specific sources of the lead in the air.[2,3,16,41,42] Azar et al.[3] obtained 24-hr air lead exposures for 150 males over a 2- to 4-week period using personal samplers. Study groups consisted of 30 men in each of 5 city-occupation categories. The subjects included cabdrivers, plant employees, and office workers. From two to eight blood samples were obtained from each subject during the air monitoring phase. Blood lead determinations were done in duplicate. Table 12-24 presents the geometric means for air lead and blood lead for the five groups. The geometric means were calculated by EPA from the raw data presented in the authors' report.[3]

TABLE 12-24. GEOMETRIC MEAN AIR AND BLOOD LEAD LEVELS (μg/100 g) FOR FIVE CITY-OCCUPATION GROUPS[3] (Data calculated by EPA)

Group	Geometric mean air lead, μg/m^3	GSD	Geometric mean blood lead, μg/100 g	GSD	Sample size
Plant employees Starke, FL	0.59	2.04	15.4	1.41	29
Plant employees Barksdale, WI	0.61	2.39	12.8	1.43	30
Cabdrivers Philadelphia, PA	2.59	1.16	22.1	1.16	30
Office workers Los Angeles, CA	2.97	1.29	18.4	1.24	30
Cabdrivers Los Angeles, CA	6.02	1.18	24.2	1.20	30

Regression equations calculated by the authors for members of each of the individual study groups revealed no slopes significantly greater than zero. In view of the rather narrow range of lead exposures observed within the groups, this result is not surprising. Examination of the slopes for each study group showed they were homogeneous and thus could be combined. The specific method of combination can be argued, however. Azar et al. chose to use dummy variables to represent the differing intercepts of the study groups because the intercepts were not homogeneous. In effect, this means drawing a line with a pooled slope of 0.153 through the average blood lead concentration.

The Tepper and Levin[2] study, described in detail previously, included both air and blood lead measurements. Housewives were recruited from "locations in the vicinity of air monitors." Women included were >19 and <80 years of age, had no history of lead poisoning, and had not eaten wild game. Table 12-25 presents the geometric mean air and blood lead values obtained in the study, as calculated by EPA from the raw data. Geometric mean air lead values ranged from 0.17 to 3.39

$\mu g/m^3$, and geometric mean blood lead values ranged from 12.5 (1.31) to 20.6 (1.33) $\mu g/dl$.

TABLE 12-25. GEOMETRIC MEAN AIR AND BLOOD LEAD VALUES FOR 11 STUDY POPULATIONS[2] (Data calculated by EPA)

Community	Geometric mean air lead, $\mu g/m^3$	Blood lead, $\mu g/dl$ GM	GSD	Sample size
Los Alamos, NM	0.17	14.9	1.28	185
Okeana, OH	0.32	15.6	1.39	156
Houston, TX	0.85	12.5	1.31	186
Port Washington, NY	1.13	15.4	1.28	196
Ardmore, PA	1.15	18.0	1.38	148
Lombard, IL	1.18	13.9	1.27	146
Washington, DC	1.19	19.2	1.26	219
Rittenhouse, PA	1.67	20.6	1.33	136
Bridgeport, IL	1.76	17.6	1.27	146
Greenwich Village, NY	2.08	16.6	1.28	139
Pasadena, CA	3.39	17.5	1.31	194

Nordman reported a population study from Finland[16] in which data from five urban and two rural areas were compared. This study was described in detail above. Air lead data were collected by stationary samplers. All levels were comparatively low, particularly in the rural environment, where a concentration of 0.025 $\mu g/m^3$ was seen. Urban-suburban levels ranged from 0.43 to 1.32 $\mu g/m^3$.

A study was undertaken by Tsuchiya et al.[41] in Tokyo using male policemen who worked, but not necessarily lived, in the vicinity of air samplers. In this study, five zones were established, based on degree of urbanization, ranging from central city to suburban. Air monitors were established at various police stations within each zone. Air sampling was conducted from September 1971 to September 1972; blood and urine samples were obtained from 2283 policemen in August and September 1971. Findings are presented in Table 12-26. A consistent correlation between air and blood lead means for the five zones is shown.

TABLE 12-26. MEAN AIR AND BLOOD LEAD VALUES FOR FIVE ZONES IN TOKYO STUDY[41]

Zones	Air lead, $\mu g/m^3$	Blood lead, μg 100 g
1	0.024	17.0
2	0.198	17.1
3	0.444	16.8
4	0.831	18.0
5	1.157	19.7

Goldsmith[42] obtained data for elementary school (9- and 10-year-olds) and high school students in 10 California communities. Lowest air lead exposures were 0.28 $\mu g/m^3$ and highest were 3.4 $\mu g/m^3$. For boys in elementary school, blood lead levels ranged from 14.3 to 23.3 $\mu g/dl$; those for girls ranged from 13.8 to 20.4 $\mu g/dl$ for the same range of air lead exposures. The high school student population was made up of only males from some of the 10 towns. The air lead range was 0.77 to 2.75 $\mu g/m^3$ and the blood lead range was from 9.0 to 12.1 $\mu g/dl$. For the high school students the town with the highest air lead value did not have the highest blood lead level. A further comment on methodology pertains to the fact that a considerable lag time occurred between the collection and analysis of the blood samples.

12.3.1.4 CLINICAL AND EXPERIMENTAL STUDIES IN RELATION TO AIR LEAD/BLOOD LEAD RATIOS

Griffin and his colleagues undertook two studies using volunteers exposed in a gas chamber to an artificially generated aerosol of submicron-sized particles of lead dioxide.[86] All volunteers were introduced into the chamber 2 weeks prior to the initiation of the exposure; the lead exposures were scheduled to last 16 weeks, although the volunteers could drop out whenever they wished. Twenty-four volunteers, including 6 controls, participated in the 10.9 $\mu g/m^3$ exposure study. Twenty-one subjects, including 6 controls, participated in the 3.2 $\mu g/m^3$ exposure study. Not all volunteers completed the exposure regimen. Blood lead levels were found to stabilize after approximately 12 weeks. Among 11 men exposed to 10.9 $\mu g/m^3$ for at least 60 days, a stabilized mean level of 34.5 $\pm$ 5.1 $\mu g/dl$ blood was obtained, as compared with an initial level of 19.4 $\pm$ 3.3 $\mu g/dl$. All but 2 of the 14 men exposed at 3.2 $\mu g/m^3$ for at least 60 days showed increases and a stabilized level of 25.6 $\pm$ 3.9 $\mu g/dl$ was found, compared with an initial level of 20.5 $\pm$ 4.4 $\mu g/dl$. This represented an increase of about 40 percent above the base level.

From the data Table 12-27 was constructed, which shows the time needed to reach specific blood lead levels at the two air lead concentrations. As can readily be seen even at the lower exposure, it takes only 7 weeks for the population mean blood level to increase by 5 $\mu g/dl$.

In the article, the authors described both the chemistry and particle size of the lead aerosols generated. In general, the aerosols used in this experiment were somewhat less complex chemically, as well as somewhat smaller, than those found in the ambient environment. Griffin et al.,[86] however, point out that good agreement was achieved on the basis of the comparison of their observed blood lead

TABLE 12-27. LENGTH OF TIME NEEDED FOR MEAN BLOOD LEAD VALUES TO REACH SPECIFIED LEVELS AT TWO EXPOSURE LEVELS

Exposure group	Air lead level, $\mu g/m^3$	Avg. baseline blood lead level, $\mu g/dl$	Target blood lead level, $\mu g/dl$	Time needed to reach target level, wk
1	10.9	20.0	25	1 to 2
1	10.9	20.0	30	4
1	10.9	20.0	35	6
2	3.2	20.8	25	7
2	3.2	20.8	30	Not reached
2	3.2	20.8	35	Not reached

levels with those predicted by Goldsmith and Hexter's equation,[87] that is, $\log_{10}$ blood lead = 1.265 + 0.2433 $\log_{10}$ atmospheric exposure.

In contrast to the study of Griffin et al. that approximates the exposure regimen of environmentally exposed persons, Kehoe studied long-term exposures under conditions approximating those of occupationally exposed individuals.[88] Kehoe exposed a subject to an air lead as the sesquioxide first at 75 $\mu g/m^3$ then at 150 $\mu g/m^3$. Definite increases in urinary and blood lead levels emerged under each exposure. There appeared to be a plateau reached in the blood lead levels upon a steady state exposure.

Gross compiled data from lead balance studies conducted by Kehoe between 1934 and 1972 and determined that increases of levels in blood, urine, and feces under controlled clinical exposure were 0.38 $\mu g/dl$, 0.88 $\mu g/day$, and 2.50 $\mu g/day$, respectively, for each increase of 1 $\mu g/m^3$ in air lead levels.[89]

The derivation of these estimates is currently unknown but was based on the results of ingestion and inhalation studies carried out on 16 individuals over 21,000 person-days. During this period, there were 102 study periods for the 16 subjects. None of the subjects experienced harmful effects as a result of the lead exposures, the highest of which were approximately 30 $\mu g/m^3$ on a 24-hr basis (every other day to 6 days per week) for study periods up to 628 days. With a single exception, in none of the subjects did the blood level exceed 40 $\mu g/dl$.

Rabinowitz and colleagues have conducted studies of lead metabolism by stable isotopes that permit the determination of blood/air lead relationships.[90,91] In one study, a single volunteer was confined in a hospital's metabolic research ward for a period of 109 days for 23 hr a day.[90] He was then removed into a "clean" room in which the air was filtered to remove the particulate lead. For the first 15 days in the room, his daily lead intake was supplemented by lead additions to the diet to compensate for the loss of air lead intake. At the end of this 15-day period the dietary lead supplement was discontinued. He immediately showed a declining blood lead level that eventually reached a minimum. He then left the "clean" room and his blood lead level went back up. Unfortunately, his blood lead did not stabilize after his exit from the "clean" room.

A further report presents data, involving additional volunteers, from which a blood to air lead ratio can be derived.[91] Subsequent to a stabilizing period in a metabolic ward, they entered the filtered air room and blood lead levels decreased. The blood lead levels did stabilize upon exit from the clean room.

Chamberlain et al.[92,93] reported on studies in which gasoline containing tetraethyl lead labeled with ^{203}Pb was burned in an internal combustion engine and the resulting tagged lead exhaust aerosol was inhaled by 6 volunteers. The lead concentration[92] was typically about 6 mg/m^3 and the total particulate 30 mg/m^3. The aggregates of particles about 0.6 μm in diameter were stable; those $\leq$ 0.01 μm tended to coagulate. Exposures were for 30 min or less, and the progress of the lead through the body was monitored. It was found that about 40 percent of the particles was retained, and that 60 percent was exhaled. The lung clearance rate for ^{203}Pb activity varied markedly, depending on whether the aerosol was irradiated. The transference of activity to the blood peaked at 50 hr after inhalation at 48 percent of the initial lung burden. At 72 hr, about half of the lead had been removed to bone and other tissues and the other half had become attached to red cells. The amount of ^{203}Pb in the blood was found to decline with a biological half life of 16 days.

Chamberlain et al. then extrapolated these high-level, short-term exposures to longer term ones. The following formula and data were used to calculate a blood-to-air level ratio:

$$\alpha = \frac{[T_{1/2}]\,[\%\text{Deposition}]\,[\%\text{Absorption}]\,[\text{Daily ventilation}]}{[\text{Blood volume}]\,[0.693]} \quad (12\text{-}7)$$

where: α = blood to air lead ratio

$T_{1/2}$ = biological half life

Data used were:

1. Airborne level = 1 $\mu g/m^3$
2. Exposure = 24 hr/day
3. Daily ventilation = 15 m^3/day
4. % Deposition = 40*
5. % Absorption = 50*
6. Blood volume = 5400 ml

*These values were determined experimentally in this study; all others are authors' assumptions.

Using the above equation and values, Chamberlain et al.[93] obtained a ratio of 1.2, in contrast to a value of 1.1 reported in an earlier report,[92] where slightly different assumptions were made. In this earlier report,[92] data from Kehoe[88] and Williams et al.[94] were used in a similar manner to calculate ratios of 1.1 and 1.1, respectively. It is interesting to note the difference in the ratios calculated by Gross[89] and Chamberlain et al.[92] from the Kehoe data. However, the extrapolation of Chamberlain et al. of the short-term to long-term exposure is in close agreement with the results of Kehoe and of Williams et al., as Chamberlain et al. calculated them.

Chamberlain's ratios have been recalculated by Bridbord[95] on the basis of a more active person's daily ventilation of 20 m^3. This, he states, would yield a ratio of 1.6 $\mu g/dl$ for each 1 $\mu g/m^3$ of air lead exposure.

12.3.1.5 BLOOD/AIR LEAD RELATIONSHIPS

Summarization of the relationship between lead in air and lead in blood requires the consideration of several distinct lines of evidence. These include: the minimal air lead concentration at which blood lead levels are first elevated, the form and magnitude of the relationship, the proportion of the population whose blood lead level exceeds any specific value at any given air lead concentration, and whether the form or magnitude of the relationship varies depending on whether the air lead exposure is increasing, remaining constant, or decreasing.

On the first point, only a few studies have sufficiently precise estimates of air lead exposures to permit this calculation, namely Yankel et al.[1] and Azar et al.[3] EPA used William's [96] test on the data from both these studies to determine the air lead levels at which blood lead levels were found to be significantly higher than the geometric mean blood lead levels of the groups exposed to the lowest air lead level, which thus served as controls. William's test is a multiple comparison test designed to make such comparisons.

For data from the Yankel et al. study,[1] EPA pooled the lowest two air lead exposure areas (V and VI) to form the control group.

The test showed that area IV was the first, in the ordered data, that showed significant elevation of blood lead values. The corresponding air lead concentration for this area was 1.7 $\mu g/m^3$.

EPA, using this same test for the Azar et al. study,[3] showed that blood lead values for the Philadelphia cabdrivers were significantly different from that for the pooled Starke and Barksdale plant employees that constituted the control population. Blood lead values for the Los Angeles office workers were also significantly higher than those of control populations. The corresponding air lead exposures were 2.6 and 3.1 $\mu g/m^3$, respectively.

The clinical study of Griffin et al.[86] provides data that support the results of the EPA analysis of Azar et al.[3] data. The data show that individuals exposed to 3.2 $\mu g/m^3$ had a definite increase in their blood leads as a result of this exposure.

Thus, the available data are consistent as to the value of air lead concentration at which blood lead levels begin to increase. The Yankel et al. data[1] demonstrated this increase at 1.7 $\mu g/m^3$; the Azar et al. data,[3] at 2.6 $\mu g/m^3$. These results are not inconsistent because the Azar et al. study did not have a population exposed to a level of air lead between 1 and 2.6 $\mu g/m^3$.

The derivation of the functional relationship between air lead exposure and blood lead levels has technical difficulties because the true form of this relationship is not linear. No matter what the difficulty in making this assessment is, the form of the relationship is extremely important because it is used to determine the effect of a change in the blood lead levels as a function of the air lead values.

Some studies, by the very nature of their design, only permit calculating the ratio between a change in blood lead and associated change in the air lead concentration. For these situations, the calculated ratio can be considered as an estimate of the average ratio over the range of the air lead levels encountered.

For those studies in which a functional relationship can be derived, this ratio can be estimated for a given air lead concentration by evaluating the derivative of the functional relationship at that

value. This ratio is subject to considerable change over the range of air lead levels encountered, depending on the form of the relationship that was fitted. We have chosen, wherever possible, to use the author's own model for the relationship.

The earliest attempt to use epidemiological data to calculate a blood-to-air lead relationship was made by Goldsmith and Hexter.[87] A linear regression equation of the logarithm of the blood lead level on the air lead level was performed on data from the Three-City Study.[40] Data from Kehoe's observations on 4 individuals experimentally exposed to 10 and 150 $\mu g/m^3$ in a pattern equivalent to a normal work exposure were found to fit the equation. The slope of this line was not significant below 2 $\mu g/m^3$ of air exposure, possibly because few observations were available in the Three-City Study below that level. The derived slope of the regression line suggests an increase of 1.3 $\mu g/dl$ for each microgram of air lead.

Azar et al.[3] used a log-log model to fit their data; the data, as well as the regression line, are presented in Figure 12-8. The slopes, that is, the ratios, were calculated from the equation, log Pb-B = 1.2557 + 0.153 (log Pb-A), at the four air lead values shown in Table 12-28. These slopes ranged from 2.6 at an air lead of 1.0 $\mu g/m^3$ to 0.7 at an air lead of 5.0 $\mu g/m^3$. It is important to note that all four air lead concentrations of interest are well within the range of the air levels observed.

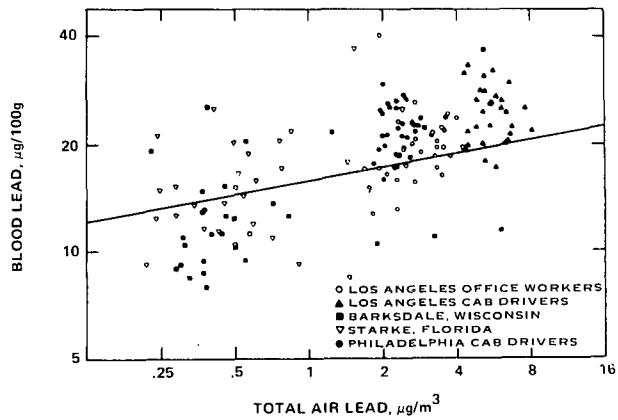

Figure 12-8. Blood lead versus air lead for urban male workers.[3]

TABLE 12-28. ESTIMATED BLOOD LEAD TO AIR LEAD RATIOS FOR FOUR AIR LEAD CONCENTRATIONS

Study	Population	Sample size	Ratio at air lead concentrations, $\mu g/m^3$ 1.0	2.0	3.5	5.0
Epidemiological						
Azar[a]	Adult males	149	2.57	1.43	0.89	0.66
Tepper-Levin[b]	Adult females	1908	0.87	0.92	1.00	1.08
Nordman[b]	Adult males	536			(0.42)[d]	
Nordman[b]	Adult females	478			(0.11)	
Fugas[b]	Adults	330			(2.64)	
Johnson[b]	Adult males	64			(0.80)	
Johnson[b]	Adult females	107			(0.60)	
Tsuchiya[b]	Adult males	591			(3.84)	
Goldsmith[b]	Children males	202			(2.30)	
Goldsmith[b]	Children females	203			(1.70)	
Yankel-von Linder[a]	Children	879	1.16	1.21	1.27	1.37
Chamberlain[c]-Williams	Adults	482			(1.10)	
Daines[b]	Black females	(unknown)			(2.30)	
Clinical						
Griffin[b]	Adult males	11 @ 10.9			(1.40)	
Griffin[b]	Adult males	14 @ 3.2			(1.65)	
Rabinowitz[b]	Adult males	2			(1.7, 2.5)	
Gross[c]	Adults	(21,000 person-days)			(0.38)	
Chamberlain[c]	Adults	7			(1.20)	
Chamberlain[c]-Kehoe	Adults	5			(1.10)	

[a] Authors' regression equation evaluated at specific air lead.
[b] EPA calculation.
[c] Authors' calculations.
[d] Ratios presented in parentheses are not calculated from any regression equation.

One of the authors, Snee,[50] has since reanalyzed the data using a more complicated model for the relationship. His newer model attributes less of the increase in blood lead to air lead exposures and more to geographic area differences. The improvement in fit by use of this newer model is insignificant. Furthermore, in the new model, the area differences are correlated with the air lead differences. For these reasons, the original model is believed to be more appropriate for estimating the total effect of air lead.

Yankel et al.[1] used a log-linear model (Equation 12-6) to fit their data. The slopes of the four air lead values shown in Table 12-28 were calculated from this equation. These ranged from 1.2 at an air lead level of 1.0 $\mu g/m^3$ to 1.4 at an air lead of 5.0 $\mu g/m^3$. Again, all air lead concentrations were within the range of the data.

One assumption inherent in the calculation of the regression of blood lead on air lead using standard least squares is that the air lead values have been measured with no error. Unfortunately, this assumption is not correct. Obviously, the monitored air lead values are not the exact values inhaled by the subjects in the exposure area. The effect of measurement error in the independent variable is discussed by Kendall and Stuart.[97] In general, the calculation regression coefficients are underestimates of the true values. If either the error in the dependent variable, or the error in the independent variable, or the ratio of the two errors were known, then improved estimates could be calculated.

The Yankel et al. study[1] gives sufficient information to estimate the effect of this problem. The authors assigned 1 of 33 different estimated exposure levels to each individual in the study. If the within level variances of blood lead values are pooled for these 33 levels, the result is a pooled GSD of 1.28. Using the value of 1.28 for the error in the dependent variable, the regression coefficient of 0.041 reported by Yankel and von Lindern becomes 0.052. This adjustment increases the estimated blood lead to air lead ratio from 1.21 to 1.44 at 2 $\mu g/m^3$ and from 1.37 to 1.69 at 5 $\mu g/m^3$.

This problem may exist in some of the other studies, but it is not a serious problem in two of the other more important studies. In the Azar study,[3] personal samplers were used, so that individual exposures were measured more accurately than in any other epidemiologic study. In the Griffin study the air lead levels were controlled extremely closely, so that there was almost no variation in the exposure value.

The reanalysis of the Tepper-Levin study[2] as reported by Hasselblad and Nelson[22] was used to estimate the relationship of air lead to blood lead levels. A log-linear model was used that allowed for age and smoking differences, as well as the air lead exposure. This form of the model was chosen because it gave a better fit to the data than did the log-log model. The slopes were calculated from the log-linear model at the four air lead values shown in Table 12-28. These slopes ranged from 0.9 at an air lead of 1.0 $\mu g/m^3$ to 1.1 at an air lead of 5.0 $\mu g/m^3$. The air lead values only ranged from 0.2 to 3.4 $\mu g/m^3$, however.

Daines et al. reported two studies examining variations in blood lead ratios with distance from busy highways.[52] The studies were conducted in Camden, New Jersey, and involved black females. Only one of these studies can be used to determine the blood lead/air lead ratio because no air lead data were reported for the other study. In this study, blood lead levels of black females living in residences that were 3.7, 38.1, and 121.9 m distant from the highway were determined. Yearly mean air and blood lead levels for these three groups are presented in Table 12-29. From these values a ratio may be calculated as follows:

$$\text{ratio} = \frac{23.1-17.6}{4.60-2.24} = 2.3 \text{ for the total population.}$$

Using a similar calculation, housewives were found to have a ratio of 3.

TABLE 12-29. YEARLY MEAN AIR AND BLOOD LEAD LEVELS OF BLACK FEMALES IN RELATION TO DISTANCE OF RESIDENCE FROM A BUSY HIGHWAY

Study area	Distance from highway, m	Air lead, $\mu g/m^3$	Blood lead, $\mu g/100\,g$
Area A	3.7	4.60	23.1
Area B	38.1	2.41	17.4
Area C	121.9	2.24	17.6

In Yugoslavia, Fugas et al. in the study described earlier,[69] estimated the weekly time-weighted air lead exposures of eight population groups. The estimates were based on air lead values monitored at various locations and estimated proportions of time the individuals spent at those locations. The time-weighted exposure estimates, sample sizes, and blood lead levels for this study were presented earlier (Table 12-22). A weighted regression analysis was chosen for these data because the sample sizes of the customs officers and policemen varied from those for the other groups. The range of air leads was from 0.079 to 3.0 $\mu g/m^3$. The resulting slope is 2.64, and is presented in Table 12-28.

Snee[50] has criticized the inclusion of the streetcar drivers because of differences in social status and habits from the other groups. The effect of removing these subjects would be to reduce the calculated slope. This group was not removed because the air lead exposure was more precisely estimated than in other studies.

Data on Tokyo policemen reported by Tsuchiya et al.[41] and discussed in detail previously in this chapter may also be used to calculate a slope. Unfortunately, the slope that is derived can only be looked upon as confirmatory evidence and not as additional evidence because of the time difference between sampling the air and sampling the blood. Another possible complicating factor is the rural-urban gradient that parallels the air lead concentrations. Weighted regression analysis was used on the blood and air lead data reported in Table 12-26. The estimated slope is 3.8 and is recorded in Table 12-28. The observed range in air lead concentrations was 0.024 to 1.157 $\mu g/m^3$.

From the Johnson et al. study in California,[6] estimates of the ratio between blood and air lead levels can be derived. Because of analysis problems encountered in the blood lead determinations of children, it was decided that a valid estimate could not be derived. Therefore, only data for adults will be treated here. It was decided to pool the data for adults and present separate ratios for males and females aged 17 and above. Geometric mean blood lead levels were used in the calculation because the blood lead data were found to follow a log-normal distribution.

For males, the pooled geometric means were 15.5 and 11.0 $\mu g/dl$ for Los Angeles and Lancaster, respectively. For females, the corresponding values are 12.1 and 8.4 $\mu g/dl$. The ratio was calculated as follows for males: ratio = (15.5-11.0)/(6.3-0.6) = 0.8. The ratio for females was 0.6. These values are tabulated in Table 12-28.

Nordman in his doctoral dissertation[16] reported on blood and air lead levels for several populations in Finland (Table 12-30). Because of the large variation in the sample sizes for these populations, EPA calculated a weighted regression equation. The slope of the equation was estimated for both males and females separately and is 0.4 and 0.1, respectively, as presented in Table 12-28. It should be noted that the range of air lead concentrations covered by this study was 0.025 and 1.32 $\mu g/m^3$.

Data from Goldsmith[42] on elementary and high school children in a number of California towns can also be used in the calculation of the slopes. EPA has

TABLE 12-30. BLOOD AND AIR LEAD LEVELS BY SEX IN FINNISH POPULATION STUDY[16]

Group	Air lead, $\mu g/m^3$	Male blood lead, $\mu g/dl$			Female blood lead, $\mu g/dl$		
		N	Avg	SD	N	Avg	SD
Pertummaa	0.025	243	12.1	4.5	256	9.6	3.5
Pyhajarui	0.025	—	—	—	93	8.6	2.5
Suburban	0.74	37	10.6	2.8	81	9.7	2.6
Downtown	0.90	142	11.4	3.3	37	8.5	2.0
Policemen	1.32	28	13.5	2.8	—	—	—
Street sweepers	1.32	86	13.3	4.1	11	10.4	3.0

separately analyzed the raw data from this study for elementary school males and females. The results of these analyses show ratios of 2.30 and 1.70, respectively (Table 12-28).

Chamberlain et al.[92] analyzed the data of Williams et al.[96] on occupationally exposed persons using personal monitors. Chamberlain adjusted the occupational exposures to 24-hr exposures by calculating the elevation in blood lead from a non-exposed population. He calculated a slope of 1.1.

Clinical studies also provide data useful in quantitating the relationship between blood and air lead. Griffin et al.,[86] in their clinical study of the largest number of subjects to date, exposed individuals to 2 levels of air lead concentrations, 10.9 and 3.2 $\mu g/m^3$. The study design, it was believed, precludes fitting an overall equation to these data, and a separate calculation of a ratio is presented for the two experiments. In both experiments, the background air lead levels were estimated to be 0.15 $\mu g/m^3$. In the 3.2 $\mu g/m^3$ air lead exposure, the men increased their mean blood lead levels from 20.5 to 25.6 $\mu g/dl$. This yields a ratio of 1.65 (25.6-20.5)/(3.2-0.15). The 10.9 $\mu g/m^3$ air lead exposure resulted in an increase of blood lead levels from 19.4 to 34.5 $\mu g/dl$. This gives a ratio of 1.40 (34.5-19.4)/(10.9-0.15). These values are shown in Table 12-28.

Chamberlain et al.[92] reanalyzed the Kehoe results by adjusting the 37.5-hr exposures per week to a 24-hr equivalent. They used data from 5 subjects whose 24-hr equivalent exposures ranged from 0.6 to 73.5 $\mu g/m^3$. The calculated ratios ranged from 0.6 to 2.0, with an overall mean of 1.1 for the data.

In contrast to the analysis of Kehoe's work by Chamberlain in which a 1.1 ratio was calculated, Gross[89] reports a ratio of 0.38 for these data. At this time, no details are available concerning his methods. Therefore, the apparent discrepancy between these two analyses cannot be evaluated.

Chamberlain et al.,[92,93] as discussed earlier, calculated ratios of 1.1 and 1.2 based on the ex-

trapolation of a short-term exposure to a long-term one. The calculation involves a number of experimentally determined as well as assumed numbers.

As described previously, Rabinowitz et al.[91] studied three individuals for metabolic changes in blood lead as a function of changes in the air lead concentration. In contrast to the other clinical studies described wherein air lead levels were increased, in this study the subjects were placed in a "clean room" in which the air was filtered. This study, therefore, pertains to the situation in which the air lead concentration has decreased. The blood lead levels were determined from the stabilized mean both when the subject was breathing normal as well as filtered air. One of the men did not have a stabilized blood lead after returning to breathing normal air; therefore, he could not be used in determining the ratio. The relevant data for calculating the ratio are included in Table 12-31.

TABLE 12-31. BLOOD AND AIR LEAD DATA FROM CLINICAL STUDY[91]

	Estimated air lead		Blood lead	
Subject	Normal air, μ g/m^3	Filtered air, μ g/m^3	Normal air, μg/100 g	Filtered air, μg/100 g
D	0.91	0.072	20.2	18.8
E	0.91	0.072	16.3	14.2

The calculation for subject D was done as follows: ratio = (20.2-18.8)/(0.91-0.072) = 1.7. The calculation for subject E results in a ratio of 2.5.

Only one data set (Azar et al.[3]) is available on which to estimate a dose-response relationship, that is, the proportion of a population exceeding a specified blood lead level for any specific exposure. The reasons for the paucity of data are twofold: (1) access is needed to the raw data and (2) the exposure data should be relatively precise.

The regression equation for the Azar study[3] has already been discussed. The mean square error (MSE) about this equation was calculated for all five areas combined. From the MSE, estimates of the percentage of the population exceeding a given blood lead level for a given air lead level are given by:

$$\text{Percent} = 100\left\{1 - N\left[\frac{\log_{10}(\text{blood lead}) - 1.2257 - 0.1531\log_{10}(\text{air lead})}{\text{MSE}^{1/2}}\right]\right\}$$

where: N(x) is the cumulative normal integral of a standard normal variable up to the point x. These percentages are given in Table 12-32 for a range of air lead values.

These tabulated percentages may not be representative of the general population, since they are based on a single study of 149 subjects. They are presented because they are the best estimates available of a dose-response relationship.

TABLE 12-32. ESTIMATED PERCENTAGE OF POPULATION EXCEEDING A SPECIFIC BLOOD LEAD LEVEL IN RELATION TO AMBIENT AIR LEAD EXPOSURE[a]

	Percent exceeding blood lead level of:		
Air lead, μg/m^3	20.0 μg/dl	30.0 μg/dl	40.0 μg/dl
0.5	15.22	0.59	0.02
1.0	26.20	1.67	0.07
1.5	34.12	2.88	0.16
2.0	40.23	4.12	0.26
2.5	45.15	5.35	0.38
3.0	49.23	6.57	0.51
3.5	52.69	7.75	0.66
4.0	55.67	8.90	0.81
4.5	58.27	10.01	0.97
5.0	60.57	11.09	1.14
6.0	64.45	13.16	1.48
7.0	67.63	15.10	1.83
8.0	70.28	16.92	2.20

[a] Data derived from the equation of Azar et al.[3]

The last element in defining the relationship between lead in blood and lead in air is a discussion of the effect that varying the concentration of lead in air has on the blood lead levels. Most of the data previously presented have dealt with steady state or increasing air lead concentrations. This section will summarize the results of studies showing the effect of decreasing the concentration of lead in air on the blood lead levels of human populations.

Rabinowitz et al.'s study [91] provides estimated ratios for two subjects under carefully controlled conditions who experienced a decrease in their air lead concentrations. For the two subjects, a 1 μg/m^3 decrease in air lead levels resulted in a 2 μg/100 g decrease in blood lead levels.

Baker[98] presented data to the EPA Science Advisory Board showing decreases in blood lead levels in the vicinity of an Idaho smelter between 1974 and 1975 (Table 12-33). Information from all study areas combined indicated that blood lead levels had decreased by 2.3 μg/dl for each 1 μg/m^3 reduction in air lead. This same investigator provided additional information in a separate communication to EPA showing that, when analyses were limited to children of nonsmelter workers, blood lead levels decreased 2.0 μg/dl in all study areas for each decrease of 1 μg/m^3 of air lead. If the analyses included only those children of nonsmelter workers exposed to air lead levels ranging from 0.5 to 10

$\mu g/m^3$, blood lead levels decreased 1.3 $\mu g/dl$ for each unit decrease in air lead and also showed a higher ratio at greater air lead concentrations. From these analyses, it seems apparent that a single ratio cannot describe the data from this study.

TABLE 12-33. COMPARISON OF BLOOD LEAD LEVELS IN CHILDREN WITH AIR LEAD LEVELS FOR 1974 AND 1975 (EPA analyses)

Study area	Blood lead levels, μ g/dl			Air lead levels, μ g/m^3			Pb-B diff./ Pb-A diff.
	1974	1975	Diff.	1974	1975	Diff.	
1	69	46	23	18	10.3	7.7	3.0
2	49	38	11	14	8.6	5.4	2.0
3	36	32	4	6.7	4.9	1.8	2.2
4	33	27	5	3.1	2.5	0.6	8.0

Data from Angle and McIntire's studies[73-76] in Omaha also provide data in this regard. They found blood lead levels of urban children, aged 6 to 18, to consistently decrease during the years 1970 to 1973. This decrease was almost 10 $\mu g/dl$ across all study groups. Furthermore, this decrease has been found to be closely correlated with a decrease in air lead from about 1.5 to less than 0.5 $\mu g/m^3$. In a reanalysis of the full data base, Angle has calculated an overall equation of Pb-B = 10.04 (Pb-A) + 17.06, r = 0.95.

Data from New York City analyzed by HUD[38] and described in detail in the demographic variability section of this chapter may also provide supportive data for the notion that a decrease in blood lead level is associated with decreased air lead exposure. In the New York lead screening program geometric mean blood lead values have been noted as decreasing consistently from 1970 to 1976. During this time, some changes occurred in the number of children sampled, so that the more recent years have far fewer data points than the earlier years. No significant break in the trend was observed as the change in sample size was noted. Data from one Hi-Vol air station provided continuous air lead values over this period in New York City. The air lead values measured there, not really representative of the exposure of the children being studied, have been following a similar pattern. It is also interesting to note that lead in gasoline in New York City was also being reduced during this period.

The quantitative estimates provided from the three studies discussed show decreasing air lead concentrations vary from a minimum of 1.3 to 8 or 10 $\mu g/dl$. These data suggest that a greater ratio may hold for decreases in air lead than for steady state or increasing exposures.

In summary, in all quantitative studies presented, a positive relationship between blood lead and air lead has been found. The form and magnitude of the relationship, however, has not been found to be constant but varies in the studies reviewed. Table 12-28 summarizes the quantitative estimates derived from the review and analysis of the literature.

In general, the data show that the blood lead to air lead ratio is not constant over the range of air exposure encountered (it varies in most studies between 1 and 2), that males appear to have higher ratios than females, and that children have a slightly higher ratio than adults. Also, the data suggest that more attention should be given to studies of decreasing air lead concentrations in that the ratios derived from such studies appear higher than those of steady state or increasing exposures.

12.3.2 Soil and Dust Exposures

The relationship of exposure to lead contained in soil and housedust and the quantity of lead in humans, particularly in children, has been the subject of scientific investigation for some time.[78,99-105] Duggan and Williams[105] have recently published an assessment of the risk of increased blood lead resulting from the ingestion of lead in dust. Some of these studies have been concerned with the effects of such exposures:[78,99-102] others have concentrated on the means by which the lead in soil and dust becomes available to the body.[103,104]

In one of the earliest investigations, Fairey and Gray conducted a retrospective study of lead poisoning cases in Charleston, South Carolina.[99] Two-inch core soil samples were collected from 170 randomly selected sites in the city and were compared with soil samples taken from the yards of homes where 37 cases of lead poisoning had occurred. The soil lead values obtained had a wide range, from 1 to 12,000 ppm, with 75 percent of the samples containing less than 500 ppm. A significant relationship between soil lead levels and lead poisoning cases was established; 500 ppm was used as the cutpoint in the chi-square contingency analysis. This study was the first to examine this complex problem and, although data support the soil lead hypothesis, they were not such as to allow for quantification of the relationship between soil lead and blood lead levels. Furthermore, because no other source of lead was measured, the association found might have been caused by confounding additional sources of lead, such as paint or air.

A later study by Galke et al., also in Charleston, used a house-to-house survey to recruit 194 black preschool children.[43] Soil lead, paint lead, and air lead exposures as measured by traffic density were established for each child. When the population was divided into 2 groups based on the median soil lead value (585 μg/g), a 5-μg/dl difference in blood lead levels was obtained. Soil lead exposure for this population ranged from 9 to 7890 μg/g. A multiple regression analysis of the data showed that vehicle traffic pattern, when defined by area of recruitment (i.e., high or low); lead level in exterior siding paint; and lead in soil were all independently and significantly related to blood lead levels.

Barltrop et al.[100] described two studies in England investigating the soil lead to blood lead relationship. In the first study, children aged 2 and 3 and their mothers from two towns chosen for their soil lead content each had their blood lead level determined from a capillary sample. Hair samples were also collected and analyzed for lead. Lead content of the suspended particulate matter and soil was measured. Soil samples for each home were a composite of several 2-in. core samples taken from the yard of each home. Chemical analysis of the lead content of soil in the two towns showed a two- to threefold difference, with the values in the control town being about 200 to 300 ppm compared with about 700 to 1000 ppm in the exposed town. A difference was also noted in the mean air lead content of the two towns, 0.69 μg/m^3 compared with 0.29 μg/m^3, respectively. Although this difference existed, both air lead values were thought low enough not to affect the blood level values differentially. Mean surface soil lead concentrations for the two communities were statistically different, the means for the high and low community being 909 and 398 ppm, respectively. Despite this difference, no statistically significant differences in mothers' blood lead levels or children's blood or hair levels of lead were noted. There was, however, suggestive evidence of a difference in hair lead levels for children. Further statistical analysis of the data, using correlational analysis on either raw or log-transformed blood lead data, likewise failed to show a statistical relationship of soil lead with either blood lead or hair lead.

The second study was reported in both preliminary and final form.[100,101] In the more detailed report,[101] children's homes were classified by their soil lead content into three groups, namely <1,000, 1000 to 10,000, and >10,000 ppm. As shown in Table 12-34, children's mean blood lead levels increased correspondingly from 20.7 to 29.0 μg/dl. Mean soil lead levels for the low and high soil exposure groups were 420 and 13,969 ppm, respectively. Mothers' blood levels, however, did not reflect this trend; nor were the children's fecal lead levels different across the soil exposure areas.

TABLE 12-34. MEAN BLOOD AND SOIL LEAD CONCENTRATIONS IN ENGLISH STUDY[101]

Category of soil lead, ppm	Sample size	Children's blood lead, μ g/dl	Soil lead, ppm
<1000	29	20.7	420
1000-10000	43	23.8	3390
>10000	10	29.0	13969

Other studies have investigated the relationship of dust lead to absorption.[33,78,102,106] Some of these also included measurements of soil lead.

Lepow et al.,[106] for example, studied the lead content of air, housedust, and dirt, as well as the lead content of dirt on hands, food, and water, to determine the cause of chronically elevated blood lead levels in ten 2- to 6-year-old children in Hartford, Connecticut. Lead based paints had been eliminated as a significant source of lead for these children. Ambient air lead concentrations varied from 1.7 to 7.0 μg/m^3. The mean lead concentration in dirt was 1,200 μg/g and in dust, 11,000 μg/g. The mean concentration of lead in dirt on children's hands was 2,400 ppm. The mean weight of samples of dirt from hands was 11 mg, which represented only a small fraction of the total dirt on hands. Observation of the mouthing behavior in these young children lead to the conclusion that the hands-in-mouth exposure route was the principal cause of excessive lead accumulation in these children.

Angle et al.,[74] studying children in Omaha, Nebraska, found several interesting associations between soil or housedust lead concentrations and blood lead levels. In this report, three groups of children were compared: (1) suburban versus urban high school, (2) suburban versus urban 10- to 12-year-olds, and (3) black elementary school children with blood lead $\leq$ 20 versus $\geq$ 20. Air lead levels, all of which were less than 1 μg/m^3, were not shown to be related to blood lead levels. Soil and housedust were associated, although not always statistically significantly.

Creason et al.,[102] studying hair metal levels in the New York metropolitan area, used both dustfall and housedust as their exposure variables. Three geographic areas in metropolitan New York were chosen to represent an exposure gradient. Limited dustfall and housedust samples were taken to verify

the gradient and to estimate its magnitude. Hair samples were collected from residents in locations enrolled in other air pollution studies. Mean total environmental and hair lead levels were then compared. Hair lead levels ranged from 12 μg/g in the low area to 17 μg/g in the high. Mean dustfall and housedust lead levels ranged from 2 to 16 mg/m^2-month, and from 279 to 766 μg/g, respectively. Hair lead levels in both children and adults were found to be significantly related to both dustfall and housedust lead. No attempt was made to determine the original source of these dusts. Further, the study design did not permit the establishment of which of the two dust types or both were the actual contributors to the hair lead levels. The investigators concluded that the primary cause of elevated blood lead levels in children was ingestion or inhalation of dust containing lead.

Two other studies, which were described in more detail in Section 12.3, can be used to examine the relationship of lead in soil and dust with lead in blood.[1,34] Yankel et al. showed that lead in both soil and dust was independently related to blood lead levels. In their opinion, 1000 ppm soil lead exposure was cause for concern. Reanalysis of the Dallas traffic study showed a significant slope of blood lead levels in relation to soil lead levels (β = 0.0662).[34] Lastly, Shellshear's case report from New Zealand ascribes a medically diagnosed case of lead poisoning to high soil lead content in the child's home environment.[107]

Two studies have investigated the mechanism by which lead from soil and dust gets into the body.[103,104] Sayre et al. in Rochester, New York, demonstrated the feasibility of housedust being a source of lead for children.[103] Two groups of houses, one inner-city and the other suburban, were chosen for the study. Lead-free sanitary paper towels were used to collect dust samples from house surfaces and the hands of children.[108] The medians for the hand and household samples were used as the cutpoints in the chi-square contingency analysis. A statistically significant difference between the urban and suburban homes for dust levels was noted, as was a relationship between household dust levels and hand dust levels.[106]

Ter Haar and Aronow[104] investigated lead absorption in children that can be attributed to ingestion of dust and dirt. They reasoned that because the proportion of the naturally occurring isotope ^{210}Pb varies for paint chips, airborne particulates, fallout dust, housedust, yard dirt, and street dirt, it would be possible to identify the sources of ingested lead. They collected 24-hr excreta from 8 hospitalized children for the first day of hospitalization. These children, 1 to 3 years old, were suspected of having elevated body burdens of lead, and one criterion for the suspicion was a history of pica. Ten children of the same age level, who lived in good housing in Detroit and the suburbs, were selected as controls and 24-hr excreta were collected for them. The excreta were dried and stable lead as well as ^{210}Pb content was determined. For seven hospitalized children, the stable lead mean value was 22.43 μg/g dry excreta, and the eighth child had a value of 1640 μg/g. The controls' mean for stable lead was 4.1 μg/g dry excreta. However, the respective means for ^{210}Pb expressed as pCi/g dry matter were 0.044 and 0.040. The authors concluded that because there is no significant difference between these means for ^{210}Pb, the hypothesis that young children with pica eat dust is not supported. However, all that the data, in fact, do show is that both groups of children were comparable as to the amounts of ^{210}Pb and vastly different in respect to stable lead per gram of dry excreta. The hospitalized children ingested larger amounts of material containing stable lead. Granting that the hospitalized children ingested leaded paint chips and the controls did not, does not permit the conclusion that all the ^{210}Pb found in all the children originated in food and that no dirt and dust was ingested by control children whereas hospitalized children ate only paint chips.

The data from all these studies can be summarized fairly succinctly. There is evidence that children can pick up lead from their environment by getting it on their hands. Duggan and Williams[105] have summarized the literature on the amounts of lead ingested by ingestion of dust. In their opinion, a quantity of 50 μg of lead is ingested daily by children by means of street dust. As yet there are no solid data directly demonstrating the next link, that is, transfer of dust and soil from hand to mouth. A clinical case report has indicated, however, that soil lead levels can lead to excessively elevated blood lead levels. Also, the data of Barltrop[101] and Galke et al.[43] indicate that soil lead exposures, often found in urban settings, can contribute between 5 and 8 μg/dl to the blood's lead burden.[33,101]

The consensus appears to be that observable increases in blood lead levels occur at soil or dust lead exposures of 500 to 1000 ppm. From the data available in the literature, a summary table (Table 12-35) was constructed by EPA. A regression analysis was used to relate the logarithm of the

blood lead to the logarithm of the soil lead. From the regression, a coefficient, b, the mean percent age increase in blood lead for a two fold increase in soil lead, can be calculated:

$$\% \text{ increase} = 100\,[\exp(b/\log_e(2))] \quad (12\text{-}7)$$

TABLE 12-35. SUMMARY OF SOIL LEAD/BLOOD LEAD RELATIONSHIPS

Study	Age, years	Regression coefficient, log-log	Geom. mean blood lead, μg/dl	Geom. mean soil level, μg/g	Mean % increase in Pb-B for 2 x soil level
Charleston, SC[43]	1-5	0.0432	36.4	451.6	3.0
Kellogg, ID[1]	1-9	0.0528	37.5	1518.1	3.7
Dallas, TX[34]	1-5	0.0662	11.4	91.6	4.7
England[101]	2-3	0.0840	23.2	1849.1	6.0

Table 12-35 shows a surprising consistency in the percentage increase in mean blood lead levels for a twofold increase in soil lead levels (3 to 6 percent), given the wide diversity in populations studied and soil levels encountered. The Charleston study involved black preschool children living in the inner city with several additional known environmental sources of lead. The Idaho study was of a smelter site in a rural setting. Barltrop's data from England showed virtually no environmental source other than that from soil. The Dallas study was of a community that was relatively lead free. It is interesting to note that the larger estimates of the percentage increase in blood lead occurred in the children with the lowest blood lead levels.

12.3.3 Food and Water Exposures

In typical urban settings, food probably constitutes the body's largest direct source of lead because almost every item in the diet contains some measurable amount of the metal.

Three approaches have been used to estimate dietary intake of lead: duplicate meals, market basket surveys, and fecal lead determinations. The estimated dietary lead intake of Americans has decreased markedly since the presentation of Kehoe's data in the 1940's, which indicated, based on fecal lead determinations, that the daily intake was between 100 and 350 μg/day.[88] Most of the more recent comparable data[2,109,110] have reduced that estimate to between 50 and 150 μg/day. The California study of Johnson et al.[7] points to a daily intake of about 100 to 150 μg, such intake being similar for both rural and urban populations. Also, Chisholm and Harrison,[109] in a study of children aged 12 to 35 months, found a mean fecal excretion rate of 132 μg/day, and Barltrop and Killola a value of 130 μg.[110]

Much recent work has been concerned with the lead content of the market basket or total diet in which the content of foods meeting typical nutritional needs is analyzed. The foodstuffs are assembled in accordance with national food sample surveys. One such study[111,112] has indicated that the lead content of the diet of young adults averages 150 to 200 μg/day, and another[113] cites a figure of 254 μg/day for 15- to 20-year-old males. At least 30 percent of this amount in the latter study was attributed to the consumption of canned foods. Kolbye[111] and Mahaffey et al.[112] have suggested an average food-based intake of 80 to 100 μg of lead for children 12 to 35 months old. Additional studies in this field have been reviewed by Mahaffey.[112]

Despite the above estimates of dietary lead content, the quantitative relationship between dietary intake and blood lead levels is not well established; the bulk of the studies described in Chapter 10 that address this relationship, however, point to a sustained value of 6 μg/dl for 100 μg of dietary lead intake.

Water, itself, can also be a source of significant quantities of lead with the metal present in the supply itself. More frequent, however, is an increase in the quantity of particulate or dissolved lead as water is delivered from the treatment plant to the user through the lead pipes often found in older housing. Most natural waters contain only from 10 to 20 μg/liter of lead and most problems occur when lead piping is used in areas in which the drinking water is lead solvent; that is, it is soft and has a low pH.

Although the use of lead piping has been largely prohibited in recent construction, occasional episodes of poisoning from this lead source still occur. These cases most frequently involve isolated farms or houses in rural areas, but a surprising situation was revealed in 1972 when Beattie et al.[114,115] showed the seriousness of the situation in Glasgow, Scotland, which had very pure but soft drinking water as its source. They demonstrated a clear association between blood lead levels and inhibition of the enzyme ALAD in children living in houses with (1) lead water pipes and lead water tanks, (2) no

lead water tank but with more than 60 ft of lead piping, and (3) less than 60 ft of lead piping. The mean lead content of the water as supplied by the reservoir was 17.9 μg/liter; that taken from the faucets of groups 1, 2, and 3 was 934, 239, and 108 μg/liter, respectively.

Another English study[116] showed a clear difference between the bone lead content of the populations of Glasgow and London, the latter having a hard, relatively nonsolvent water supply.

In a study of 1200 blood donors in Belgium,[117] persons from homes with lead piping and supplied with corrosive water had significantly higher blood lead levels.

In Boston, Mass., an investigation was made of water distributed via lead pipes. In addition to the data on lead in water, account was taken of socioeconomic and demographic factors as well as other sources of lead in the environment.[118,119] Participants, 771 persons from 383 households, were classified into age groups of <6, 6 to 20, and >20 years of age for analysis.[118] A clear association between water lead and blood lead was apparent (Table 12-36). For children under 6 years of age, 34.6 percent of those consuming water with lead above the U.S. standard of 50 μg/liter had a blood lead value ≥ 35 μg/dl, whereas only 17.4 percent of those consuming water within the standard had blood lead values of ≥ 35 μg/dl.

TABLE 12-36. BLOOD LEAD LEVELS OF 771 PERSONS IN RELATION TO LEAD CONTENT OF DRINKING WATER, BOSTON, MASS.[118]

	Persons consuming water (standing grab samples)				
Blood lead levels, μg/dl	<50 μg Pb/liter		≥50 μg Pb/liter		
	No.	Percent	No.	Percent	Total
<35	622	91	68	77.3	690
≥35	61	9	20	22.7	81
Total	683	100	88	100.0	771

$x^2 = 14.35$; df = 1.
$P < 0.01$.

Greathouse et al. have published an extensive regression analysis of these data.[119] Blood lead levels were found to be significantly related to age, education of head of household, sex, and water lead exposure. Of the two types of water samples taken, standing grab and running grab, the former was shown to be more closely related to blood lead levels than the latter.

As noted in Chapter 10 of this document, roughly 10 percent of lead in solid foodstuffs is absorbed by adults; the corresponding value for liquids is about 50 percent. The relative risk for exposure to waterborne lead is, therefore, considerably greater.

12.3.4 Effects of Lead in the Housing Environment: Lead in Paint

A major source of environmental lead exposure for the general population comes from lead contained in both interior and exterior paint on dwellings. The amount of lead present, as well as its accessibility, depends upon the age of the residence (because older buildings are painted with paint manufactured before lead content was regulated) and the physical condition of the paint. It is generally accepted by the public and by health professionals that lead based paint is the major source of pediatric lead poisoning with clinical symptoms in the United States.[120]

The level and distribution of lead paint in a dwelling is a complex function of history, geography, economics, and the decorating habits of its residents. Lead pigments were the first pigments produced on a large commercial scale when the paint industry began its growth in the early 1900's. In the 1930's lead pigments were gradually replaced with zinc and other opacifiers. By the 1940's, titanium dioxide became available and has now become the most commonly used pigment for residential coatings. There was no regulation of the use of lead in house paints until 1955, when the paint industry adopted a voluntary standard that limited the lead content in paint, for interior uses, to no more than 1 percent by weight of the nonvolatile solids. At about the same time, local jurisdictions began adopting codes and regulations that prohibited the sale and use of interior paints containing more than 1 percent lead.[121]

In spite of the change in paint technology and local regulations governing its use, and contrary to popular belief, interior paint with significant amounts of lead was still available in the 1970's. A 1971 study in New York City found that 8 of 76 paints tested had a lead content ranging from 2.6 to 10.8 percent, well above the city's legally permissible 1 percent level.[122] Later studies by the National Bureau of Standards[123] and by the Consumer Product Safety Commission[124] showed a continuing decrease in the number of interior paints with lead levels greater than 1 percent. By 1974, only 2 percent of the interior paints sampled were found to have greater than 1 percent lead in the dried film.[124]

The level of lead in paint in a residence that should be considered a hazard remains in doubt. Not only is the total amount of lead in paint important, but also the accessibility by a child of the painted

surface as well as the frequency of ingestion. Attempts to set an acceptable lead level, *in situ,* have been unsuccessful and preventive control of lead paint hazards has been concerned with levels of lead in paint currently manufactured. In one of its reviews, NAS concluded: "Since control of the lead paint hazard is difficult to accomplish once multiple layers have been applied in homes over two to three decades, and since control is more easily regulated at the time of manufacture, we recommend that the lead content of paints be set and enforced at time of manufacture."[125]

Legal control of lead paint hazards is being attempted by local communities through health or housing codes and regulations. At the Federal level, the Department of Housing and Urban Development has issued regulations for lead hazard abatement in housing units assisted or supported by its programs. Generally, the lead level considered hazardous ranges from 0.5 to 2.5 mg/cm^2, but the level of lead content selected appears to be dependent more on the sensitivity of field measurement by different regulatory bodies (using X-ray fluorescent lead detectors) than on direct biological dose-response relationships. Regulations also require lead hazard abatement when the paint is loose, flaking, peeling, or broken, or in some cases when it is on surfaces within reach of a child's mouth.

Some studies have been carried out to determine the distribution of lead levels in paint in residences. A survey of lead levels in 2370 randomly selected dwellings in Pittsburgh provides some indication of the lead levels to be found.[126] Figure 12-9 shows the distribution curves for the highest lead level found in dwellings for three age groupings. The curves bear out the statement often made that paint with high levels of lead is most frequently found in pre1940 residences. One cannot assume, however, that high level lead paint is absent in dwellings built after 1940. In the case of the houses surveyed in Pittsburgh, about 20 percent of the residences built after 1960 have at least one surface with more than 1.5 mg/cm^2 lead.

The distribution of lead within an individual dwelling varies considerably. Figure 12-10 presents the distribution of the highest paint lead measurements on walls, doors, and windows for all the buildings sampled. These data show that the lead is not uniformly distributed throughout the units. Lead paint is most frequently found on doors and windows where lead levels greater than 1.5 mg/cm^2 were found on 2 percent of the surfaces surveyed, whereas

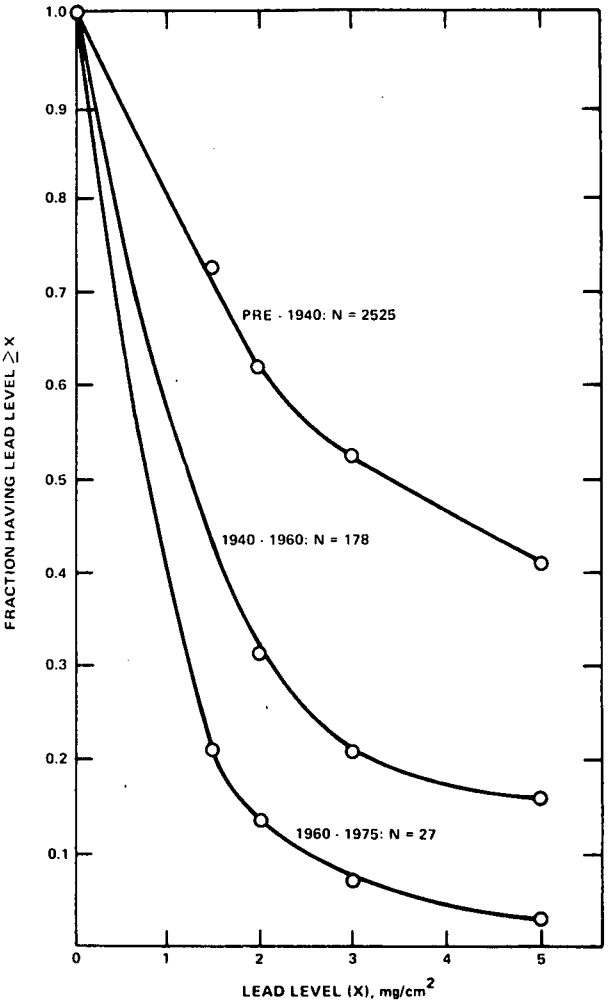

Figure 12-9. Cumulative distribution of lead levels in dwelling units.[126]

only about 1 percent of the walls had lead levels greater than 1.5 mg/cm^2.[126]

The literature[120] generally accepts the premise that the presence of lead in paint is a necessary but not sufficient condition for a hazard to be present. Accessibility in terms of peeling, flaking, or loose paint is also a necessary condition for the presence of a hazard. Figure 12-11 shows the distribution of lead levels and nonintact conditions for dwellings and surfaces for the Pittsburgh sample. Of the total samples surveyed, about 14 percent of the residences would have accessible paint with a lead content greater than 1.5 mg/cm^2.

It is not possible to extrapolate the results of the Pittsburgh survey nationally; however, additional data from a pilot study of 115 residences in Washington, D.C., showed similar results.[127]

An attempt was made in the Pittsburgh study to obtain information about the correlation between

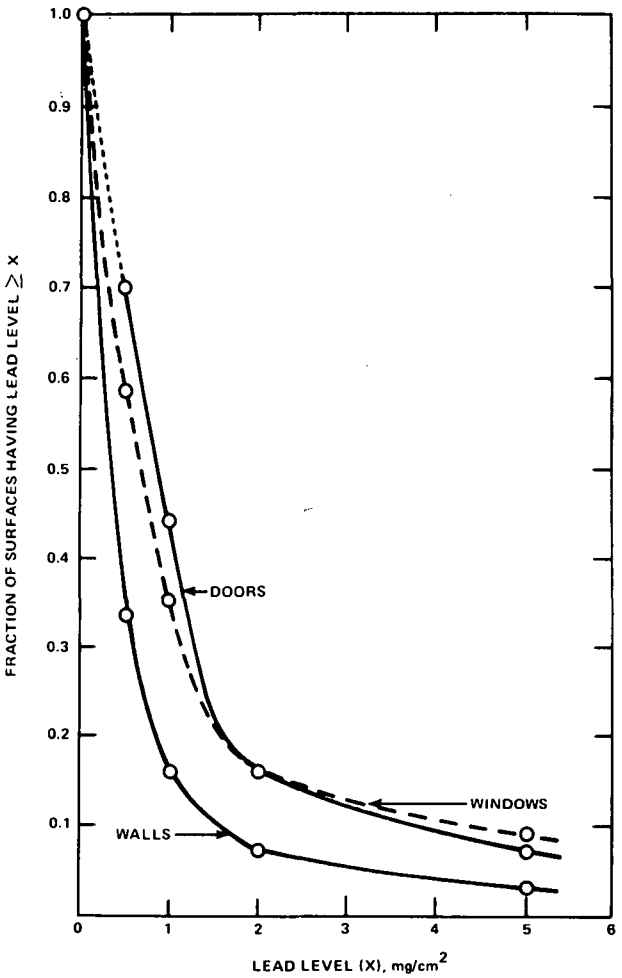

Figure 12-10. Cumulative distribution of lead levels by location in dwelling, all ages.[126]

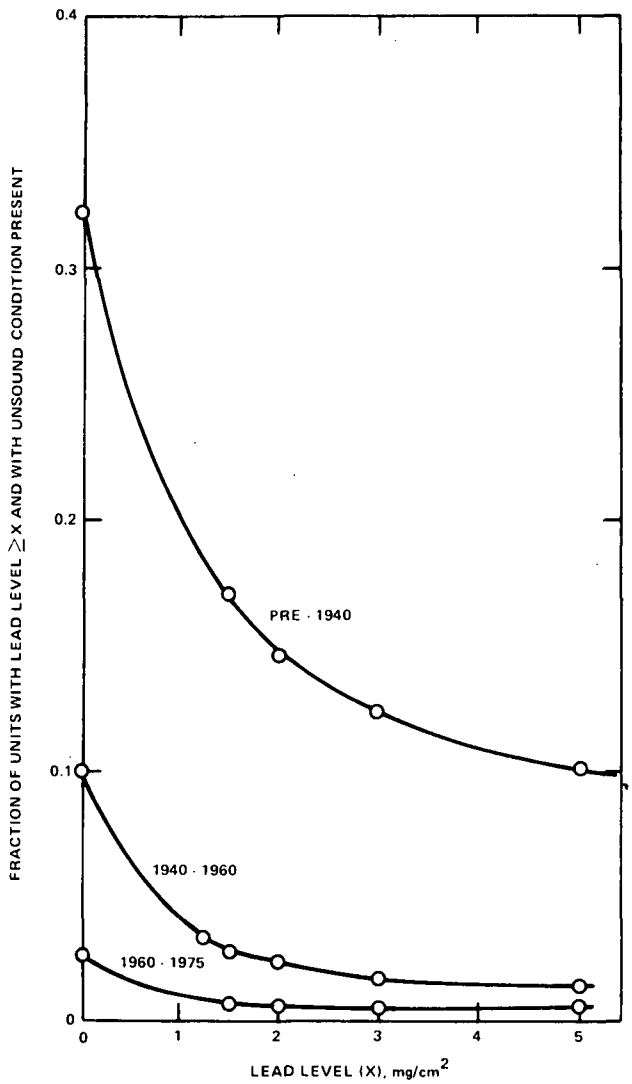

Figure 12-11. Cumulative distribution of lead levels in dwelling units with unsound paint conditions.[126]

the quantity and condition of lead paint in buildings and the blood lead of children who resided there.[128] Blood lead analyses and socioeconomic data for 456 children were obtained along with the information about lead levels in the dwelling. Figure 12-12 shows the cumulative distribution of the blood lead levels for this group. Figure 12-13 is a plot of the blood lead levels versus the fraction of surfaces within a dwelling with lead levels of at least 2 mg/cm^2. Analysis of the data shows a low correlation between the blood lead levels of the children and fraction of surfaces with lead levels above 2 mg/cm^2, but a stronger correlation between the blood lead levels and condition of the painted surfaces in the dwelling in which children reside. This latter correlation appeared to be independent of the lead levels in the dwellings.

Two other studies have attempted to relate blood lead levels and paint lead as determined by X-ray fluorescence. Reece et al. in Cincinnati studied 81 children from two lower socioeconomic communities.[129] Blood leads were analyzed by the dithizone method. There was considerable lead in the home environment, but it was not reflected in the children's blood lead. Analytic procedures used to test the hypothesis were not described; neither were the raw data presented.

Galke et al. in their study of inner-city black children measured the paint lead, both interior and exterior, as well as soil and traffic exposure.[43] In a multiple regression analysis, exterior siding paint lead was found to be significantly related to blood lead levels.

Although most of the evidence indicates that the source of exposure in childhood lead poisoning is almost invariably peeling lead paint and broken lead-impregnated plaster found in poorly main-

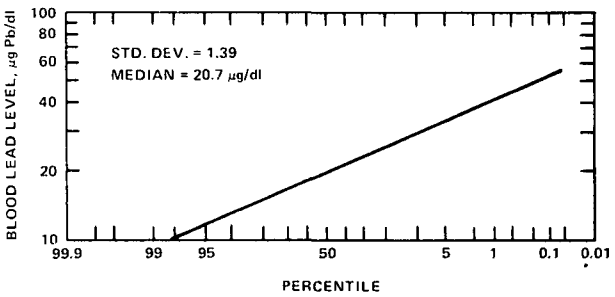

Figure 12-12. Cumulative frequency distribution of blood lead levels found in Pittsburgh housing survey.[126]

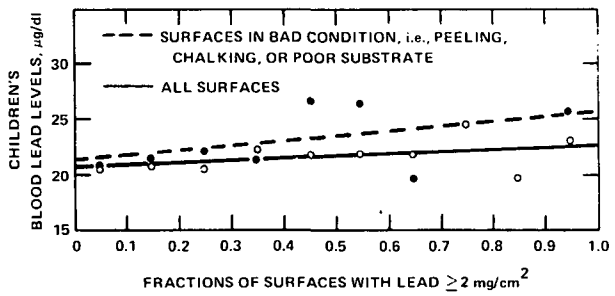

Figure 12-13. Correlation of children's blood lead levels with fractions of surfaces within a dwelling having lead concentrations ≥2 mg Pb/cm².

tained houses, there are also reports of exposure cases that cannot be equated with the presence of lead paint. Further, the analysis of paint in homes of children with lead poisoning has not consistently revealed a hazardous lead content.[120] For example, one paper reported 5466 samples of paint obtained from the home environment of lead poisoning cases in Philadelphia between 1964 and 1968. Among these 5466 samples of paint, 67 percent yielded positive findings defined as paint with more than 1 percent lead.[130]

Data published or made available by the Center for Disease Control, Department of Health, Education, and Welfare, also show that a significant number of children with undue lead absorption occupy buildings that were inspected for lead-based paint hazards, but in which no hazard could be demonstrated.[131,132] Table 12-37 summarizes the data obtained from the HEW funded lead-based paint poisoning control projects for fiscal years 1974, 1975, and 1976, plus the transition quarter July 1, 1976 to September 30, 1976. These data show that in about 40 to 45 percent of confirmed cases of elevated blood lead levels, a possible source of lead paint hazard could not be located. The implications of these findings are not clear. They should not, however, weaken the role of lead-based paint as a major environmental source of lead for children. The findings are presented in order to place in proper perspective both the concept of total lead exposure and the concept that lead paint is one source of lead that contributes to the total body load. The background contribution of lead from other sources is still not known even for those children for whom a potential lead-paint hazard has been identified; nor is it known what proportion of lead came from which source.

TABLE 12-37. RESULTS OF SCREENING AND HOUSING INSPECTION IN CHILDHOOD LEAD POISONING CONTROL PROJECT BY FISCAL YEAR[131,132]

Results	Fiscal year[a] 1976[132]	1975[131]	1974[131]
No. children screened	500,463	440,650	371,955
No. children with elevated lead exposure	69,131[b]	28,597[c]	16,228[c]
No. dwellings inspected	50,276	30,227	23,096
No. dwellings with lead hazard	28,333	17,609	13,742

[a] Fiscal year 1976 includes transition quarter.
[b] CDC Classes II-IV.
[c] Confirmed blood lead level ≥40 μg/dl.

12.3.5 Secondary Exposure of Children from Parents' Occupational Exposure

Excessive intake and absorption of lead for children can result when a parent who works in a dusty environment with a high lead content brings dust home on his clothes, shoes, or even his automobile. Once home, this dust is then available to his children.

Excessive intake and absorption also can occur when children voluntarily ingest nonfood items, such as clay, plaster, or paint chips. This is the classical pica, which refers to the intentional ingestion of nonfood material rather than to the passive, nonintentional ingestion of dust from a dirty finger or piece of candy that has been dropped and thus contaiminated.

Landrigan et al.[62] reported that the 174 children of smelter workers who lived within 24 km of the smelter had significantly higher blood lead levels, a mean of 55.1 μg/dl, than the 511 children of persons in other occupations who lived in the same areas whose mean blood lead level was 43.7 μg/dl.

Analyses by EPA staff of the data collected in Idaho showed that employment of the father at the lead smelter, at a zinc smelter, or in the lead mine

resulted in higher blood lead levels in the children living in the same house with such fathers than children whose fathers were employed in different locations (Table 12-38).

TABLE 12-38. GEOMETRIC MEAN BLOOD LEAD LEVELS (μg/dl) OF CHILDREN BY PARENTAL EMPLOYMENT (EPA analysis of 1974 data)

Age and study area	Lead smelter worker	Lead/zinc mine worker	Zinc smelter worker	Other occupation
1 to 3 years				
1	77.1(12)[a]	65.7(25)	66.3(11)	65.9(13)
2	56.8(11)	53.5(21)	55.1(6)	48.5(30)
3	33.7(6)	54.5(15)	32.3(2)	34.8(26)
4	29.6(4)	36.0(16)	41.7(4)	31.5(22)
5	—	31.8(29)	—	27.2(16)
6	—	—	—	22.4(34)
4 to 9 years				
1	73.6(32)	65.8(28)	59.3(16)	59.2(33)
2	49.6(21)	43.8(32)	51.9(4)	44.9(67)
3	33.3(21)	35.5(39)	35.2(7)	32.1(58)
4	30.9(4)	33.0(53)	35.6(5)	29.1(44)
5	24.5(2)	27.1(79)	—	26.4(60)
6	—	—	—	20.5(56)

[a] Sample sizes in parentheses.

The effect associated with parental employment appears to be much more prominent in the most contaminated study areas nearest to the smelter. This may be the effect of an intervening socioeconomic variable: the lowest paid workers, employed in the highest exposure areas within the industry, might be expected to live in the most undesirable locations, which are closest to the smelter.

The importance of the infiltration by lead dusts into clothing, particularly the undergarments, of lead workers has been demonstrated in a number of studies of the effects of smelters.[133] It was noted in the United Kingdom that elevated blood lead levels were found in the wives and children of workers even when they resided some considerable distance from the facility. It was most prominent in the families of workers who themselves had elevated blood lead levels. Quantities of lead dust were found in workers' cars and homes. It apparently is not sufficient for a factory merely to provide outer protective clothing and shower facilities for lead workers. In another study in Bristol, from 650 to 1400 ppm of lead was found in the undergarments of workers as compared with 3 to 13 ppm in undergarments of control subjects. Lead dust will remain on the clothing even after laundering: up to 500 mg of lead has been found to remain on an overall garment after washing.[134]

Baker et al.[135] found blood lead levels >30 μg/dl in 38 of 91 children whose fathers were employed at a secondary lead smelter in Memphis, Tenn. House-dust, the only source of lead in the homes of these children, contained a mean of 2687 μg/g compared with 404 μg/g in the homes of a group of matched controls. Mean blood lead levels in the workers' children were significantly higher than those for controls and were closely correlated with the lead content of household dust. In homes with lead in dust < 1000 μg/g, 18 children had a mean blood lead level of 21.8 ± 7.8 μg/dl, whereas in homes where lead in dust was >7000 μg/g, 6 children had a mean blood lead level of 78.3 ± 34.0 μg/dl.

Landrigan et al.[62] also reported a positive history of pica for 192 of the 919 children studied in Idaho. This history was obtained by physician and nurse interviews of parents. Pica was most common among 2-year-old children and only 13 percent of those with pica were above age 6. Higher blood lead levels were observed in children with pica than in those without pica. Table 12-39 shows the mean blood lead levels in children as they were affected by pica, occupation of the father, and distance of residence from the smelter. It is interesting that, among the

TABLE 12-39. GEOMETRIC MEAN BLOOD LEAD LEVELS FOR CHILDREN BASED ON REPORTED OCCUPATION OF FATHER, HISTORY OF PICA, AND DISTANCE OF RESIDENCE FROM SMELTER[62]

		Lead smelter worker		Lead/zinc mine worker		Zinc smelter worker		Other occupations	
Area	Distance from smelter, km	Pica	No pica	Pica	No pica	Pica	No pica	Pica	No pica
1	1.6	78.7	74.2	75.3	63.9	69.7	59.1	70.8	59.9
2	1.6 to 4.0	50.2	52.2	57.1	46.9	62.7	50.3	37.2	46.3
3	4.0 to 10.0	33.5	33.3	36.7	33.5	36.0	39.6	33.3	32.6
4	10.0 to 24.0	—	30.3	38.0	32.5	40.9	36.9	—	39.4
5	24.0 to 32.0	—	24.5	31.8	27.4	—	—	28.0	26.4
6	75.	—	—	—	—	—	—	17.3	21.4

populations living nearest to the smelter, environmental exposure appears to be sufficient at times to more than overshadow the effects of pica, but this finding may also be caused by inadequacies inherent in collecting data on pica.

These data indicate that in a heavily contaminated area, blood lead levels in children may be significantly increased by the intentional ingestion of nonfood materials having a high lead content.

Data on the parents' occupations are, however, more reliable. It must be remembered also that the study areas were not homogeneous socioeconomically. In addition, the type of work an individual does in an industry is probably much more important than simply being employed in a particular industry. The presence in the home of an industrial employee exposed occupationally to lead may produce increases in the blood lead levels ranging from 10 to 30 percent.

12.3.6 **Miscellaneous Sources of Lead**

Although no studies are available, it is conceivable that destruction of lead-containing plastics (to recover copper), which has caused cattle poisoning, also could become a source of lead for humans. A more general problem is waste disposal, because lead-containing materials may be incinerated and may thus contribute to increased air lead levels. This source of lead has not been studied in detail.

The consumption of illicitly distilled liquor has been shown to produce clinical cases of lead poisoning. Domestic and imported earthenware with improperly fired glazes have also been related to clinical lead poisoning. This source becomes important when foods or beverages high in acid are stored in containers made from these materials because the acid releases lead from the walls of the containers.

Particular cosmetics popular among some Oriental and Indian ethnic groups contain high percentages of lead that sometimes are absorbed by users in quantities sufficient to be toxic.

12.4 **SUMMARY**

Blood lead levels in homogeneous human populations have almost invariably been found to be lognormal. A number of such data sets were examined and they displayed a geometric standard deviation (GSD) ranging from 1.3 to 1.5.

From the lognormal distribution, given a mean blood lead level and an estimated geometric standard deviation, it is possible to predict the percentages of a population whose blood lead levels exceed a specified value. It is also possible to estimate the likely increase in mean blood lead levels for a population exposed to specific increases in environmental lead. Coupling these two procedures provides a method by which standards may be chosen to protect the health of the population.

Blood lead levels have been found to exhibit considerable geographic variability. Generally they are lowest in rural settings, higher in suburban areas, and highest in inner-city areas. These values follow the presumed lead exposure gradient. Blood lead values were also found to vary by age, sex, and race, although in a somewhat more complex fashion. Generally, young children have the highest levels, with little difference between sexes. In older segments of the population, after eliminating occupational exposure in lead workers, males have a higher blood lead than females. The published data comparing the blood lead levels of various racial and ethnic groups of the population suggest that blacks have higher blood lead levels than whites, with Puerto Ricans sometimes at an intermediate level.

Results of the numerous studies of environmental exposures of man have indicated strongly that man does indeed take up lead from each source to which he is exposed. Equally important, these studies have shown that the blood lead level is the summation of the absorption from each of these sources.

Data for the two most widespread environmental sources other than food permit summary statements concerning their quantitative relationship with blood lead levels: ratios between blood lead levels and air lead exposures were shown to range generally from 1:1 to 2:1. These were not, however, constant over the range of air lead concentrations encountered. There are suggestive data indicating that the ratios for children are in the upper end of the range and may even be slightly above it. There is also some slight suggestion that the ratios for males are higher than those for females.

For soil lead exposures, a consistent association with blood lead levels has been established. Children exposed to higher soil and housedust lead concentrations have been shown to have elevated concentrations of lead on their hands, but an association of elevated blood lead levels with elevated hand lead levels has not yet been established. Quantitatively, blood lead levels have been shown to increase 3 to 6 percent when the soil or dust lead content is doubled.

Significant water lead exposures in this country have occurred only in places using leaded pipes coupled with a soft water supply. Such exposures have been shown to be associated with significant

elevations of blood lead. They have also been linked to cases of mental retardation.

Exposure to leaded paint still comprises a very serious problem for American children in urban settings. Although new regulations governing the lead content of paint should alleviate the problem in new housing, the poorly enforced regulation and lack of regulation of the past have left a heavy burden of lead exposures from paint. Most of the studies on lead poisoning in children have assumed an association with leaded paint, but very rarely have these studies measured the amount of exposure. There is, nevertheless, strong suggestive evidence that the contribution from this source can be very significant.

Lead exposure via food is thought to be the source of a significant portion of blood lead. Direct quantitative equations describing the relationship of blood to food lead levels have not been published, but studies described in Chapter 10 do address this relationship.

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13. EVALUATION OF HUMAN HEALTH RISKS FROM EXPOSURE TO LEAD AND ITS COMPOUNDS

13.1 INTRODUCTION

The preceding chapters of this document have described lead production, the eonomics of lead utilization, the dispersion of lead in the environment — particularly in air, dust, and soil — and, finally, have reviewed the effects of lead on the health of man. Although attempting to relate these various issues to one another, this chapter specifically will attempt to assess and to quantitate the health effects that arise from exposure of man to lead in the environment and, more precisely, from exposure to lead in air. Six central questions to be addressed are as follows:

1. What are the sources of lead in the environment? (Sections 13.2 and 13.3)
2. What are the routes and mechanisms by which lead from these sources enters the body? (Sections 13.2 and 13.3)
3. What part do averaging times for these exposures play? (Section 13.4)
4. How does the body respond to the entrance of lead? (Section 13.5)
5. Are there groups within populations which are particularly vulnerable to lead? (Section 13.6)
6. What is the magnitude of the risk exposures in terms of the number of persons exposed in various subgroups of populations? (Section 13.7)

Each of the above questions is addressed separately as a subsection of this chapter, and the relevant section is noted beside each question.

Now that the questions to be addressed in this treatment of risk assessment have been outlined, it is necessary to define the terms which will be employed. These include:

1. *Dose* is the amount or concentration of a chemical that is presented over time to an organism, organ, cell, or subcellular component. Ideally, dose should be defined as the amount or concentration of the chemical at a specific intracellular site of effect.
2. *External dose* is the amount of the contaminant in the external environment (air, water, food, etc.) to which humans are exposed.
3. *Effective dose* or *internal dose* is the amount of the contaminant absorbed by the body.
4. *Effect* is a biologic change which results from exposure to a chemical.
5. *Dose-effect relationship* is a quantitative relationship between the dose and the specific effect that is established after gradations in the severity of an effect have been measured.
6. *Critical effect* is the first adverse functional change, reversible or irreversible, to be caused by exposure to a particular chemical.
7. *Subcritical effect* is a change that is demonstrable by biochemical or other test, but which does not appear to impair function; some such changes may be adaptive in nature.
8. *Critical dose* or *critical concentration* is the level of a chemical at which the critical effect appears.
9. *Critical organ* is the organ which manifests the critical effect; it need not be the organ with the highest concentration of the chemical nor that which ultimately suffers the most serious injury.

Dose-effect relationships will vary among the members of a population. Response is the proportion of the population that manifests a particular effect at a particular dose level.[1] This is a more restrictive definition of response than that used in bioassay as described by Finney.[2] The relationship between dose and the proportion responding is the dose-response relation, which will most commonly be expressed by a sigmoid-shaped curve.

13.2 SOURCES, ROUTES, AND MECHANISMS OF ENTRY

13.2.1 Sources

Of the estimated 161,225 metric tons of lead emit-

ted into the atmosphere in 1975, the combustion of gasoline additives and waste oil accounted for 95 percent of total inventoried emissions. Each of the remaining emission sources accounts for only a small part of the total quantity of lead, but has the potential of creating localized situations of high air lead concentrations, e.g., primary lead smelters.

Once lead is introduced into the air it undergoes a variety of processes including dry deposition, precipitation, and resuspension. These processes result in a variable proportion of lead being retained in the air and then being distributed over a wide area. Other portions are deposited on land, in dust, and on water, resulting in increased lead concentrations in each.

Other uses of lead result in additional human exposure. The addition of lead to paint makes lead directly available by ingestion of paint chips and paint-saturated plaster. In addition it becomes indirectly available through dust contaminated with lead freed by the weathering process of paint. This primary source is currently under regulation, but a vast stock of housing painted with high-lead-content paint still exists.

Lead's malleability and ductility have resulted in the use of this metal in pipes for carrying drinking water. When such pipes are used in areas with soft water of low pH, a potential exists for heavy lead contamination of drinking water. It is difficult to estimate the overall magnitude of this danger, but there have been specific localized examples in the United States.

A final quantitatively significant source of lead is the human diet. Lead present in foodstuffs is the sum of the amount present in the raw foodstock and of lead introduced via processing and packaging. Canned products such as vegetables and milk have been shown to contain higher quantities of lead than the same products packaged differently. This is due, in part, to the presence of lead solder in the seams of cans. Baby foods have also been shown to have higher lead contents because of the preservatives used. The origin of lead in raw food stocks is still a matter of some controversy, although part of it is likely to be the consequence of man's activities which result in making lead available for uptake by animals and plants. Such redistribution and subsequent uptake of lead by plants is well illustrated by fivefold increases in the amount of lead present in tree rings over a 50-year period.

It is important to realize that human exposure and intake are not limited to the primary sources of lead in the environment but, rather, to the sum of primary, secondary, and tertiary sources. Table 13-1 displays these sources.

TABLE 13-1. SOURCES OF LEAD FOR HUMAN EXPOSURES

Primary exposure source	Secondary exposure source	Tertiary exposure source
Air	Dust and soil	Food Runoff water
	Water	Air[a]
Paint	Dust and soil	Runoff water Air[a]
Water from leaded pipes		
Food		

[a]Reentrainment

13.2.2 Routes and Mechanisms of Entry

Chapter 10 presents data on the entry of lead into the human body. Two routes of entry are of principal importance, inhalation and ingestion. Intake of airborne lead is governed by the physical and chemical state of inhaled lead, particle size retention in the lung, and absorption from the lung into the red blood cells.

The second major route of entry is ingestion, both of food and of nonfood material. Uptake is controlled by the nutrient balance of the food ingested, particularly that of iron, by the physical nature of the lead-bearing material ingested, and by the chemical composition of the substance. Here, too, the lead is absorbed by circulating red blood cells.

The total internal dose of lead which confronts the organ systems of the body is the sum of the lead intake by both routes of entry: inhalation and ingestion. Thus the total internal dose represents the summation of all external sources to which the body is exposed. Some of these exposures may be of different relative significance in diverse population groups due to variances in metabolism or behavior among different segments of the population.

13.3 EVIDENCE OF INCREASED BLOOD LEAD LEVELS IN HUMANS EXPOSED TO ENVIRONMENTAL LEAD

13.3.1 Relationships Between Blood Lead Levels and Single-Source Exposures

Research has been conducted on all six major exposure sources — air, dust, soil, water, paint, and food. Chapter 12 provided the detailed description, evaluation, and findings of those studies. Not all sources have been studied with the same intensity,

and food has been studied least. In addition, food as a tertiary exposure source is difficult to evaluate. Lead content in food due to packaging and processing has been studied more thoroughly than contribution from that lead present at the point of origin.

Single-source studies of air have included both epidemiological and clinical investigations. Clinical data uniformly demonstrate the actual uptake of airborne lead into blood, and epidemiologic data also generally support such a relationship.

Studies concerned with dust and soil lead exposures will be considered together since in many studies the investigators did not attempt to deal with these sources separately. Considerable evidence exists that these exposures can be significant determinants of blood lead levels. Furthermore, investigations of children exposed to lead-contaminated dust have demonstrated more lead on the children's hands, thus documenting a plausible route of entry which is due to normal oral behavior in young children. It may be worth reiterating here that the dose of lead ingested from dust and soil appears to be additive to that inhaled from air.

The popular assumption that lead-based paint is the single causative agent of elevated blood lead levels in children has resulted in limiting the definition of high-risk children to those residing in older housing. As a result, lead screening programs have been established with the sole purpose of identifying children with elevated lead levels among those living in old housing. Abatement efforts have frequently been unable to find lead paint sources for children with high blood levels found by such screening programs. The possible contributory role of airborne lead to the lead burden of urban children has until recently received little attention.

Finally, studies from Glasgow and Boston have shown elevated blood lead levels in conjunction with elevated levels of lead in the drinking water.

Secondary effects of occupational exposure have been examined in children whose parents work in lead industries. It has been found that parents carry home lead-contaminated dust. Significant relationships between house dust levels and blood lead levels have invariably been established in these studies.

13.3.2 **Multiple-Source Exposures**

Studies measuring the quantity of lead in multiple sources, around primary lead smelters or in urban settings, have consistently demonstrated an additive relationship between blood lead levels and exposure to the several sources studied.

13.3.3 **Effect of Host Factors on Blood Lead Levels**

Host characteristics that mediate the relationship between exposure to lead and blood lead level have been examined in several studies. In particular, age has been shown to be a significant factor in determining blood lead levels; this relationship is discussed below in more detail in the section (13.6) on populations at greatest risk.

Sex differences have been found to be age related. Particularly among preschool boys and girls, virtually no difference has been established. In the adult population, however, males generally exhibit higher levels than females.

Data on the racial/ethnic factor are sparse. One study has reported that black children have higher lead levels than do white children. Although the significance of the racial/ethnic factor cannot be established at this time, it seems reasonable to assume that it is the socioeconomic rather than the genetic dimension of this variable that may prove to be relevant.

Socioeconomic variables such as income and education have not been examined adequately as independent factors. Associated characteristics such as residence in old housing, or proximity to high-density traffic arteries or to stationary sources such as smelters, have been shown to be directly relevant.

In epidemiological studies the health status as a variable has not been examined. Conditions such as iron deficiency anemia, other states of malnutrition, sickle cell anemia, and lactose intolerance as host factors in lead intake and determinants of physiological and pathological changes have only recently come under study. No findings are available as yet.

13.3.4 **Summary of the Quantitative Relationship**

Statistical evaluation of the data collected from population and clinical studies has been presented in the previous chapter. There it was noted that the weight of the evidence indicates that blood lead levels follow a lognormal distribution in exposed populations with a geometric standard deviation of 1.3 to 1.5. It was also seen that the lognormal distribution has properties that make it amenable to use in the standard-setting process, since it permits an estimate of the proportion of the population whose blood lead levels exceed any specified level.

Detailed examination of the clinical and epidemiological studies relating air lead levels to blood lead levels is presented in Chapter 12. Evidence indicates that a positive relationship exists be-

tween blood and air lead levels, although the exact functional relationship has not yet been clarified. Available data indicate that in the range of air lead exposures generally encountered by the population, the ratio of the increase in blood lead per unit of air lead is from 1 to 2. It appears that the ratio for children is in the upper end of the range and that ratios for males may be higher than those for females.

Quantitative relationships can also be established between blood lead levels and exposure to lead in soil. There is general agreement that blood lead levels begin to increase at soil lead levels of from 500 to 1000 ppm. Mean percent increases in blood lead levels, given a twofold increase in soil lead levels, ranged from 3 to 6. This is a remarkable consistency, given the divergence of the populations studied.

13.4 AVERAGING-TIME CONSIDERATIONS

One of the major areas of concern in dealing with quantitation of the relationship between a health effect and an external dose of some environmental pollutant is the determination of how long an exposure must occur before there is an effect.

Evidence presented in Chapter 12 indicates that a 5 μg/dl increase in blood lead can result from an air lead exposure of 3.2 $\mu g/m^3$ for a period of 7 weeks. Furthermore, FEP levels have been shown to increase within 2 weeks of an increase of blood lead levels. Therefore, an air lead exposure of 3.2 $\mu g/m^3$ lasting about 1 to 2 months can definitely increase the blood lead level.

13.5 BIOLOGICAL AND ADVERSE HEALTH EFFECTS OF LEAD IN MAN

Lead does not presently have associated with it any biological effect in man which can be considered beneficial; therefore, any consideration of the health effects of lead in man must be done from a point of view that acknowledges the absence of any health benefit/health cost ratio.

An additional and extremely important aspect of lead's effect on health impairment that must be considered in risk assessment is the question of whether these effects are reversible once present.

Physiological damage to central nervous system tissue is presently widely accepted as being irreversible; thus prevention of lead exposure is most urgent when one considers severe neurological effects. Irreversibility is also accepted in the case of renal tissue damage resulting from chronic lead exposure, particularly in cases where these effects are manifested morphologically.

We speak of physiological irreversibility in the cases of neurological or renal tissues, but the concept of irreversibility of an effect being likely or assured by nonbiological factors such as continuing, long-term exposure to airborne lead must also be considered. Hematological effects are of relevance here. Although a number of these hematological effects may be biochemically reversible, if the probability of the person being removed from the exposure setting inducing these effects is slight or nonexistent, for whatever reason, then *defacto* irreversibility exists.

This section summarizes the biological effects of lead on man with particular reference to significance of these effects for human health. Much of the attention in this section will be directed to those biological effects which may collectively be termed "subclinical." By definition, subclinical effects are disruptions in function, which may be demonstrated by special testing but not by the classic techniques of physical examination; using the term "subclinical" in no way implies that those effects are without consequences to human health.

13.5.1 Assessment of Hematological Effects of Lead

A multiplicity of effects of lead on the hematopoietic system exists. These effects were discussed in detail in Chapter 11, Section 3, and are briefly summarized here.

13.5.1.1 ANEMIA

Anemia is a classic manifestation of clinical lead intoxication, often occurring prior to neurological and other system impairment. The mechanism of anemia in lead exposure apparently involves both decreased production of hemoglobin and enhanced destruction of erythrocytes. Reports on children indicate that statistically significant decreases in hemoglobin levels begin to appear at a blood lead level of 40 μg/dl or somewhat below. In adults a significant decrease in hemoglobin level appears to become evident at a blood lead level of 50 μg/dl.

13.5.1.2 LEAD EFFECTS ON HEME SYNTHESIS

A large number of studies have been done on the effects of lead on heme synthesis in humans. Lead interferes with heme synthesis at several points along the heme-biosynthetic pathway. The two most important points of interference are: (1) the condensation of two units of δ-aminolevulinic acid dehydratase to form porphobilinogen and (2) the in-

sertion of iron into protoporphyrin IX which is catalyzed by the enzyme ferrochelatase.

13.5.1.3 EFFECT OF LEAD ON δ-AMINOLEVULINATE DEHYDRATASE (δ-ALAD) AND δ-AMINOLEVULINIC ACID (δ-ALA) EXCRETION

A number of studies have shown the high sensitivity of δ-ALAD to lead and the negative correlation between blood lead and the logarithm of δ-ALAD activity. These studies are described in Section 11.3. It appears that this relationship holds true for industrial workers, the general population, and children.

The dose-response relationship between blood lead and the logarithm of ALAD activity appears to be linear coefficient of correlation (r) = 0.84. ALAD inhibition is first noted at whole blood levels of 10 to 20 μg/dl (Chapter 11). This high degree of sensitivity makes application and interpretation of the test difficult. ALAD inhibition is virtually complete at blood lead levels of 70 to 90 μg/dl.

Data summarized by Hernberg[3] suggest that heme biosynthesis is not decreased by ALAD inhibition until activity of the enzyme has fallen to less than 20 to 30 percent of normal. In addition to its effect on red blood cell ALAD, lead appears to inhibit ALAD activity in liver. It has also been suggested that in young children lead may inhibit activity of ALAD in brain.

13.5.1.4 EFFECT OF LEAD ON IRON INSERTION INTO PROTOPORPHYRIN

Accumulation of protoporphyrin in erythrocytes in lead exposure is the result of lead-induced inhibition of the intramitochondrial enzyme, ferrochelatase. The inhibitory effect of lead on ferrochelatase may either be direct or may be mediated by a disruption in the function of mitochondrial membranes.

The effect of lead on the formation of heme is not limited to the hematopoietic system. Experimental animal studies have shown a lead effect on the heme-requiring protein, cytochrome P-450, an integral part of the hepatic mixed-function oxidase (Chapter 11), the systemic function of which is detoxification of exogenous substances. Heme synthesis inhibition also takes place in neural tissue.

The elevation of free erythrocyte protoporphyrin (FEP) has been shown by a large number of studies to be exponentially correlated with blood lead level in children and adults.

Present information shows that at relatively fixed blood lead values children and probably women have higher protoporphyrin levels in their blood than adult males. The exact reason for this is not known, but it may be of endocrinological origin.

Elevation in protoporphyrin is considered not only to be a biological indicator of impaired mitochondrial function of erythroid tissue but also an indicator of accumulation of substrate for the enzyme ferrochelatase. It therefore has the same pathophysiological meaning as increased urinary δ-ALA (*vide supra*). For these reasons accumulation of protoporphyrin has been taken to indicate physiological impairment in humans, and this clinical concensus is expressed in the 1975 Statement of the Center for Disease Control (CDC), USPHS. The criterion used by CDC to indicate an effect of lead on heme function is an FEP level of 60 μg/dl in the presence of a blood lead level above 30 μg/dl whole blood.

More recent information relating to threshold of lead effects indicates that FEP levels begin to increase at a blood lead value of 15 to 20 μg Pb/dl blood in children and women and, at a somewhat higher value, 20 to 25 μg Pb/dl blood, in adult men.

13.5.1.5 OTHER EFFECTS ON HEME SYNTHESIS

There are other abnormalities of heme synthesis that are a result of lead exposure. For example, it is well known that an increased urinary coproporphyrin level is found in lead poisoned children and lead workers. It is not known whether this effect results from specific enzyme inhibition, from upstream accumulation of substrate secondary to the inhibition of iron insertion into protoporphyrin, or from a disturbance of coproporphyrin transport through the mitochondrial membrane.

An increased activity of δ-ALA synthetase is seen in lead intoxication, but this change probably arises as a negative feedback control to δ-ALA response to inhibition upstream in the heme-biosynthetic pathway. Few data exist to quantitate the health significance of this effect.

13.5.1.6 EFFECTS OF LEAD ON GLOBIN SYNTHESES

Hemoglobin synthesis may also be impaired by the inhibition by lead of globin biosynthesis. Globin is the protein moiety of hemoglobin. One recent study shows an effect on globin synthesis *in vitro* on human reticulocytes at lead concentrations corresponding to a blood lead level of 20 μg/dl.

13.5.2 Assessment of Neurobehavioral Effects of Lead

As reviewed in Chapter 11, an extensive literature documents the adverse effects of lead on the central and peripheral nervous systems of many human and nonhuman mammalian species. Only limited dose-response data exist that might allow external lead exposure parameters to be linked directly to the occurrence of particular neurobehavioral effects. In contrast, more data exist relating blood lead levels to neurobehavioral deficits; major emphasis here is therefore focused on the concise summarization of relationships between human blood lead levels and neurobehavioral effects.

13.5.2.1 CENTRAL NERVOUS SYSTEM EFFECTS

Among the most profoundly deleterious effects of lead poisoning are those associated with severe CNS damage that occur at toxic high exposure levels. The acute overt manifestations of neural damage at high lead exposure levels include such symptoms as irritability, stupor, convulsions, and/or coma, which characterize the well-known encephalopathy syndrome. Such symptoms at times occur abruptly during the course of much milder symptomatology or even in apparently asymptomatic lead poisoned individuals and may progress to death within 48 hr.

Even in the absence of death or prolonged unconsciousness, it is now widely accepted that irreversible neural damage typically occurs as one of the sequelae of nonfatal lead encephalopathy episodes. Such permanent neural damage is reflected by signs of continuing CNS impairment ranging from subtle neurobehavioral deficits to severe mental retardation or continuing mental incompetence. What is not yet universally agreed upon, however, are the lead levels sufficient to produce lead encephalopathy and its sequelae.

In regard to the issue of threshold levels for lead encephalopathy, blood lead levels of 120 μg/dl or more are currently widely accepted as necessary to produce encephalopathy symptoms in adults. The published evidence bearing on this point, however, is very limited. Included among such evidence are a few scattered reports suggesting that acute encephalopathy or death may occur in adults at blood lead levels under 100 μg/dl (from 80 to 100 μg/dl), but the rarity of such cases and ambiguities in the reported data render it difficult to accept those reports as evidence for encephalopathy in adults at blood lead levels below 120 μg/dl.

Much better evidence exists for the occurrence of lead encephalopathy in children at blood lead levels below 120 μg/dl or even 100 μg/dl. That is, it is well documented that such symptoms occur for some children beginning at the 100 μg/dl level; also, several scattered reports suggest that somewhat lower threshold levels may obtain, i.e., in the 80 to 100 μg/dl range, although such reports must be viewed with caution as in the case for analogous results for adults.

As indicated earlier, the issue of whether apparently asymptomatic children experience subtle neurobehavioral deficits at low-to-moderate blood lead levels in the 40 to 80 μg/dl range remains a subject of much controversy. A thorough, critical review of the relevant literature presented in Chapter 11, nevertheless, leads to the conclusion that blood lead levels of 50 to 60 μg/dl are likely sufficient to cause significant neurobehavioral impairments for at least some apparently asymptomatic children. The impairments consist mainly of cognitive or sensory-motor integration deficits, but do not appear to include the occurrence of hyperactivity; that latter effect seems to be much better established as one of the neurological sequelae following encephalopathy at higher lead levels.

13.5.2.2 PERIPHERAL NEUROPATHY EFFECTS

In addition to the above CNS effects, peripheral nervous system damage also results from exposures to lead. Such effects have been best documented as occurring after long, chronic, high-level exposures in adults exhibiting other symptoms of lead intoxication. Recent studies of apparently asymptomatic adults, usually occupationally exposed to lead, however, present reasonably strong evidence for peripheral neuropathy at more moderate lead exposure levels, i.e., at blood lead levels in the range of 50 to 70 μg/dl. Peripheral neuropathy effects are typically associated with adult exposures, having been reported much less frequently for children. A few reports of lead-induced peripheral neuropathies in children, however, contain evidence for the occurrence, in some rare instances, at blood lead levels as low as 50 to 60 μg/dl.

13.5.2.3 RESULTS OF ANIMAL STUDIES AS SUPPORTIVE EVIDENCE

Review of the literature on the neurobehavioral effects of lead in animals provides evidence supportive of the above conclusions from human studies. That is, there appears to be a differential sensitivity of newborn or young animals of many species to the neurobehavioral effects of lead. This applies both to

the induction of lead encephalopathy at high exposure levels and more subtle neurobehavioral deficits at lower, more moderate exposure levels. In regard to specific types of subtle neurobehavioral effects, hyperactivity appears to occur mainly at blood lead levels in excess of 70 to 80 μg/dl and, therefore, probably most closely parallels the post encephalopathic hyperactivity well demonstrated as one of the sequelae of lead encephalopathy in humans. Other behavioral changes, interpreted as indicative of cognitive impairments resulting from CNS effects, appear to occur in animals at blood lead levels below those associated with acute encephalopathic effects, i.e., in the 30 to 80 μg/dl blood lead level range. This parallels rather closely the effects observed for humans, especially children, except that cognitive deficits have not been very well documented in the children at levels below 50 to 60 μg/dl. The external lead exposures yielding the above results for animals, however, typically appear to be much higher than those producing comparable effects in humans; the comparability of animal studies and human studies is therefore often questioned. If one focuses on the resulting blood lead levels achieved, regardless of associated external dose, however, the results of the animal studies parallel those of the human studies remarkably well.

In discussing the neurobehavioral effects of lead, above in the present section and in Chapter 11, a distinction has repeatedly been made between threshold levels yielding severe symptoms of lead encephalopathy seen at high exposure levels and more subtle neurobehavioral deficits observed at lower exposure levels. This approach may inappropriately convey an impression of such effects occurring in a discrete, step-like fashion as particular threshold blood lead levels are reached. It is important to note that this may occur insofar as shifting from apparent no-effect levels to levels at which fairly well substantiated neurobehavioral effects have been found to occur, i.e., around 50 to 60 μg/dl; beyond that point, however, further increases in relative levels of neural damage, as indicated by increasingly severe neurological or behavioral deficits, occur in a more or less smoothly ascending fashion in relation to increasing blood lead levels. These relationships are presented later in an approximate manner in Table 13-2. Due to differences in individual susceptibility, it should be emphasized that the upper end of the range of blood lead levels at which subtle neurobehavioral effects have been reported to occur for some individuals merges or overlaps substantially with the lower end of the range at which much more severe encephalopathic symptoms have been observed, and that the shift from subtle to severe neural symptoms may be quite abrupt.

13.5.3 **Effects of Lead on Reproduction and Development**

Although the effects of lead exposure in humans have usually been associated with the hematopoietic, neural, and renal systems, concern needs to be equally directed to the entire area of reproduction and development, with special emphasis on the vulnerability of pregnant women or, more accurately, the vulnerability of the fetus.

Attention in this area is focused on two aspects of reproduction: (1) the gametotoxic effects of lead, i.e., lead effects on spermatogenesis and ovarian function, and (2) postconception events through delivery.

13.5.3.1 HUMAN GAMETOTOXICITY

Some data involving effects of lead exposure on the fertility of males exist, and these have been observed at blood lead levels of 50 to 80 μg/dl under conditions of occupational exposure. With regard to women, one study on lead effects (see Reproduction and Development section, Chapter 11) raises the possibility that the ovarian cycle may be disturbed in the age range of 20 to 25 years with air lead levels around 7 $\mu g/m^3$.

13.5.3.2 POSTCONCEPTION LEAD EFFECTS

Both early literature and more current studies conclusively show that lead crosses the placental barrier. Such fetal exposure therefore commences at about the end of the first trimester (12 weeks) and continues throughout fetal development. As has already been pointed out, the distribution of lead within the fetus at different stages of development is probably more important than the total amount present at birth.

Tissue analysis also demonstrates that, in Americans from newborns through persons aged 19 years, brain lead levels appear to be most elevated at birth and then diminish with development.

A number of studies show passage of lead through the placental barrier by comparing cord blood lead and maternal blood lead levels. These studies further serve to shed some light on the effect of various factors in infant blood lead values.

In a group of cord blood/maternal blood matchings, infant blood levels were highly correlated with those of their mothers. A second study showed that

blood values for infants whose mothers were urban residents were significantly higher than those of rural infants.

A study done in a lead-belt area of the United States raises the possibility that lead may affect the course of normal delivery of children since there were more incidents of preterm delivery and premature membrane rupture in pregnant women in this region compared to a group from a relatively unexposed area.

13.5.4 **Other Health Effects**

13.5.4.1 RENAL EFFECTS

Nephropathy is a condition usually considered in its chronic form and that can best be related to prolonged exposure to lead with a corresponding blood lead level of about 70 μg/dl. Because chronic lead nephropathy results only after prolonged or repeated exposures, it is impossible to recapitulate accurately the exposure history; therefore, determination of an exposure threshold for this condition is impossible.

13.5.4.2 EFFECTS OF LEAD ON THE ENDOCRINOLOGICAL, HEPATIC, CARDIOVASCULAR, AND IMMUNOLOGICAL SYSTEMS

Although some studies have been done in reference to each of the systems in this subsection, there exists too little quantitative information relating blood lead levels to the endocrinological, hepatic, and cardiovascular systems.

13.5.5 **Does-Effect/Response Relationships**

In any discussion of the risk assessment directed toward a particular agent, such as lead, two questions arise:

1. What are the lowest levels of the internal dose (blood lead level) that give rise to any biological effect?
2. What dose-response relationships are obtained that define a proportion of a population manifesting a given biological effect at a particular internal dose?

Information summarized in the preceding section dealt with relationships between blood lead levels and various biological effects of lead. Many of the data discussed above concerned threshold levels at which health effects of lead are first observed in different population groups. Table 13-2 summarizes the threshold levels at which various specific hematological and neurobehavioral effects have been observed for particular subpopulations.

A number of investigators have attempted to quantitate more precisely lead's dose-response relationship, i.e., the proportion of a population exhibiting health effects at a given blood lead level.

TABLE 13-2. SUMMARY OF LOWEST OBSERVED EFFECT LEVELS

Lowest observed effect level	Effect	Population group
10	ALAD inhibition	Children and adults
15 - 20	Erythrocyte protoporphyrin elevation	Women and children
25 - 30	Erythrocyte protoporphyrin elevation	Adult males
40	Increased urinary ALA excretion	Children and adults
40	Anemia	Children
40	Coproporphyrin elevation	Adults and children
50	Anemia	Adults
50 - 60	Cognitive (CNS) deficits	Children
50 - 60	Peripheral neuropathies	Adults and children
80 - 100	Encephalopathic symptoms	Children
100 - 120	Encephalopathic symptoms	Adults

Due to the limited availability of data, most such attempts have been restricted to effects on the hematologic system, in particular the elevation of FEP, the inhibition of ALAD activity, and the excretion of ALA in the urine.

In regard to defining dose-response relationships for hematological effects, three different assessments of such relationships have been carried out[4-6] and published. For example, in the approach of Zielhuis,[4] dose-response relationships were developed for ALAD, ALA-U, and FEP as obtained for adults, male and female, and children. In Figure 13-1 are presented the dose-response data for children and adults for ALAD at inhibition levels of 40 and 70 percent. In Figure 13-2, a corresponding relationship for urinary ALA is given for adult males, and Figure 13-3 presents the corresponding

data for FEP in adult males, adult females, and children.

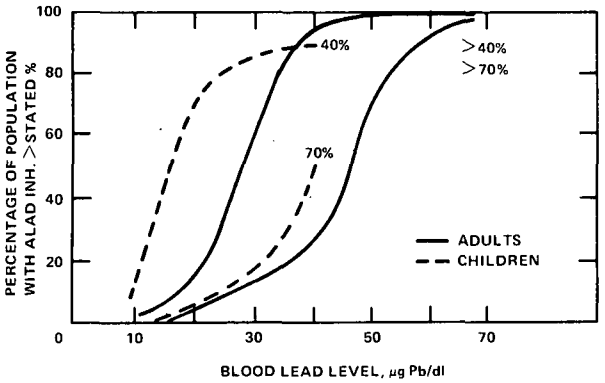

Figure 13-1. Dose-response curve for percent ALAD inhibition for adults and children as a function of blood lead level.[4]

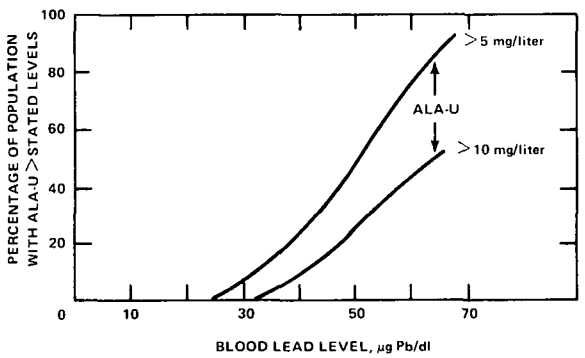

Figure 13-2. Dose-response curve for ALA in urine (ALA-U) as a function of blood lead level.[4]

As can be seen from Figure 13-1, there appears to be a marked difference at 40 percent inhibition of ALAD activity between children and adults, such a difference decreasing as one goes to 70 percent inhibition. For example, at 20 μg/dl blood lead, approximately 10 percent of adults show 40 percent enzyme inhibition, whereas the corresponding value for children is somewhat above 80 percent. It should also be noted that there is apparently a steep rise in the linear portion of these sigmoid relationships, e.g., 20 percent of adults show a 40 percent inhibition in ALAD at 20 μg/dl blood lead, whereas virtually all of the adult population shows 40 percent inhibition at 40 μg/dl. A similar steepness in the curve is seen in regard to children.

Figure 13-2 presents dose-response data for ALA in urine exceeding two discrete levels, >5 and >10 mg/liter, with increasing blood lead. It may be seen that the response in the linear portion of the curve is much less steep than for ALAD. For example, for approximately 5 percent of adults, the no-response level for ALA >5 mg/liter is about 30 μg/dl blood lead. At 60 μg/dl blood lead, the corresponding percentage of the population showing this response is in excess of 80 percent. The corresponding plot for ALA >10 mg/liter shows a less steep slope than the former case. At 60 μg/dl blood lead, the corresponding percentage of the adult population is approximately 40.

The composite dose-response plot presented in Figure 13-3 shows an increased response in FEP in adult females compared to adult males. Children show a greater response than adult males only up to blood lead levels of about 45 μg/dl. The data of Zielhuis are extracted from a number of reports. In Figure 13-4, interestingly, wherein are contained the

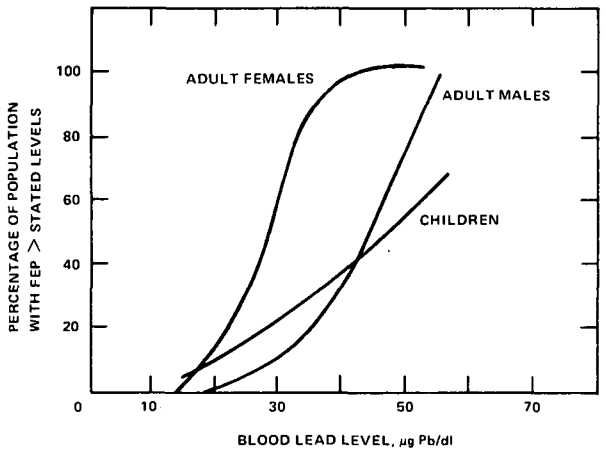

Figure 13-3. Dose-response curve for FEP as a function of blood lead level.[4]

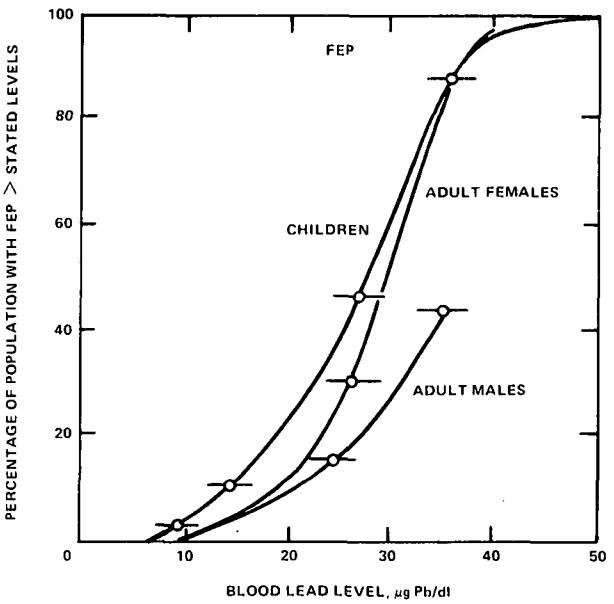

Figure 13-4. Dose-response curve for FEP as a function of blood lead level.[5]

dose-response data of Roels et al.[5] for FEP in adult males, adult females, and children, it appears that children show the most heightened response, followed by adult females, and the least response in adult males. The slope for the linear portion of the response curve is quite steep in the case of children; 20 percent of the children show elevated response (82 μg/dl rbc) at 20 μg/dl blood lead, whereas virtually all the children exceed this value at 35 μg/dl blood lead.

The dose-response data of Piomelli[6] are presented in Figure 13-5 and consist of composite plots for mean plus 1 standard deviation (33 μg/dl whole blood) and the mean plus 2 standard deviations (51 μg FEP/dl whole blood). In the data presented in Figure 13-5, blood lead levels in excess of 28 μg/dl whole blood were not used in the calculations. It appears from the above that there exists a threshold at about 15 μg/dl whole blood.

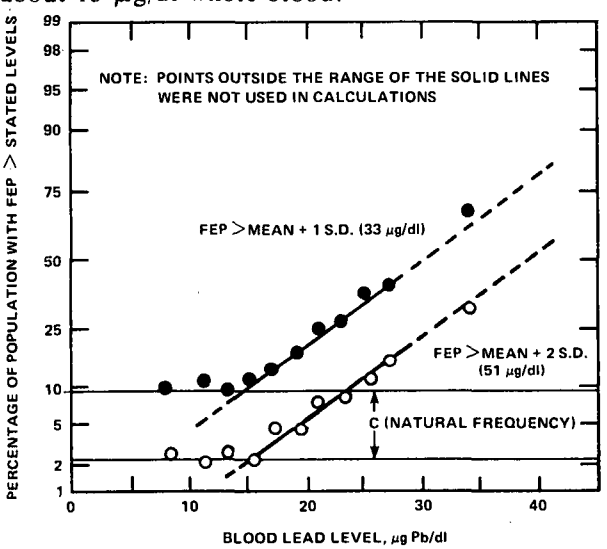

Figure 13-5. Dose-response curve for FEP as a function of blood lead level.[6]

EPA has carried out analyses of the data from the Azar et al. study[7] and calculated a dose-response curve for urinary ALA (Figure 13-6). These dose-response curves were plotted for two different cut-off points. These points were the mean values for blood lead levels less than 13 μg/100 g, plus 1 standard deviation and plus 2 standard deviations, respectively. From the mean plus 2 standard deviations curve, it is readily apparent that the linear portion of the curve is quite steep. At a blood lead level of 20 μg/dl, only 6 percent of the population exceed the mean plus 2 standard deviations value of the control population, whereas at a blood lead level of 50, 50 percent of the population exceeds that value. Furthermore, when one examines the figure at 40 μg/dl, the value at which ALA in urine is taken to suggest health impairment, the Azar et al. data show that about 30 percent of the population shows an elevation in this parameter.

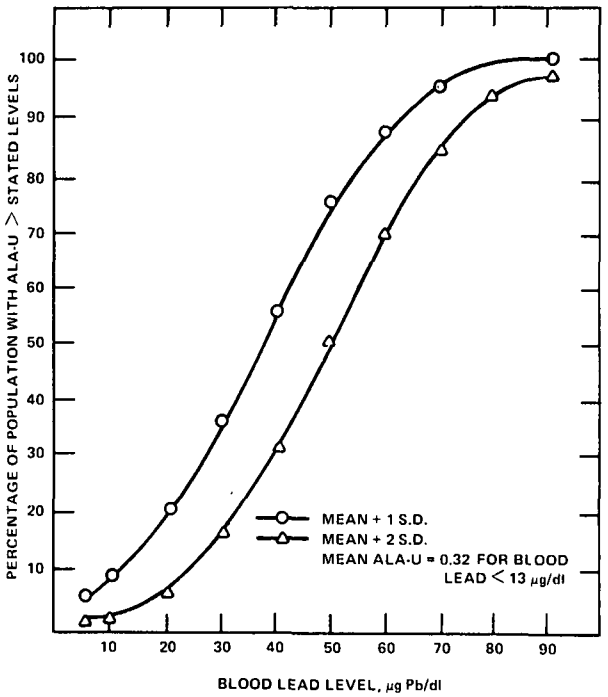

Figure 13-6. EPA calculated dose-response curve for ALA-U (from Azar et al.[7]).

In Table 13-3 are tabulated proportions of the study populations in the Zielhuis and Azar reports showing elevated urinary ALA versus blood lead level. The data for Zielhuis are as cited in Figure 13-2, the percentage of subjects with ALA-U greater than 5 mg/liter being used. The Azar data in Table 13-3 refer to the mean plus two standard deviations data set. For purposes of comparison of dose-response data for FEP, the studies of Zielhuis,[4] Roels,[5] and Piomelli[6] are tabulated in Table 13-4. As in the case for the table of ALA-U data, it should be kept in mind that differences exist in cut-off points for FEP response to lead in the various studies.

TABLE 13-3. ESTIMATED PERCENTAGE OF SUBJECTS WITH ALA-U EXCEEDING 5 mg/liter FOR VARIOUS BLOOD LEAD LEVELS

Blood lead levels, μg/dl	Zielhuis,[4] %	Azar et al.,[7] %
10	0	2
20	0	6
30	6	16
40	24	31
50	48	50
60	76	69
70	96	84

TABLE 13-4. ESTIMATED PERCENTAGE OF CHILDREN WITH EP EXCEEDING CUT-OFF POINTS FOR VARIOUS BLOOD LEAD LEVELS

Blood lead level, μg/dl	Zielhuis.[a]%	Roels et al..[b]%	Piomelli.[c]%
10	0	3	9
20	6	27	11
30	22	73	48
40	37	100	80
50	49	--	--
60	--	--	--
70	--	--	--
80	--	--	--

[a]EP > EP of children with Pb-B < 20 μg/dl.
[b]EP > 82 μg/dl cells.
[c]EP > EP of 33 μg/dl.

13.6 POPULATIONS AT RISK

Population at risk is a segment of a defined population exhibiting characteristics associated with significantly higher probability of developing a condition, illness, or other abnormal status. This high risk may result from either greater inherent susceptibility or from exposure situations peculiar to that group. What is meant by inherent susceptibility is a host characteristic or status that predisposes the host to a greater risk of heightened response to an external stimulus or agent.

In regard to lead, two such populations are definable. They are preschool age children, especially those living in urban settings, and pregnant women, the latter group owing mainly to the risk to the conceptus. Children are such a population for both of the reasons above, whereas pregnant women are at risk primarily due to the inherent susceptibility of the conceptus.

13.6.1 Children as a Population at Risk

Children are developing and growing organisms exhibiting certain differences from adults in terms of basic physiologic mechanisms, capability of coping with physiologic stress, and their relative metabolism of lead. Also, the behavior of children frequently places them in different relationship to sources of lead in the environment, thereby enhancing the opportunity for them to absorb lead. Furthermore, the occurrence of excessive exposure often is not realized until serious harm is done. Young children do not readily communicate a medical history of lead exposure, the early signs of such being common to so many other disease states that lead is frequently not recognized early as a possible etiological factor contributing to the manifestation of other symptoms.

13.6.1.1 INHERENT SUSCEPTIBILITY OF THE YOUNG

Discussion of the physiological vulnerability of the young must address two discrete areas. Not only should the basic physiological differences be considered that one would expect to predispose children to a heightened vulnerability to lead, but also the actual clinical evidence must be considered that shows such vulnerabilty does indeed exist.

In Chapter 10, Section 10.6 was devoted to the metabolic considerations in identifying susceptible subgroups. Factors discussed in that section included: (1) greater lead intake of infants on a per unit body weight basis, which is probably related to greater caloric and water requirement; (2) greater intake as well as net absorption (see GI section), greater net respiratory intake as well as greater net absorption and retention from the GI tract; (3) rapid growth rate may reduce the margin of safety against a variety of stresses including iron, calcium, and vitamin deficiency; (4) dietary habits of children are quite different from adults; normal hand-to-mouth activity probably results in the transfer of lead-contaminated dust and dirt via thumb sucking or in retrieval of dirt-contaminated foodstuffs; (5) the metabolic requirements for protein, calcium, and iron are so great relative to intake that a negative balance in these factors may exist; (6) in very young children metabolic pathways and factors such as the blood-brain barrier are known to be incompletely developed; and (7) partitioning of lead in the bones of children is different from that of adults. Only 60 to 65 percent of the lead body burden is in the bones of children, and this fraction may be more labile.

Hematologic and neurologic effects in children have been shown to have lower thresholds per unit of blood lead than in adults. In particular, the lowest observed effect levels for FEP and anemia are lower for children than adults. With reference to neurologic effects, the onset of encephalopathy and other injury to the nervous system appears to vary both regarding likely lower thresholds in children for some effects and in the typical pattern of neurologic effects presented, e.g., in encephalopathy or other CNS deficits being more common in children versus peripheral neuropathy being more often seen in adults. Not only are the effects more acute in children than in adults, but also the neurologic sequelae are usually much more severe in children.

Upon careful examination of the data, it should be noted that certain geographic or socioeconomic fac-

tors appear to emerge as important factors determining the differential susceptibility of some groups of children for lead-induced neurologic damage. That is, there seems to be distinct variation in effects or a lack thereof as reported for children in different studies depending upon the geographic areas from which the study populations were drawn. For example, the few credible reports of lead encephalopathy in children at blood lead levels less than 100 μg/dl all concern children from inner-city areas. Similarly, statistically significant effects or borderline effects indicative of more subtle neurobehavioral deficits in lead-exposed children at moderately elevated blood lead levels have been reported for groups of children drawn from inner-city populations of urban centers. In contrast, only a few statistically significant neurobehavioral effects have yet been reported for populations of children experiencing similar elevations in blood lead levels, but residing near primary smelter facilities in semirural areas.

One cannot determine with any certainty the specific factors that might contribute to the apparent differential sensitivity of inner-city children to the neurobehavioral effects of lead. Several possibilities, however, might be reasonably considered, including the following:

1. Parameters of lead exposure probably differed substantially for the populations under study; the smelter area children, for example, may have experienced much more gradual accumulations of lead during the course of long-term, low-level exposures versus probable repeated brief episodes of somewhat higher level exposures being superimposed on any long-term, low-level exposures for the inner-city children.
2. The exposures of the smelter children likely included significantly higher levels of other metallic species, e.g., zinc, that are known to reduce the pathological impact of lead on many organ systems.
3. Differences in nutritional status likely existed between the smelter and inner-city children, with the latter probably having a higher incidence of iron, calcium, and vitamin deficiency; or other differences in dietary content and habits might be invoked as an explanation.
4. Interactions between lead exposures and other factors associated with the stresses of urban versus nonurban living may also contribute to the apparent differential susceptibility of inner-city chilren.

13.6.1.2 EXPOSURE CONSIDERATIONS

Children's dietary habits as well as the diets themselves differ markedly from adults and, as a result, place children in a different relationship to several sources of lead. The dominance of canned milk and processed baby food in the diet of many young children is an important factor is assessing their exposure to lead since both those foodstuffs have been shown to contain higher amounts of lead than components of the adult diet. The importance of these lead sources is not their relationship to airborne lead directly but, rather, their role in providing a higher baseline lead burden to which the airborne contribution is added

Children ordinarily undergo a stage of development in which they exhibit mouthing behavior, for example, thumbsucking. At this time they are at risk of picking up lead-contaminated soil and dust on their hands and hence into their mouths where it can be absorbed. Scientific evidence documenting at least the first part of the chain is available.

There is, however, an abnormal extension of the mouthing behavior, called pica, which occurs in some children. Although diagnosis of this is difficult, children who exhibit this trait have been shown to purposefully eat nonfood items. Much of the lead-based paint problem is known to occur because children actually ingest chips of leaded paint.

13.6.2 **Pregnant Women and the Conceptus as a Population at Risk**

There are some rather inconclusive data indicating that women may in general be at somewhat higher risk to lead than men. However, pregnant women and their concepti as a subgroup are demonstrably at higher risk. It should be pointed out that, in fact, it really is not the pregnant woman *per se* who is at greatest risk but, rather, the unborn child she is carrying. Because of obstetric complications, however, the mother herself can also be at somewhat greater risk. This section will first describe the general evidence for all women and then the evidence that pertains to pregnant women exclusively.

Studies have demonstrated that women, like children, in general tend to show a heightened response of erythrocyte protoporphyrin levels upon exposure to lead. The exact reason for this heightened response is not known but may relate to endocrine differences between men and women. In

particular, the levels of testosterone may play a role in this response.

As stated above, the primary reason pregnant women are a high-risk group is because of the fetus each is carrying. In addition, there is some suggestive evidence that lead exposures may affect maternal complications of delivery.

With reference to maternal complications at delivery, information in the literature suggests the incidence of preterm delivery and premature membrane rupture relates to maternal blood lead level. Further study of this relationship as well as studies relating to discrete health effects in the newborn are required.

Vulnerability of the developing fetus to lead exposure arising from transplacental transfer of mother's blood lead content was discussed in Section 11.6. This process starts at the end of the first trimester. Cord blood studies involving mother-infant pairs repeatedly have shown a correlation between maternal and fetal blood lead levels. Furthermore, the observed positive correlation of urinary ALA levels with blood lead levels in newborns indicates that some heme-biosynthetic derangement is apparent at birth and must therefore have commenced *in utero*.

Further suggestive evidence, cited in Chapter 11, has been advanced for prenatal lead exposures of fetuses possibly leading to later higher instances of postnatal mental retardation among the affected offspring. The available data are insufficient to state with any certainty that such effects occur or to determine with any precision what levels of lead exposure might be required prior to or during pregnancy in order to produce such effects.

13.7 DESCRIPTION OF U.S. POPULATION IN RELATION TO PROBABLE LEAD EXPOSURES

In this section estimates are provided of the number of individuals potentially at risk to lead exposures. Unfortunately the latest census data are only from 1970,[8] although some estimates are available from the National Center for Health Statistics for 1975.[9] This is unfortunate since some significant changes are thought to have occurred in the population structure since the 1970 census.

Because most lead exposures, excepting areas with primary lead smelters, occur in what the Bureau of the Census calls urban areas, an estimate of the potential risk of airborne lead exposure can be made from the total urban population of the United States. That this may be an acceptable first approximation can be gleaned by comparing the frequency distribution of air lead concentrations for urban and rural National Air Sampling Network stations in Chapter 7. This comparison readily shows a distinct difference in exposure between the two types of stations. Based on examination of the urban stations as well as of literature data on both air lead and soil and dust lead values, a strong case can be made to support the assumption that the area which the Bureau of the Census calls the central city of the urban areas is at even higher risk of lead exposure.

Therefore, in regard to exposures other than localized point stationary sources of lead, the population at risk is the urban one and, in particular, the central city residents. For the United States in 1970, these values were 149 and 64 million people, respectively[8] (Table 13-5). From the table it can

TABLE 13-5. POPULATION AND PERCENT DISTRIBUTION, URBAN AND RURAL, BY RACE 1970 CENSUS[4]

Area	White, % (10^3)	Black and other, % (10^3)	Total, % (10^3)
Urban	128,773 (72.4)	20,552 (80.7)	149,325 (73.5)
Inside urbanized areas	100,952 (56.8)	17,495 (68.7)	118,447 (58.3)
Central cities	49,547 (27.9)	14,375 (56.5)	63,922 (31.5)
Urban fringes	51,405 (28.9)	3,120 (12.3)	54,525 (26.8)
Outside urbanized areas	27,822 (15.7)	3,057 (12.0)	30,878 (15.2)
Rural	48,976 (27.6)	4,911 (19.3)	53,887 (26.5)
Total, United States	177,773	25,463	203,212

readily be seen that a higher proportion of the nonwhite population lives in urban areas than whites (80.7 versus 72.4 percent) and is possibly subject to greater exposure to airborne lead. Furthermore, this disparity is even greater when one considers the central city population only, which may be subject to even higher levels of lead pollution from a multitude of sources.

From the previous discussion of populations at risk, however, two subgroups of this total population were defined as being at even higher risk — children, especially those under 5, and pregnant

TABLE 13-6. NUMBER OF BIRTHS BY RACE AND SIZE OF POPULATION[8]

Urban areas of given size from 1970 census	Births			
	White	Black	Others	Total
≥100,000	772,230	321,412	24,394	1,118,036
50-99,999	286,706	37,024	4,182	327,912
10-49,999	600,166	65,790	10,394	676,350
≤9,999	1,432,162	148,136	28,790	1,609,088
Total	3,091,264	572,362	67,760	3,731,386

Urban areas of given size from 1975 census	Births			
	White	Black	Others	Total
≥100,000	571,478	276,387	26,332	874,197
50-99,999	222,735	37,885	5,921	266,541
10-49,999	478,382	64,481	13,039	555,902
≤9,999	1,279,401	132,828	35,329	1,447,558
Total	2,551,996	511,581	80,621	3,144,198

women. There is insufficient evidence at this time to determine whether any racial or ethnic group suffers an innate susceptibility to lead.

In the United States in 1970 about 12 million children under 5 years of age lived in urban areas. Approximately 5 million of these children lived in central city areas.[8] Since between-census population estimates are not available for urban-rural comparisons, the only way to use the 1975 population estimates is to assume that the percent distribution obtained in 1970 still holds true. If in fact that is the case, the more recent estimates would be about 11 million children in urbanized areas and 4.6 million in the central city. An estimate made by the National Bureau of Standards of the total child population with blood lead values equal to or greater than 40 μg/dl in a recent year was 600,000.[10] This total is clearly a cause for concern in view of the health data presented in Section 13.4 above. Of course, the use of this figure, based on the many lead-screening programs conducted in this country, is not meant to imply that all of these values resulted from airborne lead. They probably do not, since paint lead exposures are an additional important source. But, on the other hand, the addition of an airborne component of lead exposure on top of these levels would adversely affect the public health. If airborne lead were the only contribution to these children's lead values, the potential health effects ascribable to that exposure could be significant.

The difficulty in estimating the number of pregnant women exposed to air lead is even greater; this is because the number of pregnant women is not tabulated on an urban-rural basis. Therefore, for this document, the number of pregnant women will be estimated from the number of live births (Table 13-6).[8] Unfortunately these data also are not tabulated on an urban-rural basis but, rather, on a population size of place of residence. It can readily be seen that the total number of births has declined in the time 1970 to 1975. If one assumes only the highest population size category to be at risk of lead exposure, there are still almost 900,000 newborns at risk of lead absorption from their mothers.

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APPENDIX A
GLOSSARY*

Absorption (of lead): Transfer of lead into an organism via intestinal wall, alveolar surface, or skin.

Accumulation (of lead): Net positive difference between intake and output of lead over an extended period.

Acetyl coenzyme A (CoA): Coenzyme, derived principally from the metabolism of glucose and fatty acids, that takes part in many biological acetylation reactions; oxidized in the Krebs cycle.

Acetylcholine: Compound released from certain autonomic nerve endings; acts in the transmission of nerve impulses to excitable membranes.

Acetylcholinesterase: Enzyme in excitable membranes that inactivates acetylcholine.

β-Acetyl glucosaminadase: Enzyme that hydrolyzes the terminal glucosaminidic bonds of odd-numbered oligosaccharides to yield N-acetylglucosamine and the next lower even-numbered oligosaccharide.

Acid-fast: Describes a cell or bacterium that retains a dye that has a negatively charged molecule.

Acid phosphatase: Enzyme that hydrolyzes, in an acid medium, monophosphoric esters, with liberation of inorganic phosphate.

Adenocarcinoma: Carcinoma derived from glandular tissue or in which the tumor cells form recognizable glandular structures.

Adenoma: Benign epithelial tumor in which the cells form recognizable glandular structures or in which the cells are clearly derived from glandular epithelium.

Adenosine diphosphate (ADP): Coenzyme composed of adenosine and two molecules of phosphoric acid; important in intermediate cellular metabolism; a product of the hydrolysis of adenosine triphosphate (ATP).

Adenosine triphosphate (ATP): Nucleotide occurring in all cells, where it serves in the storage of energy and in the transfer of energy in metabolic processes; composed of adenosine and three molecules of phosphoric acid.

Adenosine triphosphatase (ATPase): Enzyme that mediates the removal of water from ATP: ATP + $H_2O \rightarrow$ ADP + orthophosphate.

Adenyl cyclase: Enzyme that catalyzes the formation of cyclic adenosine-3', 5'-monophosphate (cyclic AMP).

Adenylic acid: (1) Generic name for a group of isomeric nucleotides; (2) Phosphoric acid ester of adenosine; also known as adenosine monophosphate (AMP).

Adrenaline: See Epinephrine.

Adrenergic: Describes the chemical activity of epinephrine or epinephrine-like substances.

Adrenergic synapse: Synapse at which norepinephrine is liberated when a nerve impulse passes.

Advection: Process of transport of an atmospheric property, or substance within the atmosphere, solely by the mass motion of the atmosphere.

Aerodynamic diameter: Expression of aerodynamic behavior of an irregularly shaped particle in terms of the diameter of an idealized particle; that is, aerodynamic diameter is the diameter of a sphere of unit density that has aerodynamic behavior identical to that of the particle in question. Thus, particles having the same aerodynamic diameter may have different dimensions and shapes.

Aerodynamic drag: Aerodynamic resistance; retarding force that acts upon a body moving through a gaseous fluid and that is parallel with the direction of motion of the body.

Aerodynamic particle size: Sphere of unit density that has aerodynamic behavior identical to that of the particle in question.

Aerosol: System in which the dispersion medium is a gas and the dispersed phase—composed of solid particles or liquid droplets—does not settle out under the influence of gravity.

Aerosol particles: Solid particles 10^{-12} to 10^{-1} μm in diameter, dispersed in a gas.

*Compiled from standard reference works and, to a lesser extent, from information furnished by experts in the respective disciplines.

Agglomeration: Process by which precipitation particles grow by collision with an assimilation of cloud particles or other precipitation particles.

Aitken dust counter: Instrument for determining dust content of the atmosphere; a sample of air is mixed, in an expandable chamber, with a large volume of dust-free air containing water vapor. Upon sudden expansion, the chamber cools adiabatically below its dewpoint, and droplets form with the dust particles as nuclei and are counted by means of a grid under a microscope.

Aitken nuclei: Microscopic particles in the atmosphere that serve as condensation nuclei for droplet growth during the rapid adiabatic expansion produced by an Aitken dust counter (see above).

Aldolase: Enzyme that acts on a ketose-l-phosphate to yield dihydroxy-acetone phosphate plus an aldehyde; e.g., fructose-l, 6-diphosphate = dihydroxyacetone phosphate + D-glyceraldehyde-3-phosphate.

Alkaline phosphatase: Enzyme that hydrolyzes, in alkaline medium, monophosphoric esters, with liberation of inorganic phosphate; found in plasma and serum, bone, etc.

Alkalinity: Excess of hydroxyl ions over hydrogen ions, generally expressed as milliequivalents per liter.

Alveolar macrophages: Rounded granular phagocytic cells, within the alveoli of the lungs, that ingest inhaled material.

Ambient air: The surrounding, well-mixed air.

Aminoacyl synthetase: Enzyme that catalyzes the coupled reactions of amino acid activation in which an amino acid is first attached to adenosine monophosphate and then to a transfer-RNA molecule.

ϵ-Amino group of lysine: The amino group, NH_2, attached to ϵ, or 5th, carbon atom from the carboxyl carbon in the amino acid, lysine: $H_2N\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH(NH_2)\text{-}COOH$.

δ-Aminolevulinic acid (ALA, or δ-ALA): $COOH\text{-}CH_2\text{-}CH_2\text{-}CO\text{-}CH_2\text{-}NH_2$; intermediate in the biosynthesis of heme-containing compounds; formed from succinyl-coenzyme A and glycine.

δ-Aminolevulinic acid dehydratase (ALAD): Enzyme in heme biosynthetic pathway that mediates formation of porphobilinogen from δ-aminolevulinic acid.

δ-Aminolevulinic acid synthetase (ALAS): Enzyme in heme biosynthetic pathway that mediates the formation of δ-aminolevulinic acid from succinyl-CoA via 2-amino-3-ketoadipate.

Amphetamine: α-Methylphenethylamine. Drug used to stimulate the central nervous system, increase blood pressure, reduce appetite, and reduce nasal congestion. Abuse may lead to dependence, characterized by strong psychic dependence associated with an increase in REM (rapid-eye-movement) sleep, hunger, apathy, and depression.

Anamnestic response: Rapidly increased antibody level following renewed contact with a specific antigen, even after several years.

Anodic stripping voltammetry: An electrochemical method of analysis.

Anophthalmia: Developmental defect characterized by complete absence of the eyes or by the presence of vestigial eyes.

Anorexia: Loss of appetite.

Anoxia: Relative lack of oxygen; caused by inadequate perfusion of tissues by blood carrying normal amounts of oxygen or by normal perfusion of blood carrying reduced amounts of oxygen.

Antipyrine ($C_{11}H_{12}ON_2$): Compound used as an antipyretic, analgesic, and antirheumatic drug.

Area source: Consists of a number of point sources arranged in a two-dimensional array.

Astrocytic proliferation (astrocytosis): Proliferation of astrocytes owing to the destruction of nearby neurons during a hypoxic or hypoglycemic episode.

Ataxia: Failure of muscular coordination.

Atmospheric turbulence: Motion of the air (or other fluids) in which local velocities and pressures fluctuate irregularly in a random manner.

Avoidance task: Behavioral testing procedure used to measure an animal's avoidance and escape performance. In a one-way task only one response is appropriate, whereas in a two-way task either of two responses is appropriate, depending on the existing test conditions.

Axonal degeneration: Degeneration of axons, the processes or nerve fibers that carry the unidirectional nerve impulse away from the nerve cell body.

Balance experiments: Experiments on man or other animals that involve quantitative measurements of intake (via respiration and ingestion) and loss (via exhalation and excretion) of a specific element or substance. A positive balance means that more is taken in than is lost over a specific time.

Basophilic stippling: Spotted appearance of relatively immature red blood cells that contain cytoplasmic material that stains deeply with basic dyes.

Biosphere: The part of the earth's crust, waters, and atmosphere where living organisms can subsist.

Blood-brain barrier: The barrier created by semipermeable cell walls and membranes to passage of some molecules from the blood to the cells of the central nervous system.

Body burden: The total amount of a specific substance (for example, lead) in an organism, including the amount stored, the amount that is mobile, and the amount absorbed.

Bond energy: The enthalpy change that accompanies the breaking of a chemical bond between two atoms. The total bond energy of a molecule gives a measure of its thermodynamic stability.

Boundary layer: Layer of fluid in the immediate vicinity of a bounding surface; refers ambiguously to the (1) laminar, (2) turbulent, (3) planetary, or (4) surface boundary layers.

Brainstem: Stemlike portion of the brain connecting the cerebral hemispheres with the spinal cord.

Bremsstrahlung: Radiation that is emitted by an electron accelerated in its collision with the nucleus of an atom.

Brownian movement: Random movements of dispersed small particles suspended in a fluid; results from random collisions between the molecules of the dispersing medium and the particles of the dispersed phase.

CaEDTA: Edathamil calcium disodium, which is the calcium disodium salt of ethylenediaminetetraacetate, a chelating agent. CaEDTA is used in the study, diagnosis, and treatment of poisoning by various heavy metals, including lead.

CaEDTA mobilization test: Test in which a known quantity of CaEDTA is injected parenterally and the amount of lead excreted in urine during a known period beginning immediately thereafter is measured. This procedure is used both clinically and experimentally and is thought to provide an index of the mobile fraction of the total body burden of lead.

Carcinogenesis: Development of carcinoma; or, in more recent usage, producing any kind of malignancy.

Carcinoma: Malignant new growth made up of epithelial cells tending to infiltrate the surrounding tissues and give rise to metastases.

Cascade impactors: Low-speed impaction device for use in sampling both solid and liquid atmospheric suspensoids; consists of four pairs of jets (each of progressively smaller size) and sampling plates working in series and designed so that each plate collects particles of one size range.

Catalase: Enzyme that catalyzes the decomposition of hydrogen peroxide; contains four hematin groups per molecule; found in liver and red blood cells.

Catecholamines: Group of sympathomimetic amines containing a catechol moiety; especially epinephrine, norepinephrine, and dopamine.

Catenation: Property of an element that enables it to link to itself to form chains, e.g., carbon.

Cerebellum: Large dorsally projecting part of the brain having the special function of muscle coordination and maintenance of equilibrium.

Cerebral anoxia: Relative lack of oxygen in the brain.

Cerebral cortex: Thin layer of gray matter on the surface of the cerebral hemisphere, folded into gyri, with about two-thirds of its area buried in the depths of the fissures.

Chelate: Chemical compound in which a metallic ion is sequestered and bound into a ring by covalent bonds to two or more nonmetallic atoms in the same molecule.

Chelant: Chemical compound that will react with metals to form chelates; a chelating agent.

Cholinergic: Stimulated, activated, or transmitted by acetylcholine; applied to those nerve fibers that liberate acetylcholine at a synapse when a nerve impulse passes.

Cholinesterase: Enzyme that catalyzes the hydrolysis of acylcholine to choline and an anion.

Chemical energy: Energy produced or absorbed in the process of a chemical reaction.

Chi-square test: Test of statistical significance based on frequency of occurrence; used to test probabilities or probability distributions (goodness of fit), statistical dependence or independence (association), and common population (homogeneity).

Chlorinity: Measure of chloride content, by mass (g/kg), of water; sometimes determined to permit calculation of salinity.

Choroid plexus: Any of the highly vascular, folded processes that project into the third, fourth, and lateral ventricles of the brain.

Chromatid: One of the pair of stands, formed by longitudinal splitting of a chromosome, that are joined by a single centromere in somatic cells during mitosis; one of a tetrad of strands formed by lengthwise splitting of paired chromosomes during the diplotene stage of meiosis.

Chromophore: Any chemical group whose presence gives a decided color to a compound and that united with certain other groups to form dyes.

Chromosomes: Threadlike structures in animal or plant nuclei, seen during karyokinesis (nuclear division characteristic of mitosis), that carry the linearly arranged genetic material.

Chronic nephritis: Chronic inflammation of the kidneys.

Coagulation: Process that converts numerous droplets into a smaller number of larger precipitation particles.

Coalescence: Merging of two liquid drops into a single larger drop.

Colic: Paroxysmal pain in the abdomen, caused by spasm, distention, or obstruction of any one of the hollow viscera.

Colloidal materials: See Colloidal system.

Colloidal system: An intimate mixture of two substances, one of which, called the dispersed phase (or colloid), is uniformly distributed in a finely divided state through the second substance (dispersion medium); the dispersion medium may be a gas, liquid, or solid.

Combustion nucleus: Condensation nucleus formed as a result of industrial or natural combustion processes.

Complement: Complex proteins in normal serum that interact to combine with antigen-antibody complex, producing lysis when the antigen is in an intact cell; important in host defense mechanism against invading microorganisms.

Complex: Chemical compound in which a part of the molecular bonding is of the coordinate type.

Complexing: Formation of a complex compound; see Complex.

Condensation: Physical process by which a vapor becomes a liquid or solid; opposite of evaporation. In meteorology, the term is limited to transformation of vapor to a liquid.

Condensation nucleus: Particle, either liquid or solid, upon which condensation of water vapor begins in the atmosphere.

Condensation particles: See Aitken nuclei.

Confidence interval: A range of values ($a_1 < a < a_2$) determined from a sample by definite rules so chosen that, in repeated random samples from the hypothesized population, an arbitarily fixed proportion ($1-\epsilon$) of that range will include the true value, x, of an estimated parameter.

The limits, a_1 and a_2, are called confidence limits; the relative frequency ($1-\epsilon$) with which these limits include α is called the confidence coefficient; and the complementary probability, ϵ, is called the confidence level. As with significance levels, confidence levels are commonly chosen as .05 or .01, the corresponding confidence coefficients being .95, .99.

Confidence intervals should not be interpreted as implying that the parameter itself has a range of values; it has only one value, α. On the other hand, the confidence limits (a_1, a_2), being derived from a sample, are random variables the values of which on a particular sample either do or do not include the true value α of the parameter. However, in repeated samples, a certain proportion (namely $1-\epsilon$) of these intervals will include α_1 provided that the actual population satisfied the initial hypothesis.

Contamination: Contact with an admixture of an unnatural agent, with the implication that the amount is measurable.

Convection: Atmospheric motions that are predominantly vertical, resulting in vertical transport and mixing of atmospheric properties.

Convulsions: Violent, involuntary contraction or series of contractions of the voluntary muscles.

Coprogen III: Coproporphyrinogen III, an intermediary metabolite in heme biosynthesis. It is a natural precursor of heme.

Coprogenase: Coproporphyrinogenase, the enzyme that converts coproporphyrinogen III to protoporphyrin IX.

Coproporphyrin: Urinary pigment derived from coproporphyrinogen, an intermediate in the biosynthesis of heme.

Coproporphyrinogen (syn. coprogen): A fully reduced colorless tetracarboxylic tetrapyrrole. Isomers I and III are found in biologic systems.

Cortex: See Cerebral cortex.

Corpus callosum: Band of nerve tissue connecting the cerebral hemispheres in man and higher mammals.

Corpus striatum: A subcortical mass of gray and white substance in each cerebral hemisphere, containing the caudate nucleus and the lentiform nucleus.

Cortical atrophy: Wasting away of the outer layer(s), e.g., of the brain or kidney.

Creatinine: $C_4H_2ON_3$; compound formed by dehydration of creatine; found in urine, blood, and muscle.

Cristae: Inner membranes of mitochondria, the surfaces of which are studded with roughly spherical particles attached to the cristae by stalks.

Cumulative frequency distribution: Proportion of a distribution that lies below a given value.

Curie: Unit of radioactivity; quantity of radionuclide that has 3.7×10^{10} disintegrations per minute (dpm).

Cysteine: Amino acid that occurs as a constituent of glutatione and of cystine.

Cytochrome *c*: Small heme protein containing one atom of iron per molecule; its principal biologic function is in electron transport. See Cytochromes.

Cytochrome *c* oxidase (cyt. a_3): Enzyme that catalyzes the oxidation of cytochrome *c*: 4 reduced cytochrome *c* + O_2 = 4 oxidized cytochrome *c* + $2H_2O$.

Cytochrome *c* reductase: Enzyme that catalyzes the reduction of oxidized cytochrome *c*: $NADH_2$ + oxidized cytochrome *c* = NAD + reduced cytochrome *c*.

Cytochrome P-450: a *b*-type cytochrome, one of the mixed-function oxidases in the microsomal system responsible for the oxidation of steroids and drugs and other foreign compounds.

Cytochromes: Complex protein/heme respiratory pigments occurring in plant and animal cells, usually in mitochondria, that function as electron carriers in biological oxidation.

Demyelination: Destruction of the myelin, a fatlike substance forming a sheath around the nerve fibers.

Density: Ratio of mass of a substance to the volume occupied by it (usually expressed in g/cm^3).

Dentine: Also dentin; chief substance or tissue of the teeth, that surrounds the tooth pulp and is covered by enamel on the crown and by cementum on the roots of the teeth.

Denver Development Screening Test: Rating scales employed to assess four areas of child development: (1) gross motor, (2) fine motor-adaptive, (3) personal-social, and (4) language.

Deoxyribonucleic acid (DNA): A nucleic acid in the form of a doublestranded helix of a linear polymer; made up of repeating units of 2-deoxyribose, phosphate, and a purine or a pyrimidine; carrier of genetic information coded in the sequence of purines or pyrimidines (organic bases).

Deposition: (1) Deposit of particles from the ambient air or atmosphere onto a surface; (2) removal of particles from inhaled air by the respiratory tract.

Detection limit: A limit below which an element or compound can not be detected by the method or instrument being used for analysis.

Dichotomous sampler: Air-sampling device that separates particulates into two fractions on the basis of diameter; the cutpoint varies with the size of the aperture.

Diffusion: In meteorology, the exchange of fluid parcels between regions in space in apparently random small-scale motions.

p-Dimethylaminobenzaldehyde: Ehrlich's reagent; $(CH_3)_2N \cdot C_6H_4 \cdot CHO$.

Diphenylthiocarbazone: See Dithizone.

Dispersion: Distribution of finely divided particles in a medium.

Dithizone: Diphenylthiocarbazone; $C_6H_5N{:}N\text{-}CS\text{-}NH \cdot NH\text{-}C_6H_5$; reagent used in the analysis of lead.

Dithizone methods: Colorimetric methods of analysis for lead that involve the reaction of lead with dithizone to form lead dithizonate, which is measured spectrophotometrically at 510 nm.

Dopamine: Hydroxytyramine, produced by the decarboxylation of dopa (dihydroxyphenylalanine), which is an intermediate product in the synthesis of norepinephrine.

Dorsal root ganglion: Group of sensory nerve cell bodies located on the posterior root of each spinal nerve; joins peripherally with ventral, or motor, root to form the nerve before it passes outside the vertebral column.

Downwind: In the same direction that the wind is blowing; on or toward the lee side.

Dry deposition: The deposit of particles on a surface in the absence of precipitation.

Dust: Solid materials suspended in the atmosphere in the form of small irregular particles, many of which are microscopic in size.

Dustfall: Dry deposition of airborne dust particles.

Dysoria: Any abnormality of vascular permeability.

E. coli: Short, gram-negative, rod-shaped, enteric bacterium.

Edema: Presence of abnormally large amounts of fluid in the intercellular tissue spaces of the body; usually applied to the demonstrable accumulation of excessive fluid in the subcutaneous tissues.

Electromyographic: Pertaining to electromyography, the recording and study of the intrinsic electrical properties of skeletal muscle.

Electron microprobe: X-ray method in which electrons from a hot-filament source are accelerated electrostatically, then focused to an extremely small point on the surface of a specimen by an electromagnetic lens; method for nondestructive analysis of chemical composition by measurement of resulting backscatter or other phenomena.

Electronegativity: Electro-affinity.

Encephalitis: Inflammation of the brain.

Encephalopathy: Any degenerative disease of the brain.

Epidemiology: Study of the distribution and determinants of disease in human population groups.

Epinephrine: Hormone secreted by adrenal medulla that acts to increase blood pressure by means of stimulation of heart action and constriction of peripheral blood vessels.

Episodal: Adjective in current usage that denotes an air pollution episode; that is the occurrence of short-term, peak air pollutant concentrations of crisis proportions.

Epithelial: Pertaining to or composed of epithelium; that is, covering of external or internal body surfaces, including linings of vessels and other small cavities, composed of cells joined together with cementing substances.

Equilibrium vapor pressure: Vapor pressure of a system in which two or more phases of a substance coexist in equilibrium.

Erosion: Movement of soil or rock from one point to another by the action of the sea, running water, moving ice, precipitation, or wind.

Erythrocyte porphyrin: See Free erythrocyte protoporphyrin.

Erythrocyte protoporphyrin: See Free Erythrocyte portoporphyrin.

Erythrocytes: Red blood cells.

Erythropoiesis: Formation of red blood cells.

Ethylenediaminetetraacetic acid (EDTA): Used in the form of calcium-disodium salt as a chelating agent to complex with lead and other metals and remove them from the body by urinary excretion.

Evaporation: Physical process by which a liquid or solid is transformed to the gaseous state; opposite of condensation.

Evoked-response technique: A technique widely used in electrophysiology in which a stimulus (e.g., electric shock, light flash, click) is applied peripherally to the electrode used to detect the response.

Exencephaly: A developmental anomaly characterized by an imperfect cranium, the brain lying outside the skull.

Exposure level: Concentration of a contaminant to which the population in question is exposed.

Exudate: Material, such as fluid, cells, or cellular debris, that has escaped from blood vessels and has been deposited in tissues or on tissue surfaces, usually as a result of inflammation; contains high content of protein, cells, or solid materials derived from cells.

Fallout: In air pollution, particulate matter that falls to the surface of the earth through the action of gravity; a passive phenomenon unrelated to atmospheric or mechanical motion.

Fanconi syndrome: In this document, the triad of glycosuria, hyperaminoaciduria, and hypophosphatemia in the presence of hyperphosphaturia that is associated with injury to proximal renal tubular cells.

Flinch/jump thresholds: Behavioral testing procedure used to measure pain threshold by measuring sensitivity to shock. The shock intensity at which animals first flinch and first jump in response to foot shock is recorded.

Flux: Rate of flow of some quantity, often used in reference to some form of energy; also called transport.

Fornix: General term for an archlike structure or the vaultlike space created by such a structure; fornix of cerebrum—efferent pathway of the hippocampus.

Free erythrocyte porphyrin (FED): See Free erythrocyte protoporphyrin.

Free erythrocyte protoporphyrin (FEP): Intermediate in the biosynthesis of heme; specifically, the immediate precursor to heme synthesis in which one atom of iron is inserted into the protoporphyrin nucleus to form heme. Used interchangeably with erythrocyte protoporphyrin and erythrocyte porphyrin.

Fugitive dust: Dust that escapes from industrial processes, soil surfaces, roadways, etc.; dust that cannot be contained by air pollution control practices.

β-Galactosidase: Enzyme that hydrolyzes galactosides (compounds containing a sugar and a nonsugar component) to produce D-galactose.

Galena: Lead sulfide ore.

Ganglia: Plural of ganglion, a general term for a group of nerve cell bodies located outside the central nervous system; basal ganglia—masses of gray matter in the cerebral hemisphere.

Gastrointestinal mucosa: Mucous membrane of the stomach and intestine.

Geometric mean: An estimate of the median of a lognormal distribution, calculated as the antilogarithm of the mean of the logarithms of the observations.

Geometric standard deviation: A measure of dispersion for a lognormal distribution; it is the antilogarithm of the standard deviation of the logarithms of the observations. (Also known as standard geometric deviation.)

Glacier: Mass of land ice flowing slowly (at present or in the past) from an accumulation area to an area of ablation.

Glacier ice: Any ice that is or once was part of a glacier.

Glomerular filtration: Filtration of plasma by the glomeruli of the kidney that removes fluids, electrolytes, glucose, amino acids, and other small molecules; 80 to 85 percent of water and virtually all of the other substances are reabsorbed by the proximal tubules.

Glomerulus: Anatomical term designating a tuft or cluster of blood vessels or nerves; often used alone to designate renal glomeruli, which are coils of blood vessels, one projecting into the expanded end or capsule of each of the uriniferous tubules of the kidney.

Glucose-6-phosphate dehydrogenase: Enzyme important in maintenance of adequate concentrations of reduced glutathione in red blood cells. Deficiency of this enzyme is inherited as a sex-linked trait; it mediates the reaction, D-glucose-6-phosphate + NADP = D-glucono-δ-lactone 6-phosphate + $NADPH_2$.

β-Glucuronidase: Enzyme that mediates the hydrolysis of natural and synthetic glucuronides; yields β-D-glucuronate as a product.

Glutamate dehydrogenase: Enzyme that mediates the removal of hydrogen atom(s) from glutamate, the salt or ester of glutamic acid, which is a dicarboxylic amino acid.

Glutathione: Tripeptide that serves as a coenzyme and acts as a respiratory carrier of oxygen. Reduced glutathione (GSH) is present in red cells and is associated with glucose-6-phosphate dehydrogenase and reduced nicotinamide adenine dinucleotide phosphate in maintenance of red cell integrity.

Glycosuria: Presence in the urine of glucose, a simple sugar formed from more complex sugars and normally retained in the body as a source of energy.

Grignard process: A relatively common synthetic procedure for the preparation of organometallic compounds from an organomagnesium precursor.

Groundwater: All subsurface water, especially that part that is in the zone of saturation.

Half-life: Time required for a system decaying at an exponential rate (such as an element in radioactive disintegration) to be reduced to one-half its initial size, intensity, or numerical amount.

Haze: Fine dust or salt particles dispersed through a portion of the atmosphere; the particles are so small they cannot be felt or individually seen with the naked eye, but they diminish horizontal visibility and give the atmosphere a characteristic opalescent appearance that subdues all colors.

Hematofluorometer: Commercially available portable spectrofluorometer used to measure erythrocyte protoporphyrin (porphyrin) directly; in wide use in lead screening programs.

Hematopoiesis: Formation and development of blood cells.

Hematopoietic system: System of cells in bone marrow, spleen, and lymph nodes concerned with formation of cellular elements of the blood.

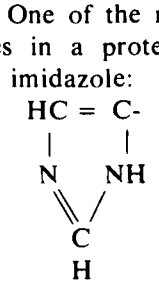
Hemin: Crystalline chloride of heme, $C_{34}H_{33}N_4O_4FeCl$.

Heparin: Mucopolysaccharide acid occurring naturally in various tissues, especially the liver and lungs; sodium heparin, a mixture obtained from animal tissues, is an anticoagulant used *in vivo* and *in vitro*.

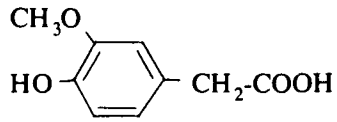
High-volume sampler: Device for taking a large sample of air in a minimal span of time, routinely about 2000 m^3/24 hr (1.38 m^3/min), or even as high as 2880 m^3/24 hr (2 m^3/min).

Hippocampus: Curved elevation in the inferior horn of the lateral ventricle of the brain; important functional component of the limbic system, the system controlling autonomic functions and certain aspects of emotion and behavior.

Histidine residue: One of the naturally occurring peptide linkages in a protein, containing the chemical group, imidazole:



Homovanillic acid: A methylated metabolite of hydroxytyramine:



Hydrocephalus: Condition characterized by abnormal accumulation of fluid in the cranial vault, accompanied by enlargement of the head, prominence of the forehead, atrophy of the brain, mental deterioration, and convulsions.

Hyperactivity: Abnormally increased activity. Developmental hyperactivity of children is characterized by constant motion—exploring, experimenting, etc.—and is usually accompanied by distractibility and low tolerance for frustration. It usually abates during adolescence. May result from brain damage or psychoses.

Hyperkinesia: Abnormally increased motor function or activity; see Hyperactivity.

Hyperkinetic: Characterized by abnormally increased muscular movement.

Hyperkinetic-aggressive behavior disorder: A disorder characterized by overactivity, restlessness, distractibility, and short attention span.

Hyperphosphaturia: Above-normal amounts of phosphate compounds in the urine.

Hyperuricemia: Abnormal amounts of uric acid in the blood.

Hypochromic anemia: A condition characterized by a disproportionate reduction of red cell hemoglobin, compared with the volume of packed cells.

Hypophosphatemia: Abnormally decreased amount of phosphates in the blood.

Hypothalamus: Portion of the diencephalon that forms the floor and part of the lateral wall of the third ventricle of the brain.

Imidazole group: See Histidine residue.

Impactor: General term for instruments that sample atmospheric particles by impaction; such devices consist of a housing that constrains the air flow past a sensitized sampling plate.

Impinger: Device used to sample dust or other particles in the air; draws in a measured volume of air and directs it through a jet to impact on a wetted surface.

In situ: In the original location.

Interstitial fibrosis: A progressive formation of fibrous tissue in the interstices in any structure; in the lungs, it reduces aeration of the blood.

In vitro: Outside the living organism.

In vivo: Within the living organism.

Iron deficiency: A deficiency of iron-containing foods in the diet such that not enough iron is available for incorporation into newly formed hemoglobin; iron deficiency within the body may also result from poor intestinal absorption of iron in spite of a dietary sufficiency.

Ischemia: Deficiency of blood in a part, caused by functional constriction or actual obstruction of a blood vessel.

Ischemic: Pertaining to, or affected with, ischemia.

Isocortex: Neopallium; that portion of the cerebral cortex showing stratification and organization characteristic of the most highly evolved type of cerebral tissue.

Isokinetic sampling: Taking a sample of air without changing the speed or direction of the air as it enters the sampler.

Jiggle platform: Apparatus used in behavioral testing to measure an animal's activity. Generally consists of a spring-loaded platform equipped with a detector for measuring movement.

α-Ketoglutarate: Salt of α-ketoglutaric acid, a dibasic keto acid occurring as an intermediate in carbohydrate (Krebs cycle) and protein metabolism.

Kilocalorie: Unit of heat energy equal to 1000 calories; also known as large calorie.

Lactic acid dehydrogenase (LDH): Catalyzes reduction of pyruvic acid by reduced nicotinamide adenine dinucleotide; prevents buildup of pyruvate in anaerobic glycolysis.

Leached: Subjected to the action of percolating water or other liquid that removes the soluble substances.

Lead particles: Lead-containing particles.

Lead poisoning (syn. lead intoxication, plumbism, saturnism): A disease condition reflecting the adverse effects of the absorption of lead into the system.

Lead subacetate (syn. lead monosubacetate, monobasic lead acetate): $Pb(C_2H_3O_2)_2 \cdot 2Pb(OH)_2$.

Learning paradigm: A particular set of experimental conditions used to study learning.

Ligand: A molecule, ion, or atom that is attached to the central atom of a coordination compound, a chelate, or other complex.

Line source: Consists of a number of point sources arranged in a straight line, usually across wind (see Point source).

Lipoamide dehydrogenase: Trivial name for lipoamide oxidoreductase; enzyme catalyzing the reaction, NAD + dihydro-lipoamide = $NADH_2$ + oxidized lipoamide.

Lithosphere: The rigid outer crust of rock on the earth, about 80 km deep; more recently, with development of plate tectonics theory, the outer 100 km of the earth's surface.

Lognormal distribution: A variable whose logarithms follow a normal distribution.

Lumen: The cavity or channel within a tubular organ; in this document, intestinal.

Lymphocyte: Mononuclear leukocyte (a white blood cell) with a deeply staining nucleus containing dense chromatin; chiefly a product of lymphoid tissue, it participates in humoral and cell-mediated immunity.

Lysosome: Submicroscopic organelle, found by electron microscope in many types of cells, that contains various hydrolytic enzymes and is normally involved in localized intracellular digestion.

α-Mannosidase: Enzyme that catalyzes the hydrolysis of α-D-mannoside to an aocohol and D-mannose, a simple sugar.

Mass median diameter (MMD): Geometric median size of a distribution of particles, based on weight.

Mass median equivalent diameter (MMED): Convenient parameter for characterizing airborne particulates; divides the total mass of aerosol particles into two equal parts: half the mass resides in a relatively smaller number of particles larger than this median size and half resides in a relatively larger number of particles having diameters below this median size.

Maze: System of intersecting paths used in tests of intelligence and learning in experimental animals.

McCarthy Scales of Intelligence: A standardized intellectual assessment instrument (appropriate for ages 2.5 to 8.5 yr), consisting of five subtests yielding individual scores in (1) verbal, (2) perceptual-performance, (3) quantitative, (4) memory, and (5) motor, as well as yielding a general cognitive index comparable to an intellectual quotient (I.Q.) score.

Mean: Used synonymously with the arithmetic mean; that is, the sum of the observations divided by the sample size.

Meninges: Three membranes that envelope the brain and spinal cord; the dura mater, pia mater, and arachnoid.

Messenger RNA (mRNA): Linear polymer of nucleotides that is transcribed from and complementary to a single strand of DNA; carries information for protein synthesis to the ribosomes.

Metabolites: End products of metabolic processes that transform one compound into another in living cells.

Microcytic anemia: Condition in which the majority of the red cells are smaller than normal.

Micromelia: Developmental anomaly characterized by abnormal smallness or shortness of the limbs.

Microsome: One of the finer granular elements of protoplasm; part of the endoplasmic reticulum, site of various metabolic and synthetic processes including incorporation of amino acids into proteins.

Mist: Microscopic and more or less hygroscopic water droplets suspended in the atmosphere. Relative humidity when mist is present is often less than 95 percent.

Mitochondria: Small organelles found in the cytoplasm of cells; principal sites of generation of energy, they contain enzymes of the Krebs and fatty acid cycles and the respiratory pathway.

Mobilizable lead: The fraction of the total lead content of the body that can be removed by chelating agents.

Molal: Containing one mole or one gram molecular weight in 1000 grams (1 kg) of solute.

Molar: Containing one mole or one gram molecular weight of solute in 1000 ml (1 liter) of solution.

Mole: That amount of chemical compound whose mass in grams is equivalent to its formula mass, i.e., mass numerically equal to the molecular weight and most frequently expressed as the gram molecular weight (the weight of one mole expressed in grams).

Midbrain: Mesencephalon; portions of the adult brain derived from the embryonic midbrain.

Miniature end-plate potentials (MEPP's): Small potential changes in the neighborhood of the end plate representing the response of the membrane to release of acetylcholine in quantities insufficient to depolarize the membrane to threshold levels.

Monoamine: Organic compound to which an amine ($-NH_2$ group) is attached; e.g., serotonin.

Monamine oxidase: Flavoprotein that catalyzes the aerobic oxidation of physiological amines to the corresponding aldehydes and ammonia; acts upon serotonin, a nervous system regulator, to yield 5-hydroxy-indolealdehyde.

Monominergic: Stimulated, activated, or transmitted by monoamines; applied to nerve fibers that liberate monoamines at a synapse when a nerve impulse passes.

Motor skills: Skilled movements that depend on the integrity of the nervous system for control.

Mutagenicity: Property of being able to induce genetic mutation, i.e., a permanent, transmissable change in the genetic material.

Myelopathy: Pathology of the muscle fibers.

Myxedema: Nonpitting edema characterized by dry, waxy type of swelling, with abnormal deposits of mucin in the skin and other tissues; associated with hypothyroidism.

Nasopharynx: The part of the pharynx that lies above the level of the soft palate; the pharynx being the muscular, membranous sac between the mouth, the nares, and the esophagus.

National Air Surveillance Networks (NASN): Networks of monitoring stations for sampling air to determine extent of pollution. Established jointly by Federal and state governments.

Neoplasm: An aberrant new growth of abnormal cells or tissue in which the growth is uncontrollable and progressive.

Nephritis: Inflammation of the kidney.

Nephropathy: Disease of the kidneys.

Nerve conduction: Passage of a nerve impulse manifested by an electric impulse that travels along the nerve.

Neuropathy: Functional disturbances and/or pathological changes in the peripheral nervous system; affects the neurons (nerve cells, including cell body, axon, and dendrites).

Neuropil: Dense feltwork of interwoven cytoplasmic processes of nerve cells and of neuroglial cells in the central nervous system and in some parts of the peripheral nervous system.

Nictitating membrane: Thin membrane, or inner or third eyelid, present in many animals; capable of being drawn across the eyeball, as for protection.

Norepinephrine: Hormone secreted by neurons; acts as a transmitter substance at the peripheral sympathetic nerve endings and probably in certain synapses in the central nervous system.

Normal distribution (Gaussian distribution): Fundamental frequency distribution of statistical analysis. A continuous variate, $\times$, is said to have a normal distribution or to be normally distributed if it possesses a density function, f(x), that satisfied the equation:

$$f(x) = \frac{1}{\sigma 2\pi} e^{-(x-\mu)^2/2\sigma^2}, (-\infty < x < \infty),$$

where μ is the arithmetic mean (or first moment) and σ is the standard deviation. About two-thirds of the total area under the curve is included between $\times = \mu - \sigma$ and $\times = \mu + \sigma$.

Normal population: Collection of quantities having a normal distribution.

Normoblast: Nucleated percursor cell intermediate in the formation of erythrocytes.

Nuclear inclusion bodies: Round, oval, or irregularly shaped bodies appearing in the nuclei of cells.

Nucleus: Small mass of differentiated protoplasm rich in nucleoproteins and surrounded by a membrane; found in most animal and plant cells; contains chromosomes and functions in metabolism, growth, and reproduction.

One-way avoidance tasks: See Avoidance task.

Optical emission spectrography: Analytical method in which the sample is vaporized and decomposed, and the constituent elements excited by an electrical arc or a high voltage spark. The light emitted as a consequence of the excitation passes through a spectrograph and the resulting spectrum is recorded photographically.

Paraplegia: Paralysis of the legs and lower part of the body.

Parenchyma: General term to designate functional elements of an organ as distinguished from its framework, or stroma.

Particle eddy diffusivity: The diffusion of particles by eddies in a turbulent flow.

D-penicillamine: Product of penicillin; whitish crystalline powder used as a metal complexing agent to remove excess metals from the body.

Peptidergic: Stimulated, activated, or transmitted by peptides; applied to those nerve fibers that liberate peptides at a synapse when a nerve impulse passes.

Photolysis: Chemical decomposition by the action of light.

Phrenic nerve: Arising from the third, fourth, and fifth cervical segments of the spinal cord, the nerve that innervates the diaphragm.

Pica: Habitual ingestion of nonfood items.

Pinna: Projecting part of the ear lying outside the head.

Plumbism: Lead poisoning; saturnism.

Point source: A single isolated stationary source of pollution.

Polarography: An electroanalytical technique in which the current through an electrolysis cell is measured as a function of the applied potential.

Polyneuropathy: Disease that involves several nerves.

Polysomes: Complex of ribosomes bound together by a single messenger ribonucleic acid (mRNA) molecule. Also known as polyribosome.

Porphobilinogen (PBG): Intermediate in the biosynthesis of heme that does not accumulate under normal circumstances.

Porphyrin: Any one of a group of iron-free or magnesium-free cyclic tetrapyrrole derivatives that occur universally in protoplasm. They form the basis of the respiratory pigments, such as cytochromes and chlorophyll, of animals and plants.

Precipitation: Any or all forms of water particles, liquid or solid, that fall from the atmosphere and reach the ground.

Prevailing wind direction: Wind direction most frequently observed during a given period.

Primary smelting: Extraction of metal from ore.

Promotional energy: Energy required to promote an electron from its free atom ground state to the hybridization state required for bonding.

Protoporphyrin (PP): Porphyrin that is the protein-free precursor to hemoglobin, myoglobin, catalase, and certain respiratory pigments.

Protoporphyrin IX: An isomer of protoporphyrin.

Proximal convoluted tubules: Convoluted portion of the vertebrate nephron (functional unit of the kidney) lying between Bowman's capsule and the loop of Henle; functions in resorption of sugar, Na^+, Cl^-, and water.

Psychomotor: Pertaining to motor effects of cerebral or psychic activity.

Pyrimidine-5'-nucleotidase: Enzyme that mediates hydrolysis of pyrimidine-5'-phosphate to yeild inorganic phosphorus and the corresponding pyrimidine nucleoside.

Pyrrole: Heterocyclic ring compound, consisting of four carbon atoms, one nitrogen atom, and five hydrogen atoms, that is a component of chlorophyll, hemin, and many other important naturally occurring substances.

Pyruvate: Salt of pyruvic acid, an important intermediate in carbohydrate (Krebs cycle) and protein metabolism.

Reentrainment: Resuspension of particulate matter, especially dust, in the ambient air; see text dicussion of resuspension.

Reference method: In this document, the official, accepted method for sampling and analysis of an element or compound; method to which other methods are compared for accuracy and precision, and/or for reporting of data.

Relative humidity: Dimensionless ratio of actual vapor pressure of the air to the saturation vapor pressure; usually expressed as percent.

Renal insufficiency: State in which the kidneys are unable to remove a sufficient proportion of the effete, or spent, matter of the blood.

Reticulocytosis: Increase in the number of reticulocytes (young red blood cells showing basophilic network under vital staining) in the peripheral blood.

Ribonucleic acid (RNA): Nucleic acid in the form of a linear polymer, usually a single strand, composed of repeating units of nucleotides (the organic bases; adenine, cytosine, guanine, and uracil) conjugated to ribose and kept in sequence by phosphodiester bonds. Involved intracellularly in protein synthesis.

Ribosomes: Complex small particles in the living cell, composed of various proteins and three molecules of RNA; site of synthesis of proteins.

Sampling error: Difference between a measured value and the true value that results from sampling techniques and procedures.

Sampling train: Pollutant collecting device consisting of a series of components through which an air stream passes. Components usually include prefitter; pipes or ducts; means for measuring air flow; an air pump; and a detector or sensor that gives an immediate reading *or* a collector in which the pollutant is subsequently measured.

Saturnism: Lead poisoning.

Schwann cell: One of the large nucleated masses of protoplasm lining the inner surface of the neurilemma, a membrane wrapping the nerve fiber.

Secondary smelting: Extraction of metal from scrap and salvage.

Sedimentation: The act or process of deposition of sediment; can refer (1) to the deposition of airborne particulate matter on a surface or (2) to the deposition and accumulation of solid matter on the bed of a body of water.

Seizure: Sudden onset or recurrence of a disease or an attack; specifically, an epileptic attack, or convulsion.

Septum-frontal forebrain: Describes anatomical connections in the brain between the septal area and the forebrain.

Sequela: Any lesion or affection that follows or is caused by an attack of disease.

Serotonin: A vasoconstrictor, 5-hydroxytryptamine, found in serum and many body tissues, including the intestinal mucosa, pineal body, and central nervous system, especially the hypothalamus, midbrain, basal ganglia, and spinal cord; believed to be a neurotransmitter that plays a regulatory role in the central nervous system.

Serum glutamic-oxaloacetic transaminase (SGOT): Enzyme that transfers an amino group from L-glutamic acid to oxaloacetic acid, forming δ-ketoglutaric acid plus L-aspartic acid. Oxaloacetic and δ-ketoglutaric acids are both major intermediates in the citric acid cycle (Krebs cycle), the energy-generating cycle.

Serum glutamic-pyruvic transaminase (SGPT): Enzyme that transfers an amino group from L-glutamic acid to pyruvic acid, forming δ-ketoglutaric acid plus L-alanine. δ-Ketoglutaric acid is a major intermediate in the Krebs cycle, and pyruvic acid is the immediate precursor of acetylcoenzyme A, which combines with oxaloacetic acid to form citric acid in the citric acid cycle (Krebs cycle).

Shuttle box: Two-compartment chamber used in animal behavior; the movement from one compartment to the other is the behavior that is studied.

Soret band: Band in the violet end of the spectrum of hemoglobin.

Spina bifida: Developmental anomaly characterized by defective closure of the bony encasement of the spinal cord.

Stabilimeter: Device used to measure an animal's activity by measuring vertical movement of the floor.

Stack emissions: Effluents released into the atmosphere from the exhaust flue of a building; usually refers to pollutants but can refer to steam or other nonpolluting effluents.

Standard deviation: A measure of dispersion or variation, usually taken as the square root of the variance.

Standard geometric deviation: Measure of dispersion of values about a geometric mean; the portion of the frequency distribution that is one standard geometric deviation to either side of the geometric mean accounts for 68 percent of the total samples.

Standard normal deviation: Measure of dispersion of values about a mean value; the positive square root of the average of the squares of the individual deviations from the mean.

Stanford-Binet I.Q. Test: A standardized intellectual assessment instrument (appropriate for ages 2 yr to adult), yielding a general intelligence quotient (I.Q.) score.

Steady state exposure: Exposure to an environmental pollutant whose concentration remains constant for a period of time.

Stoichiometry: Numerical relationship of elements and compounds as reactants and products in chemical reactions.

Stratosphere: Atmospheric shell about 55 km deep that begins where the troposphere ends, at 10 to 20 km from the earth's surface.

Striatum: Corpus striatum; subcortical mass of gray and white substance in front of and lateral to the thalamus in each cerebral hemisphere.

Stroma: Supporting tissue or matrix of an organ, as distinquished from its functional element, or parenchyma.

Subclinical lead poisoning: Toxic effects of lead that do not produce clinically discernible signs.

Succinate: Salt of succinic acid, important intermediate in carbohydrate (Krebs cycle) and protein metabolism.

Succinoxidase: Complex enzyme system, containing succinic dehydrogenase and cytochromes, that catalyzes the conversion of succinate and molecular oxygen to fumarate (a Krebs cycle intermediate).

Succinyl coenzyme A: $COOH(CH_2)_2COOH$-S-CoA; compound formed from succinic acid and coenzyme A in the citric acid cycle (Krebs cycle). It provides free energy for the synthesis of a molecule of ATP and can participate in acylating reactions for the introduction of a succinyl group; it also participates in other metabolic reactions, such as the synthesis of porphyrins.

Sulfhydryl group: The -SH group occurring in reduced glutatione and in cysteine.

Superior cervical ganglion: A group of nerve cell bodies located outside the central nervous system, situated near the cervix.

Surface water: All bodies of water on the surface of the earth.

Synapse: Region of contact between processes of two adjacent neurons.

Synaptic uptake: Movement of a chemical into the neuron in the area of the synapse.

Synaptosomal transport: Uptake of a chemical into isolated synapses.

Synergetic: Working together; an agent that works synergistically with one or more other agents.

Synergistic effects: Joint effects of two or more agents, such as drugs that increase each other's effectiveness when taken together.

Telencephalon: Paired cerebral vesicles, from which the cerebral hemispheres are derived.

Teratology: Science that deals with abnormal development of the fetus and congenital malformations.

Teratospermia: Presence of malformed spermatozoa in the semen.

Temperature inversion: Layer of air in which temperature increases with altitude; very little turbulent exchange occurs within it.

Terminal velocity: See Terminal fall velocity.

Terminal fall velocity (terminal velocity): Particular falling speed, for any given object moving through a fluid medium of specified physical properties, at which the drag forces and buoyant forces exerted by the fluid on the object just equal the gravitational force acting on the object, after which it falls at constant speed unless it moves into air layers of different physical properties. In the atmosphere, the latter effect is so gradual that objects such as raindrops, which attain terminal velocity at great heights above the surface, may be regarded as continuously adjusting their speeds to remain at all times essentially in the terminal fall condition.

Topography: (1) General configuration of a surface, including its relief; may be a land or water-bottom surface; (2) natural surface features of a region, treated collectively as to form.

Transaminases: Enzymes that catalyze the transfer of an amino group of an amino acid to a keto acid to form another amino acid; also known as aminotransferases.

Transfer RNA (tRNA): Smallest ribonucleic acid molecule found in cells; its structure is complementary to messenger RNA and it functions in transferring amino acids from their free state to a growing polypeptide chain.

Transformation: In this document, changes in physical or chemical form of lead-containing particles or compounds that occur with time and space during atmospheric and environmental residence and/or transport.

Translocation: Transfer of metabolites, nutritive materials, or other substances from one part of a plant to another.

Transport: In this document, movement of lead and its compounds from one place to another in the environment.

Transudation: Passage of serum or other body fluid through a membrane or tissue surface; may or may not be the result of inflammation.

Troposphere: The atmospheric shell extending about 10 to 20 km from the earth's surface.

Trypan Blue: An acid, azo dye used in vital staining; under normal conditions, it does not enter most areas of the brain from the blood.

Tumor: Any abnormal mass of cells resulting from excessive cellular multiplication.

Turbulence: State of fluid flow in which instantaneous velocities exhibit irregular and apparently random fluctuations so that, in practice, only statistical properties can be recognized and analyzed; turbulence can transport suspended matter at rates far in excess of rates of transport by diffusion and conduction in a laminar flow.

Two-way aviodance tasks: See Avoidance task.

Tyrosine: Amino acid (*p*-hydroxyphenylalanine, $C_9H_{11}O_3N$) found in most proteins and synthesized metabolically from phenylalanine. It is a precursor of dopamine and of the hormones, epinephrine, norepinephrine, and triiodothyronine.

Ultradian rhythms: Biological rhythm with a frequency higher than circadian (24 hr).

Uncertainty: Standard deviation of a sufficiently large number of measurements of the same quantity by the same instrument or methods; the noncorrectable inaccuracy of the instrument.

Upwind: Toward the direction from which the wind is flowing; counter to the wind.

Urobilinogen: Colorless compound formed in the intestine by the reduction of bilirubin (a bile pigment that is a breakdown product of heme); some is excreted in the feces where it is oxidized to urobilin; some is reabsorbed and reexcreted in the bile (as bilirubin) or in the urine.

Uroporphyrin: Any of several isomeric, metal-free porphyrins, occurring in small quantities in normal urine and feces.

Vacuolization: Formation of vacuoles, any small spaces or cavities formed in the protoplasm of a cell.

Vacutainers: Registered trademark of sealed ampules, maintained under a slight vacuum and containing an anticoagulant, into which blood samples may be drawn directly.

Vanillyl mandelic acid (vanilmandelic acid): A major metabolite of the catechloamines; used to assess quantitatively the endogenous production of catecholamines.

Variance: A measure of dispersion or variation of a sample from its expected value. It is usually calculated as a sum of squared deviations about a mean divided by the sample size.

Wechsler Intelligence Test (WISC): A standardized intellectual assessment instrument (appropriate for ages 6 yr to 16 yr 11 mo), consisting of 12 subtests designed to yield verbal and performance intellectual scores.

Wet deposition: Removal of particles from the atmosphere via precipitation; rainout.

Wind: Air motion relative to the surface of the earth. Vertical components are relatively small, especially near the surface of the earth; hence, the term denotes almost exclusively the horizontal component.

WPPSI Test: A version of the WISC test, but consisting of 10 subtests representing a downward extension of the WISC appropriate for younger children (ages 4 to 6.5 yr).

Xenobiotics: Chemicals foreign to biologic systems.

X-ray diffraction analysis: Analysis of the crystal structure of materials by passing Xrays through them and registering the diffraction (scattering) image of the rays.

X-ray powder diffraction techniques: Analytical techniques in which an X-ray beam of known wavelength strikes a finely ground powder sample; the crystal planes of the powder diffract the beam and these diffraction lines are recorded on photographic film.

X-ray spectrography: Analytical method employing an X-ray spectrometer (instrument for producing the X-ray spectrum of a material and measuring the wavelengths of components) that is equipped with photographic or other recording apparatus.

Zinc erythrocyte porphyrin: The biochemically correct form for the erythrocyte protoporthyrin or porphyrin that is elevated in lead exposure or iron deficiency anemia. Used interchangeably in this document with erythrocyte porphyrin, erythrocyte protoporthyrin, and free erythrocyte porphyrin or protoporthyrin.

APPENDIX B
PHYSICAL/CHEMICAL DATA FOR LEAD COMPOUNDS

B.1 DATA TABLES

TABLE B-1. PHYSICAL PROPERTIES OF INORGANIC LEAD COMPOUNDS[1]

Compound	Formula	M.W.	S.G.	M.P.	Solubility, g/100 ml		
					Cold water	Hot water	Other solvents
Lead	Pb	207.19	11.35	327.5	i	i	sa
Acetate	$Pb(C_2H_3O_2)_2$	325.28	3.25	280	44.3	22^{150}	s glyc
Azide	$Pb(N_3)_2$	291.23	—	expl.	0.023	0.09^{70}	—
Bromate	$Pb(BrO_3)_2 \cdot H_2O$	481.02	5.53	d180	1.38	sl s	—
Bromide	$PbBr_2$	367.01	6.66	373	0.8441	4.71^{100}	sa
Carbonate	$PbCO_3$	267.20	6.6	d315	0.00011	d	sa,alk
Carbonate, basic	$2PbCO_3 \cdot Pb(OH)_2$	775.60	6.14	d400	i	i	s HNO_3
Chloride	$PbCl_2$	278.10	5.85	501	0.99	3.34^{100}	i al
Chlorobromide	PbClBr	322.56	—	—	—	—	—
Chromate	$PbCrO_4$	323.18	6.12	844	$6x10^{-6}$	i	sa,alk
Chromate, basic	$PbCrO_4 \cdot PbO$	546.37	6.63	—	i	i	sa,alk
Cyamide	$Pb(CN)_2$	259.23	—	—	sl s	s	s KCN
Fluoride	PbF_2	245.19	8.24	855	0.064	—	s HNO_3
Fluorochloride	PbFCl	261.64	7.05	601	0.037	0.1081	—
Formate	$Pb(CHO)_2$	297.23	4.63	d190	1.6	20	i al
Hydride	PbH_2	209.21	—	d	—	—	—
Hydroxide	$Pb(OH)_2$	241.20	—	d145	0.0155	sl s	sa,alk
Iodate	$Pb(IO_3)_2$	557.00	6.155	d300	0.0012	0.003	s HNO_3
Iodide	PbI_2	461.00	6.16	402	0.063	0.41	s,alk
Nitrate	$Pb(NO_3)_2$	331.20	4.53	d470	37.65	127	s,alk
Nitrate, basic	$Pb(OH)(NO_3)$	286.20	5.93	d180	19.4	s	sa
Oxalate	PbC_2O_4	295.21	5.28	d300	0.00016	—	sa
Oxide	PbO	223.19	9.53	888	0.0017	—	s,alk
di Oxide	PbO_2	239.19	9.375	d290	i	i	sa
Oxide (red)	Pb_3O_4	685.57	9.1	d500	i	i	sa
Phosphate	$Pb_3(PO_4)_2$	811.51	7	1014	$1.4x10^{-5}$	i	s,alk
Sulfate	$PbSO_4$	303.25	6.2	1170	0.00425	0.0056	—
Sulfide	PbS	239.25	7.5	1114	$8.6x10^{-5}$	—	sa
Sulfite	$PbSO_3$	287.25	—	d	i	i	sa
Thiocyanate	$Pb(SCN)_2$	323.35	3.82	d190	0.05	0.2	s,alk

Abbreviations:
a - acid
al - alcohol
alk - alkali
d - decomposes
expl - explodes
glyc - glycol
i - insoluble
s - soluble
M.W. - molecular weight
S.G. - specific gravity
M.P. - melting point

TABLE B-2. TEMPERATURE VARIATION OF THE VAPOR PRESSURES OF COMMON LEAD COMPOUNDS[2]

Name	Formula	M.P.	Temperature °C					
			1 mm	10mm	40mm	100mm	400mm	760mm
Lead	Pb	327.4	973	1162	1309	1421	1630	1744
Lead bromide	$PbBr_2$	373	513	610	686	745	856	914
Lead chloride	$PbCl_2$	501	547	648	725	784	893	954
Lead flouride	PbF_2	855	solid	904	1003	1080	1219	1293
Lead iodide	PbI_2	402	479	571	644	701	807	872
Lead oxide	PbO	890	943	1085	1189	1265	1402	1472
Lead sulfide	PbS	1114	852 (solid)	975 (solid)	1048 (solid)	1108 (solid)	1221	1281

B.2. THE CHELATE EFFECT

The stability constants of chelated complexes are normally several orders of magnitude higher than those of comparable monodentate complexes; this effect is called the chelate effect and is very readily explained in terms of kinetic considerations. A comparison of the binding of a single bidentate ligand with that of two molecules of a chemically similar monodentate ligand shows that, for the monodentate case, the process can be represented by the equations:

$$M + B \underset{k_b}{\overset{k_a}{\rightleftharpoons}} M\text{-}B \qquad \text{(B-1)}$$

$$M\text{-}B + B \underset{k_d}{\overset{k_c}{\rightleftharpoons}} MB_2 \qquad \text{(B-2)}$$

The related expressions for the bidentate case are:

$$M + B\text{-}B \underset{k_2}{\overset{k_1}{\rightleftharpoons}} M\text{-}B\text{-}B \qquad \text{(B-3)}$$

$$M\text{-}B\text{-}B \underset{k_4}{\overset{k_3}{\rightleftharpoons}} M\begin{pmatrix} B \\ B \end{pmatrix} \qquad \text{(B-4)}$$

The overall equilibrium constants, therefore, are:

$$K_1 = \frac{k_a k_c}{k_b k_d}; \quad K_2 = \frac{k_1 k_3}{k_2 k_4}$$

For a given metal, M, and two ligands, B and B-B, which are chemically similar, it is established that k_1 and k_a have values similar to each other, as do k_2 and k_b, k_4 and k_d; each of these pairs of terms represents chemically similar processes. The origin of the chelate effect lies in the very large value of k_3 relative to that of k_c. This comes about because k_3 represents a unimolecular process, whereas k_c is a bimolecular rate constant. Consequently, $K_2 >> K_1$.

This concept can, of course, be extended to polydentate ligands; in general, the more extensive the chelation, the more stable the metal complex. Hence, one would anticipate, correctly, that polydentate chelating agents such as penicillamine or EDTA can form extremely stable complexes with metal ions.

B.3 REFERENCES FOR APPENDIX B

1. Handbook of Chemistry and Physics, 56th Ed. R.C. Weast (ed.). Cleveland, The Chemical Rubber Co. 1975.
2. Stull, D.R. Vapor pressure of pure substances: Organic compounds. Ind. Eng. Chem. *39*(4):517-540, 1947.

APPENDIX C
ADDITIONAL STUDIES OF ENVIRONMENTAL CONCENTRATIONS OF LEAD

This collection of studies is intended to extend and detail the general picture of lead concentrations in the environment and in proximity to identified major sources as portrayed in Chapter 7. The list is by no means all-inclusive, but is intended to be representative and to supplement the data cited in Chapter 7.

C.1 GENERAL AMBIENT AIR CONCENTRATIONS

C.1.1 Seven-City Study

A special lead study (Seven-City Study) was conducted for 12-month periods between 1968 and 1971 in Cincinnati, Los Angeles, Philadelphia, Houston, New York City, Washington, D.C., and Chicago. Samples of ambient air were analyzed by atomic absorption spectroscopy. The monthly average lead concentrations obtained are summarized in Table C-1.

This study, specifically designed to measure ambient lead concentrations at a variety of sites within each of the cities, incorporated techniques that would provide the most precise measure of ambient lead concentrations available. A membrane filter was used instead of a glass filter, and the samples were collected continuously over 2 to 3 days rather than collected in biweekly 24-hr periods as in the NASN. The high annual average lead concentrations found in the Los Angeles area are largely attributable to heavy automotive emissions.

C.1.2 Birmingham, Alabama

During 1964 and 1965, seasonal levels of trace metals were determined from suspended particulate samples collected at 10 area sampling sites at Birmingham, Alabama, as a part of the Alabama Respiratory Disease and Air Pollution Study initiated in 1962. This monitoring study produced data representative of area source industrial pollution. Samples from each of the 10 sites were composited on a seasonal basis to give a total of 40 pooled samples. The lead data are summarized in Table C-2. The maximum seasonal lead concentration (3.5 $\mu g/m^3$) occurred at Birmingham site 4 during the winter. Only 2 sites showed average concentrations > 2 $\mu g/m^3$ for the year, Birmingham site 4 (3.0 $\mu g/m^3$) and Tarrant (2.3 $\mu g/m^3$). These results are typical for a medium-sized industrialized urban area.

C.1.3 Kanawha Valley, West Virginia[3]

A comprehensive air pollution study was conducted in the Kanawha River Valley in the vicinity of Charleston, West Virginia (Figure C-1), during 1964 and 1965. Twenty-four-hour samples of suspended particulate matter were collected at 14 strategically located sites. Samples from selected sites were composited on a seasonal basis (fall 1964, winter 1964 and 1965, and summer 1965) and the composites were analyzed for trace-metal content by the NASN emission spectrographic procedure. The data for lead are presented in Table C-3. Highest concentrations of suspended lead were found during the fall of 1964 at the St. Albans, Kanawha City, and Charleston sites.

Lead in dustfall measurements (settled particulates) for the same stations are also presented in Table C-3. The dustfall was collected by exposing wide-mouth jars for a period of 1 month; then composite samples were analyzed. The highest average concentrations of settled lead occurred at the Smithers site (11.2 mg/m^2-mo), and at the South Charleston-East site (11.6 mg/m^2-mo).

The combustion of solid fuels (coal and coke) is the primary source of lead emissions in the Kanawha Valley. Additional sources are metallurgical operations, asphalt hot-mix production, and other industrial processes. In most cases, these sources have inadequate air pollution control equipment. The lead concentrations found are somewhat low when

TABLE C-1. SUMMARY OF MONTHLY AVERAGE LEAD CONCENTRATIONS FOUND IN SEVEN-CITY STUDY[1]

City	Site type[a]	Months of data	Monthly concentration, $\mu g/m^3$ Min.	Max.	Avg.
Los Angeles	C	12	2.4	5.8	4.2
	C	12	2.6	6.8	4.5
	R	12	2.1	5.0	3.6
	R	12	2.7	5.4	3.8
	R	12	2.1	4.4	3.1
	R	12	1.4	3.9	2.5
	I	12	1.7	7.0	3.7
	C	12	2.5	7.6	4.8
Philadelphia	M	12	1.3	2.7	1.9
	C	12	1.2	2.6	1.8
	C	12	2.6	5.1	3.8
	I	12	1.5	3.0	2.2
	R	12	0.9	2.0	1.4
	M	12	0.6	1.7	1.1
	R	12	0.6	1.5	1.1
	R	12	1.1	2.6	1.7
	R	12	0.8	1.7	1.3
	R	12	0.7	1.6	1.0
Cincinnati	C	12	1.3	3.1	2.0
	R	12	0.8	2.6	1.5
	I	12	1.2	2.8	2.2
	P	12	0.5	1.2	0.9
	F	12	0.1	0.5	0.3
	F	12	0.2	0.5	0.3
Los Alamos	R	12	0.1	0.3	0.2
	C	12	0.1	0.3	0.2
Houston	R	12	0.7	2.7	1.2
	C	12	0.7	1.9	1.1
	C	12	1.2	3.2	2.2
	C	12	1.5	4.1	2.4
	M	12	1.0	2.2	1.3
	R	12	0.6	1.4	0.9
	R	12	0.6	1.2	0.8
Chicago	R	12	1.0	1.7	1.3
	M	12	1.1	1.7	1.4
	R	12	1.0	2.1	1.6
	M	12	1.3	2.2	1.8
	C	12	1.4	2.3	1.9
	R	12	1.2	2.2	1.6
	R	7	0.9	2.7	1.3
	M	12	1.1	2.1	1.6
	R	12	1.2	3.5	2.0
Washington, D.C.	R	12	0.7	1.6	1.1
	C	7	1.2	2.2	1.7
	C	12	1.6	3.9	2.3
	R	12	1.4	2.8	1.8
	R	12	1.0	1.7	1.2
	F	12	0.9	1.6	1.1
	R	12	1.8	3.5	2.4
	R	12	0.8	1.8	1.1
New York	M	11	1.1	2.9	1.7
	M	12	1.4	2.6	2.1
	R	12	1.4	2.1	1.7
	R	12	1.3	2.2	1.7
	M	12	1.2	2.7	2.1
	R	12	0.8	1.9	1.4
	R	12	0.9	1.6	1.2
	R	12	0.9	1.4	1.2
	R	12	0.8	1.4	1.1

[a] C - commercial; I - industrial; R - residential; M - mixed; F - farm; and P - park.

TABLE C-2. SEASONAL LEAD CONCENTRATIONS IN BIRMINGHAM, ALABAMA, AREA, 1964-1965 ($\mu g/m^3$)

Place	Site	Seasonal average concentrations Spring	Summer	Fall	Winter	Study period average concentration
Bessemer	1	0.9	0.7	1.1	0.6	0.8
Birmingham	3	0.7	1.4	1.7	1.4	1.3
Birmingham	4	3.2	2.8	2.3	3.5	3.0
Birmingham	5	1.2	1.6	1.8	0.8	1.4
Birmingham	7	1.2	1.4	1.3	1.8	1.4
Fairfield	1	0.6	0.5	0.6	0.3	0.5
Irondale	1	0.6	0.4	0.9	0.6	0.6
Mt. Brook	1	0.5	0.6	1.0	0.5	0.6
Tarrant	1	1.1	1.8	3.0	3.4	2.3
Vestavia	1	0.8	0.8	0.5	0.7	0.7

one considers the diversity of industrial activity and the meteorological and topographic characteristics prevailing. The highest values found were associated with sampling sites adjacent to major traffic arteries, which demonstrates the contribution from mobile sources.

C.1.4 Study of Lead Deposition in 77 Cities[4]

Settled particulates were collected in 77 midwestern cities from September through December 1968. Within each city, sites were chosen to represent residential, commercial, and industrial areas. The lead content of the settled particulates was determined by atomic absorption spectrophotometry, and the depositions were expressed as mg/m^2-mo. The highest amounts found in residential, commercial, and industrial areas were in South Bend, Indiana (80 mg/m^2-mo in November); Nashville, Tennessee (346 mg/m^2-mo in October); and Omaha, Nebraska (137 mg/m^2-mo in November); respectively. Maximum readings by month occurred in Muncie, Indiana (industrial) (105 mg/m^2-mo in September); Nashville, Tennessee (commercial) (346 mg/m^2-mo in October); Omaha, Nebraska (industrial) (137 mg/m^2-mo in November); and Waterloo, Iowa (industrial) (94 mg/m^2-mo in December). The data are summarized in Table C-4.

C.2 SOURCE-ORIENTED AMBIENT AIR CONCENTRATIONS

C.2.1 Southern Solano County, California[5]

The State of California Air Resources Board coordinated a joint study, conducted by several state agencies between March 1970 and November 1971, to determine the cause of death of a number of horses in the Benicia area from 1968 to 1970. Figure C-2 is a map of this area showing sampling site locations. The evidence strongly suggested that the

TABLE C-3. LEAD DATA FROM KANAWHA VALLEY STUDY[3]

Sampling sites, location and no.	Lead in suspended particulates, $\mu g/m^3$					Lead in settled particulates, $mg/m^2/mo.$ study period average
	Fall 1964	Winter 1964-1965	Spring 1965	Summer 1965	Study period average	
Falls View (1)	—	0.2	—	—	—	—
Smithers (5)	0.4	0.3	0.3	0.0	0.2	11.2
Montgomery (6)	—	0.6	—	—	—	6.7
Cedar Grove (7)	0.5	0.4	0.2	0.4	0.4	4.8
Marmet (11)	—	0.5	—	—	—	3.8
Kanawha City (13)	2.1	0.8	0.6	0.5	1.0	2.8
Charleston (15)	—	0.9	—	—	—	—
West Charleston (17)	—	0.7	—	—	—	—
North Charleston-W (19)	—	0.7	—	—	—	8.6
South Charleston-E (20)	2.7	0.6	0.6	1.0	1.2	11.6
Dunbar (22)	—	0.4	—	—	—	—
St. Albans (24)	1.3	0.9	0.3	0.4	0.7	3.0
Nitro (25)	1.0	1.4	0.2	0.3	0.7	3.4
Nitro-West (27)	—	0.1	—	—	—	—

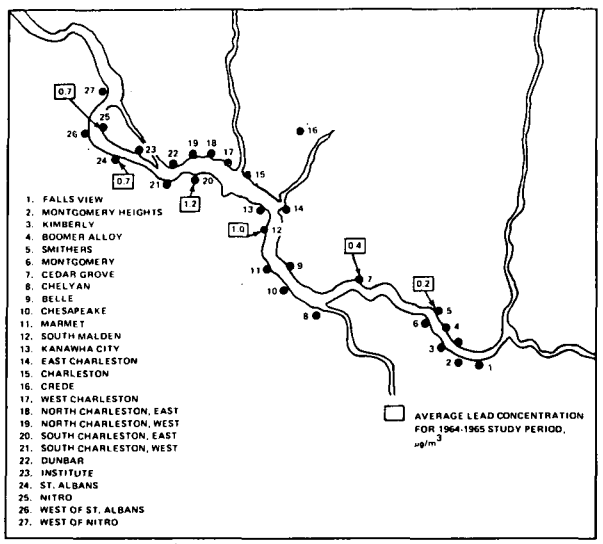


Figure C-1. Locations of fixed sampling stations in Kanawha River Valley.[3]

TABLE C-4. DATA ON LEAD DEPOSITION IN 77 MIDWESTERN CITIES[4] ($mg/m^2/mo$)

Area	Lead deposition, Concentration, geometric mean	Month	Lead deposition, Concentration, geometric mean
Residential	5.24	September	9.11
Commercial	9.80	October	8.71
Industrial	12.78	November	9.15
		December	8.06

horses died of lead poisoning that was caused by ingestion of lead deposited on pasture grass from a smelter plant at Selby, California. The ambient air concentrations of particulate lead were typical of those found in urban and suburban areas. It was concluded that horses in this area should not be allowed to subsist on pasture grass alone, but should receive supplemental feed. Tables C-5 and C-6 contain the data on suspended and deposited lead obtained during the study. Note that the fallout rates are on a daily basis.

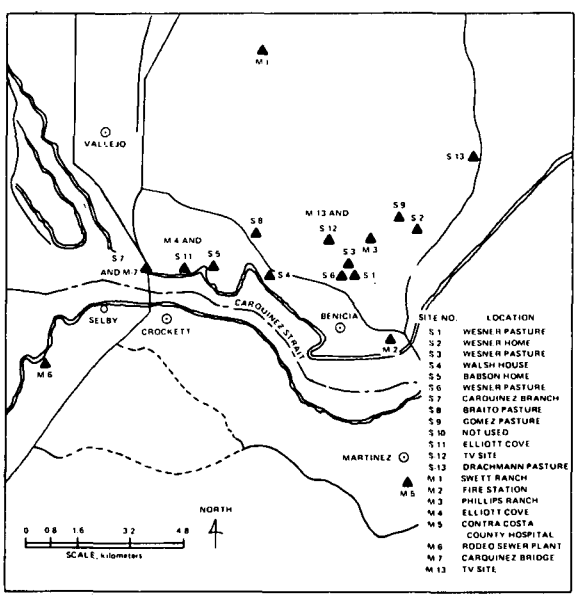


Figure C-2. Air sampling sites for Southern Solano County, California, study.[5]

C.2.2 Omaha, Nebraska[6]

In April and May of 1968, a study of settled lead by the EPA Division of Health Effects Research showed central Omaha, Nebraska, to have the highest concentrations of deposited lead of 22 midwestern cities. Because automobile emissions should reflect the relatively low population density, the possibility of a significant contribution to air lead

TABLE C-5. LEAD CONCENTRATIONS IN AIR DETERMINED BY ANALYSIS OF SUSPENDED PARTICULATE, SOUTHERN SOLANO COUNTY, CALIFORNIA, MARCH-MAY 1970[5]

Site	Distance from Selby,[a] km	Lead concentrations, $\mu g/m^3$		
		High	Low	Mean
Carquinez Bridge	1.9	8.45	0.35	3.49
Elliot Cove	3.0	0.93	0.27	0.52
Babson house	3.7	0.82	0.58	0.70
Braito dump	5.6	0.69	0.07	0.64
Walsh house	5.7	0.62	0.14	0.40
Braito TV transmitter site	7.7	1.07	0.25	0.59
Wesner pasture	7.8	0.56	0.40	0.42
Wesner pasture	8.0	0.66	0.11	0.38
Wesner pasture	8.3	0.51	0.03	0.27
Gomez pasture	10.0	0.28	0.03	0.11
Wesner house	10.2	0.22	0.02	0.14
San Francisco[b]	22.0	3.50	1.15	2.12
Fremont[b]	20.0	2.24	0.59	1.04
San Rafael[b]	19.2	2.04	0.41	1.14

[a] Location of suspected lead emissions source. See text.
[b] 1969 data provided by Bay Area Air Pollution Control District.

TABLE C-6. TOTAL LEAD AND LEAD FALLOUT DETERMINED BY ANALYSIS OF DUSTFALL SAMPLES, SOUTHERN SOLANO COUNTY, CALIFORNIA, JUNE-SEPTEMBER 1970[5]

Site	Distance from Selby,[a] km	Sample period, days	Total solids, mg	Total lead, μg	Lead fallout, mg/m^2-day
Carquinez Bridge	1.9	30	49.2	1435	2.78
Braito dump	5.6	30	58.7	195	0.38
Braito TV transmitter site	7.7	60	101.7	520	0.50
Wesner pasture	8.0	31	370	185	0.35
Wesner pasture	8.0	31	162	155	0.29
Wesner pasture	8.0	31	171.4	195	0.37
Wesner pasture	8.0	31	109.8	255	0.48
Wesner pasture	8.0	31	351.7	210	0.39
Wesner pasture	8.0	31	220.2	4535	8.51
Wesner pasture	8.0	30	83.5	430	0.83
Wesner pasture	8.3	30	163.6	705	1.37
Gomez pasture	10.0	32	45.0	150	0.27
Drachman pasture	13.4	30	26.5	75	0.15

[a] Location of suspected lead emissions source. See text.

from other sources (two battery plants, one refinery) in the central city area was considered. Consequently, from May to November 1970, monitoring of air lead in Omaha was conducted at five sites: one industrial (I), one commercial (C), one mixed (M), and two residential (R). All samples were taken at 15-ft elevation, and all data were reported as the composited averages of 24-hr samples collected 3 times weekly. The monthly composite average of air lead concentrations at the sampling sites is shown in Figure C-3. Air lead levels in central Omaha at sites C and I were not only comparable with those of similar sites in Chicago, New York City, and Houston from the same months, as reported by EPA, but the maximum monthly mean at the industrial site (in July) exceeded the maximum monthly mean of all sites in these other cities.

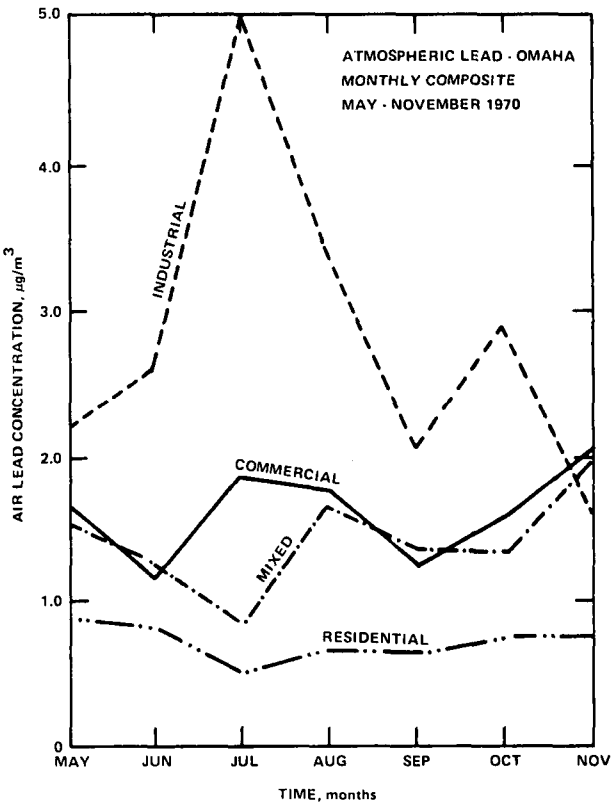


Figure C-3. Omaha, Nebraska study: mean monthly composite atmospheric lead at industrial, commercial, mixed, and two residential sites. Mean is that of representative 24-hour samples collected three times weekly. The autumnal peak at all but the industrial site parallels the usual Omaha pattern for particulates.[6]

C.2.3 El Paso, Texas[7,8]

The El Paso, Texas, study was initiated in 1971 as a result of the discovery of increased lead deposition in the vicinity of a local smelter whose emissions

rose from 256 MT in 1969 to 463 MT in 1970. The El Paso City-County Health Department then began special ambient air and soil sampling in addition to routine operation of their nine-station particulate sampling network. Particulate samples were collected with high-volume samplers over 24-hr periods and were then analyzed for lead by atomic absorption spectroscopy. The results for 1971 from the nine-station network are given in Table C-7. Daily sampling at 6 selected sites in Smeltertown was continued beginning in February 1972. Daily lead concentrations at four ground level sites ranged from 0.49 to 75 $\mu g/m^3$ and averaged 6.6 $\mu g/m^3$ over 86 days. Average concentrations of 3.6 and 6.5 $\mu g/m^3$ were found at 2 rooftop sites.

TABLE C-7. LEAD CONCENTRATIONS IN SUSPENDED PARTICULATE AIR SAMPLES FROM EL PASO, TEXAS, 1971[7]

Location	Distance from smelter, km	No. of samples	Suspended atmospheric lead concentration, $\mu g/m^3$	
			Range	Average
Airport	12.8 E	84	0.38 to 5.82	0.96
Northeast	16 NE	73	0.12 to 3.68	0.76
Canutillo	15.2 NW	45	0.10 to 1.50	0.46
Shorty Way	8 NW	75	0.18 to 4.51	1.03
Tillman	4.8 SE	70	0.02 to 22.16	2.69
Ysleta	21.6 SE	71	0.18 to 4.81	1.39
Coronado	4.8 N	94	0.08 to 8.62	0.83
Kern	2.4E	26	0.12 to 7.28	2.72
Executive	1.6 NE	65	0.26 to 6.67	1.16

C.2.4 Helena Valley, Montana[9]

During the summer and fall of 1969, a source-oriented study of the Helena Valley, Montana, area (Figure C-4) was undertaken using dustfall bucket and high-volume sampling techniques. During this period, Helena residents were exposed to an average daily lead concentration of 0.1 $\mu g/m^3$, with maximum concentrations of up to 0.7 $\mu g/m^3$. The residents of the East Helena area were exposed to an average daily concentration of 0.4 to 4.0 $\mu g/m^3$, depending upon proximity to the source, with maximum daily exposures of up to 15 $\mu g/m^3$. Within a 1-mile radius of the East Helena smelter, settled particulate lead values ranged from 30 to 108 $mg/m^2/mo$. Table C-8 summarizes the dustfall and suspended particulate data acquired during this study, and Figure C-4 shows the deposition of lead (dustfall) in the area.

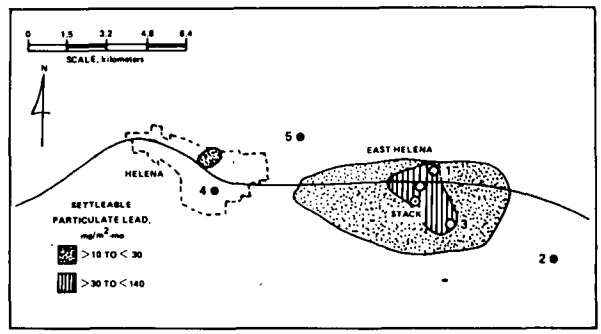


Figure C-4. Settleable particulate lead radial distribution from Helena Valley environmental pollution study.[9]

C.2.5 Southeast Missouri[10]

Studies were carried out in 1971 in the Viburnum Trend or New Lead Belt in southeast Missouri to determine the magnitude and distribution of atmospheric pollutants from lead mining and smelting operations. This industrial district has become one of the world's largest lead-producing areas by mining more than 392,277 MT of lead, or 75 percent of the entire U.S. lead production, during 1970. Settleable particulates were collected monthly at 10 locations in western Iron County shown in Figure C-5. Annual averages for each site are included in the figure; monthly maximum values are listed in Table C-9. Annual averages for suspended lead collected in Glover, Mo. (Site 43, southeastern Iron County), by high-volume sampler were 3.4 $\mu g/m^3$ (20 samples) in 1970, 5.3 $\mu g/m^3$ (32 samples) in 1971, and 5.6 $\mu g/m^3$ (28 samples) in 1972.

TABLE C-8. PARTICULATE DATA SUMMARY FROM HELENA VALLEY, MONT., ENVIRONMENTAL POLLUTION STUDY[9]

Station	Location[a]	Settleable particulate lead, $mg/m^2/mo$					Suspended particulate lead in glass fiber filter sample, $\mu g/m^3$			
		Jun.	Jul.	Aug.	Sept.	Oct.	No. samples	Max.	Min.	Average
1	0.8 mi; 34°	3	19	10	19	40	76	5.3	< md[b]	0.45
2	2.5 mi; 105°	1	4	3	9	10	87	2.5	< md	0.24
3	0.4 mi; 112°	54	106	5	63	108	85	16.0	< md	1.25
4	4.5 mi; 274°	1	4	3	7	7	82	7.0	< md	0.10
6	0.5 mi; 2°	—	—	—	27	60	34	15.0	0.2	3.89

[a] Distance and compass direction from smelter stack.
[b] Minimum detectable.

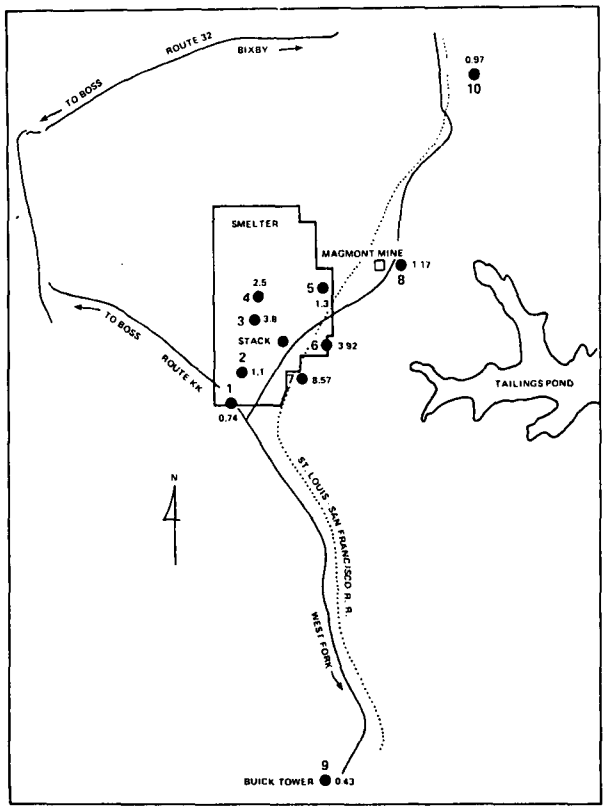


Figure C-5. Annual average of settleable particulate lead at sites near Missouri lead mine and smelter, g/m²/mo.[10]

C.2.6 **Helsinki, Finland[11]**

Investigators for the Agricultural Research Center in Tikkurila, Finland, an industrial and residential area near Helsinki, found high lead levels in soil. To clarify the origin of this excess lead, the Institute of Occupational Health conducted a dustfall lead survey in the area. Eighty collectors were located over a 40-km² area for a period of 1 month, October 6 to November 7, 1970. Individual ashed samples were analyzed by emission spectrography and the water-soluble fractions were analyzed by atomic absorption spectroscopy.

The highest lead deposition values in Helsinki were observed in areas with heavy traffic and ranged from 10 to 20 mg/m²/mo as compared to 0 to 4 mg/m²/mo in predominantly housing and residential areas.

In the Tikkurila area, industrial contributions increased deposited lead values fortyfold in some areas. The deposited lead values ranged from background in outlying areas to as high as 200 mg/m²/mo near a lead smelter, with most of the values below 100 mg/m²/mo.

C.2.7 **Meza River Valley, Yugoslavia[12]**

In 1967, work was initiated in the community of Zerjav, situated in the Slovenian Alps on the Meza River, to investigate contamination by lead of the air, water, snow, soil, vegetation, and animal life, as well as the human population. The smelter in this community produces about 19,954 MT of lead annually; until 1969 the stack emitted lead oxides without control by filters or other devices. Five sampling sites with high-volume samplers operating on a 24-hr basis were established in the four principal settlements within the Meza River Valley (Figure C-6): (1) Zerjav, in the center, the site of the smelter, housing 1503 inhabitants; (2) Rudarjevo, about 2 km to the south of Zerjav with a population of 100; (3) Crna, some 5 km to the southwest, population 2198, where there are two sites (Crna-SE and Crna-W); and (4) Mezica, a village about 10 km to the northwest of the smelter with 2515 inhabitants. The data in Table C-10 are sufficient to depict general environmental contamination of striking proportions.

TABLE C-9. PEAK DEPOSITION RATES OF LEAD MEASURED IN SOUTHEAST MISSOURI[10]

1971	Station no.	Wind direction	Distance, m	Lead deposition rate, mg/m²/mo	Wind frequency, % prevailing direction
May-June	6	E	81	5.88	18(S), 12(WNW)
July	7	SSE	91	5.54	14(SSE), 13(S), 10(SSW)
August	10	NE	633	4.57	14(SSE), 11(S), 10(SSW)
September	7	SSE	91	7.76	22(S), 12(SSE), 12(SSW)
October	7	SSE	91	5.10	10(N), 10(W), 10(SE), 11 (ESE)
November	3	WNW	61	2.01	26(S), 12(SSW), 10(WSW), 8(SSE)

C.2.8 **Ontario, Canada[13]**

Studies of lead concentrations in soils, vegetation, and the ambient air were conducted in the vicinity of a secondary smelter and a battery manufacturing plant in a large urban area in southern Ontario. For comparative purposes, data were also collected in a similar control neighborhood that had no such industrial sources. Emissions of lead from the smelter were estimated to be 17 tons per year; from the battery plant, 6 tons per year. Averages and ranges of

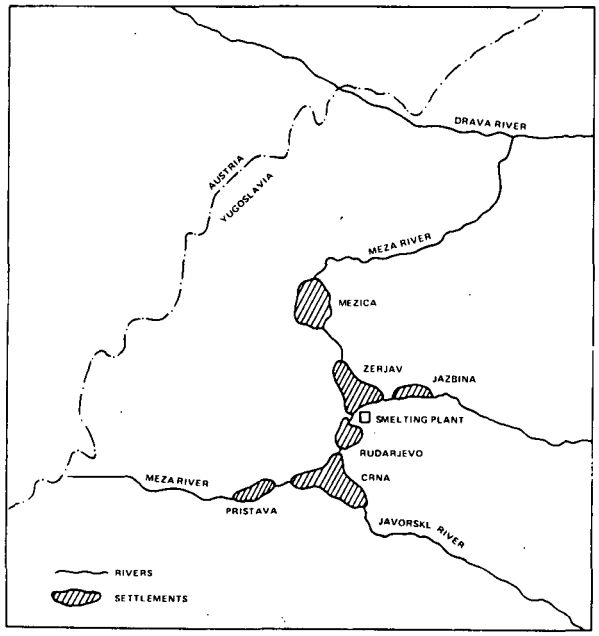


Figure C-6. Schematic plan of lead mine and smelter from Meza Valley, Yugoslavia, study.[12]

TABLE C-10. ATMOSPHERIC LEAD CONCENTRATIONS (24-hr) IN THE MEZA VALLEY, YUGOSLAVIA, NOVEMBER 1971 TO AUGUST 1972[12]

Site	Pb concentration $\mu g/m^3$		
	Minimum	Maximum	Average
Mezica	0.1	236.0	24.2
Zerjav	0.3	216.5	29.5
Rudarjevo	0.5	328.0	38.4
Crna SE	0.1	258.5	33.7
Crna W	0.1	222.0	28.4

lead concentrations are summarized in Table C-11. Both soil and foliage samples showed definite trends toward reduced concentrations with increasing distance from the industrial sources.

C.3 CONCENTRATIONS OF LEAD IN SOILS AND URBAN DUSTS

As mentioned in Chapter 5, surficial materials in the continental United States contain an average of about 15 ppm of lead; 94 percent of the measurements showed 30 ppm or less. Higher concentrations are encountered in the vicinity of lead ore deposits and, of course, in the proximity of human activities involving lead. Soils apparently receive lead in the amounts of about 1 $\mu g/cm^2/yr$ from precipitation and 0.2 $\mu g/cm^2/yr$ from dustfall[14] in areas remote from intensive human activity. These small additions to the lead content of the soil are not detectable by ordinary means because they add only about 0.2 percent to the total lead in the top 6 in of the soil. Lead levels are higher in surface soils than in deeper layers. Swain and Mitchell[15] studied lead profiles in 8 soil types in Scotland and showed that the lead content at 115 cm (45 in) averaged one-half that at the surface. The reduction of concentration with depth is also substantiated by the findings of others. Goldschmidt[16] proposed the theory that lead is concentrated in the humus or organic fraction of soils in forests because it is taken up slowly by tree roots and transported to the leaves, which fall and decay. Tyler[17] points out that a passive ion exchange favors an accumulation of lead and other heavy metals in dead organic matter, litter, and humus. He also states that most plant material subjected to decomposition usually shows an increase in the concentration of lead, cadmium, nickel, iron, copper, etc., calculated on dry weight.

The use of leaded gasolines has produced elevated soil lead levels adjacent to most streets and roadways. This phenomenon was first observed as early as 1933 in England,[18] and has been intensively

TABLE C-11. COMPARISON OF LEAD LEVELS IN THE SURROUNDINGS OF TWO LEAD INDUSTRY FACILITIES AND AN URBAN CONTROL AREA[13]

Industry or area	Soil, ppm (0.5 cm depth)	Tree foliage ppm		Air, $\mu g/m^3$ (24-hour samples)
		Unwashed	Washed	
Secondary smelter				
Mean	2,615	250	187	3.87[a]
Range	133 to 21,200	38 to 3,530	27 to 2,740	Max 74.4
Battery plant				
Mean	1,996	149	76	2.21[b]
Range	95 to 17,300	34 to 459	16 to 387	Max 31.0
Urban control area				
Mean	482	73	43	1.02[c]
Range	18 to 1,450	15 to 253	10 to 124	Max 4.0

[a]April 1973 to May 1974.
[b]November 1973 to May 1974.
[c]January 1974 to April 1974.

studied in recent years.[19] An example of this phenomenon is taken from a study of the Saline Branch watershed, which includes Champaign, Illinois. One facet of this comprehensive study[20] consisted of analyses for lead in soil at increasing distances from a low-traffic-volume street (400 vehicles/day) and a high-traffic-volume street (14,000 vehicles/day). As shown on curve A in Figure C-7, lead concentrations stabilized at about 20 ppm beyond 15 meters from the low-volume street and rose slightly near the house. Unfortunately, the exterior construction of the house is not described. As curve B in Figure C-7 shows, lead concentrations of about 1800 ppm in the soil adjacent to the high-volume street are 9 times higher than in soil adjacent to the low-volume street; the concentration drops rapidly to a minimum of 30 ppm a little more than 20 m from the street and then rises again abruptly near the house to 90 ppm. This house is described as brick and unguttered. Although some leaching of lead from painted trim may be involved, the increase near the house is believed attributable chiefly to lead particles in traffic dust washed from the unguttered roof by rain and deposited in the soil next to the house.

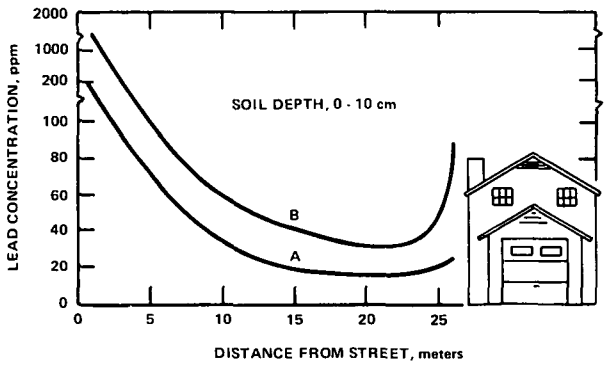


Figure C-7. Soil transects by two streets: Curve A = low-traffic-volume (400 veh/day); Curve B = high-traffic-volume (14,000 veh/day).[20]

Soil lead levels in the vicinity of stationary sources of lead emissions are often very high, and, unlike the rapid drop-off near highways, very extensive. This is particularly true for old installations. Figure C-8 shows levels recently found near an old smelter in El Paso, Texas.[21] Similar data, compiled from a 3-year-old Russian lead smelter,[22] are shown in Table C-12. The concentration decrease with both depth and distance is also apparent here. Information on soluble lead levels in soil near a similar complex in Great Britian is presented in a report by Little and Martin.[23] Barltrop reported values up to 30,000 μg/g in villages in the eastern half of Derbyshire County, England.[24] In this instance, the soil included lead contamination from old mine tailings and possible natural mineralization, i.e., the concentrations were not exclusively atmospheric in origin.

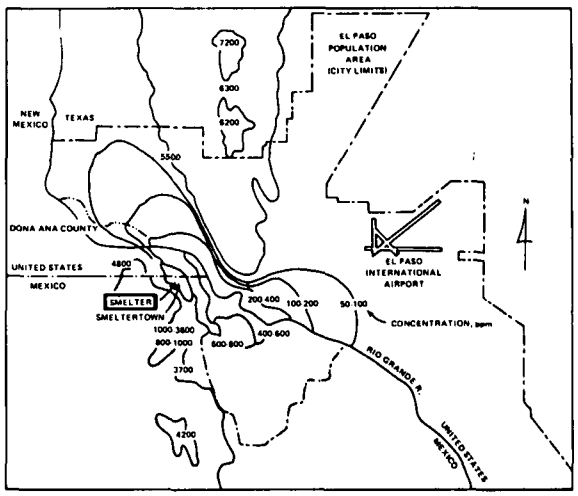


Figure C-8. Surface soil levels (ppm) of lead in El Paso, Texas, and Dona Ana County, New Mexico, 1972.[21]

TABLE C-12. LEAD CONTENT OF SOIL NEAR 3-YEAR-OLD RUSSIAN SMELTER, E. KAZAKHSTAN (mg/100 g air-dried soil)[a]

Distance from source, m	Surface layer	Soil depth	
		25 cm	75 to 100 cm
500	23.9711	4.1747	0.0748
1,000	9.0163	1.8368	—
2,000	1.4207	0.7432	0.0545
3,000	1.2192	0.5991	0.0474
5,000	0.1031	0.0649	0.0233
16,000	0.0943	0.0778	0.0292

[a]Multiplying by 10 yields ppm.

Table C-13, derived from studies done in 1959 and 1960,[25] gives lead levels of soil adjacent to another Russian lead smelter. The plant is located in a valley surrounded by mountains that hinder natural ventilation. In addition, plant emissions are inadequately controlled. Methods of sample preparation and analysis of the soil samples are not given, however; nor is it stated whether the soil weights used were for dried or undried material.

Paluch and Karweta[26] reported observations on soil lead near a new lead-zinc primary smelter in Poland. Soil analyses were made in several areas prior to operation of the factory and after 1 year of operation. Samples were extracted with hot concentrated hydrochloric acid and analyzed for lead content by the dithizone method. Levels found are given in milligrams of lead per kilogram of dried soil. Values

TABLE C-13. LEAD CONTENT OF SOIL IN VICINITY OF RUSSIAN LEAD PLANT IN KAZAKHSTAN[25]

Distance from source km	Number of samples	Lead content of soil, mg/100 g[a]					
		0 to 1 cm depth			25 cm depth		
		Maximum	Minimum	Average	Maximum	Minimum	Average
On grounds	12	11.170.0	1.300.0	5.546.0	6.800.0	510.0	3.143.0
0.5	10	2.420.0	470.0	1.156.0	650.0	130.0	458.0
1.0	20	1.170.0	130.0	613.0	990.0	200.0	430.0
1.5	6	720.0	170.0	369.0	720.0	70.0	340.0
2.0	6	1.070.0	250.0	530.0	610.0	70.0	260.0
3.0	4	340.0	130.0	235.0	260.0	100.0	180.0
5.0	4	97.0	80.0	88.5	46.0	40.0	43.0
40.0	4	3.0	2.5	2.7	Trace	Trace	Trace

[a]Multiplying by 10 yields ppm.

given are the average of three samples. Two sites are of particular interest, a woods of young pines 2 km from the smelter and a tree nursery at 3 km. Before and after lead levels in the top 5 cm of soil at these locations were 39 and 89 mg/kg for the former, and 54 and 81 mg/kg for the latter. At other sampling sites the data were quite variable, but these were agricultural lands subject to cultivation, to fertilization, or to both. The wooded sites were not disturbed in this manner.

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APPENDIX D

UNITS AND METRIC CONVERSION FACTORS

In each of the disciplines dealing with lead in a sector of the environment, conventions for units have evolved that are convenient to each but not always familiarly translatable from one to the other, even when expressed in metric units. There are also two distinct categories of measurements: concentrations and transfer rates. Within each category of measurements, straightforward conversion factors translate the quantitites from one system of units to another. Connections between the two categories are bridged only by mathematical models of varying complexity that account for all significant transfer rates, both into and out of a given context, as well as measure that context's capacity to distribute and equilibrate any net change that will add to or substract from its initial concentration.

D.1 CONCENTRATIONS

Airborne lead concentrations are customarily reported in units of mass per volume: micrograms of lead per cubic meter of air ($\mu g/m^3$). Concentrations of lead in soils and dusts are reported in units of mass per mass: micrograms of lead per gram of the parent material ($\mu g/g$), or as parts per million (ppm). When ppm refers to mass, the expression is interchangeable with $\mu g/g$.

Concentrations of lead in water (dissolved or suspended) may be reported in parts per billion (ppb) or micrograms per liter (μg/liter). For our purposes, a liter of water can be equated with 1000 g, and units of μg/liter can be interchanged with ppb or nanograms per gram (ng/g).

Concentrations of lead in food are usually given in parts per million (ppm), micrograms per gram ($\mu g/g$), or milligrams per kilogram (mg/kg), all of which are interchangeable.

Concentrations of lead in blood may be reported in micrograms per deciliter (μg/dl) or in micrograms per 100 grams (μg/100 g). These are not equivalent since 1 dl of blood weighs between 105 and 106 g.

D.2 TRANSFER RATES

In general, transfer rates describe the movement of material from one medium or context to another in units of mass per time or mass per quantity (mass or volume) of a parent material. Some rates include a linear or area dimension to express the transfer per unit of interface between media.

The lead in ores that is transfered to smelters and hence to manufactured products is described by production figures and reported in tons (short) per year (tons/yr) or tonnes (metric) per year (MT/yr). The attendant dispersal of some of that lead into the air, water, and soil is described by emission factors: tons per year (tons/yr), kilograms per day (kg/day), pounds per ton of raw material or product (lb/ton), pounds per thousand gallons ($lb/10^3$ gal), grams per kilometer (g/km), etc.

The most familiar transfer rate between media is perhaps the dustfall or deposition rate, reported in tons per square mile per year ($tons/mi^2/yr$), milligrams per square meter per month ($mg/m^2/mo$), etc.

The culminating concern is with transfer rates, involving the human body, through inhalation and ingestion followed by retention and absorption into fluids and tissues, and, finally, excretion, all of which are commonly expressed in micrograms per day, micrograms per kilogram of body weight per day, or, even, as micrograms per square meter of body surface.

D.3 UNITS

1 m = 10^6 μm = 10^2 cm = 10^{-3} km = 3.281 ft = 39.37 in

1 m^2 = 10^4 cm^2 = 10^{-6} km^2 = 10.76 ft^2 = 1550 in^2

1 m^3 = 10^6 cm^3 = 999.97 liters = 35.31 ft^3 = 6.1 x 10^4 in^3 = 264.2 gal

1 g = 10^6 μg = 10^3 mg = 10^{-3} kg = 0.035 oz = 0.0022 lb

1 tonne (metric) = 1000 kg = 10^6 g = 1.1023 tons (short)

D.4 CONCENTRATION CONVERSION FACTORS

1 ppb (mass) = 1 ng/g = 1 μg/kg
1 ppm (mass) = 1 μg/g = 1 mg/kg
1 mg/liter (water) ≃ 1 ppm ≃ 1 μg/g
1 μg/liter (water) ≃ 1 ppb
1 μg/dl (blood) ≃ 0.95 μg/100 g (blood)

D.5 TRANSFER RATE CONVERSION FACTORS

1 $mg/m^2/mo$ = 2.85 x 10^{-3} tons (short)/mi^{-2}/mo
1 tonne/yr = 2.74 kg/day = 1.1023 tons (short)/yr
1 μg/day = 3.53 x 10^{-8} oz (av.)/day

APPENDIX E
ABSTRACT OF A REVIEW OF THREE STUDIES ON THE EFFECTS OF LEAD SMELTER EMISSIONS IN EL PASO, TEXAS

Presented by Warren R. Muir
Council on Environmental Quality
Washington, D.C.
At the International Conference on Heavy Metals in the Environment
Toronto, Ontario, Canada
October 1975

The committee reviewed two independent studies conducted in 1973 by Dr. Landrigan (CDC) and Dr. McNeil (ILZRO) to determine the effects of community lead exposures near the ASARCO smelter in El Paso, Texas. The CDC study used a random sample approach to group participating children, and in the ILZRO study match paired groups were selected on the basis of residence. In both studies the criteria for subclassification with regard to lead exposure were blood lead levels. Neuropsychological dysfunction was evaluated by several tests including WISC, WPPSI, and McCarthy scales. Statistical differences in test results could not be directly correlated to blood lead levels.

The opinion of the committee was that no firm conclusions could be drawn from the studies as to whether or not there are subclinical effects of lead on children in El Paso and that the reports and data made available have not clearly demonstrated any psychologic or neurologic effects in the children under study. It noted the absence of major chronic clinical effects, and concluded that these studies therefore do not bear upon the conclusions of other investigations under different conditions and those in which clinical effects have been confirmed. However, because of inherent problems of study design and the limitations in the tests used, this finding should not lead to a conclusion that low levels of lead have no effects on neuropsychological performance. Ellen Silbergeld, Ph.D., NIH, Eileen Higham, Ph.D., and Mr. Russell Jobaris, Johns Hopkins University, Department of Medical Psychology, served as special consultants.

The committee decided to limit its focus to a review of the three studies, and to attempt to account for and interpret the differences between the studies. Thus, aspects not related to differences were not emphasized.

The committee limited its consideration to the following materials: (1) reports of the three studies under consideration; (2) other materials provided by the authors of the studies; (3) background information and documents collected by Dr. Muir in El Paso. This presentation today consists of excerpts from a draft committee report.

E.1 HISTORY

El Paso is situated on the Mexican border in the western part of Texas. A lead smelter owned by American Smelting and Refining Company (ASARCO) has been located on the southwestern border of the city, on the Rio Grande River, since 1887. The area most conspicuously involved in the studies, Smeltertown, was a 2 x 6 block area located between the plant and the river. Smeltertown is no longer in existence, having been destroyed in December 1972. About 2 km south of Smeltertown is Old Fort Bliss, a considerably smaller community, whose inhabitants were considered in some, but not all, of the studies.

The ASARCO smelter produces lead, zinc, copper, and cadmium. Particulate matter is removed from airborne wastes in a series of baghouses; remaining emissions contain approximately 40 lb of lead per day.

The El Paso City County Health Department began an investigation of the ASARCO smelter in early 1970, in preparation for an air pollution suit filed by the city in April 1970. As part of this investigation, Dr.

Bertram Carnow was hired by the city as a consultant. At his suggestion, the city began to sample the blood lead levels of El Paso children to determine whether any had been over-exposed to lead. This included a large number of Smeltertown children. Based upon early results in 1971, Dr. Carnow visited El Paso, and saw a selected group of children with high blood lead levels. He interviewed the children, and reviewed their medical records. The information contained in the medical histories, and Dr. Carnow's interviews, constitute the observations reported by Dr. Carnow in the paper presented to the American Pollution Control Association (APCA). The clinical observations were in a paragraph of a paper otherwise devoted to a consideration of the effects of the smelter on the environment as a whole, and the extent of its emissions. This report contains no details on the age, exposures, individual signs and symptoms, or diagnostic criteria used in the ten cases reported. Our committee focused its attention, therefore, upon the two full-scale follow-up epidemiological studies conducted by Dr. Landrigan (CDC) and Dr. McNeil (ILZRO).

In 1973 ASARCO began a separate investigation of the population of Smeltertown, and asked Dr. James McNeil of the International Lead Zinc Research Organization (ILZRO) for his assistance in the examination and possible treatment of children with elevated blood levels greater than 60 mg/100 ml.

As a result of public concern over widespread lead poisoning throughout the city of El Paso, the mayor requested aid from the Federal Government. A separate protocol for a Center for Disease Control (CDC) study was submitted to and approved by the Public Health Board in 1973 with the understanding that the two studies would proceed independently, with those children in the ILZRO sponsored study being excluded from the CDC study.

In the summer of 1973, CDC and ILZRO proceeded independently to collect data for their respective studies. CDC's examinations were done in two weeks in June 1973, while McNeil's were carried out over the course of the summer with the aid of the El Paso public school system.

The CDC group supplied to the Committee data in detail, which were sufficient to allow the committee to conduct statistical tests and analyze characteristics of groups. For the ILZRO study, this committee requested data sufficient to carry out similar in-depth analyses. All of the requested data were supplied; however, they were not in such a form as to allow recalculation of most of the statistical findings of the study or to allow comparison with the CDC findings.

E.2 **STUDY DESIGN**

The environmental sampling that was performed was common for both of these studies. In the selection of study and control populations, the Landrigan CDC study used a classical approach of a random sample survey to determine the prevalence of abnormal blood lead values. The 13 census tracts most adjacent to the smelter were divided into three areas. The sampling frame was designed to obtain about 100 study subjects from each area for various age groups. Of 833 occupied residences, interviews were obtained from 758 study subjects in the 1-19 age group. The participating children were divided into a lead-absorption group (40-80 μg/100 ml) of 46 and a control group (< 40 μg/100 ml) of 78. There is no detailed description as to how the children were chosen.

CDC used these same children as the basis for the later study of neuropsychological dysfunction. All but 3 children chosen for study came from the 1972 prevalence survey; 5 children with known preexisting defects such as with a history of symptoms compatible with acute lead poisoning or acute lead encephalopathy and those who had received chelation therapy were excluded.

While it is understood that a number of Smeltertown children with blood lead levels over 40 μg/100 ml were eventually involved in litigation, most of them took part in the studies. However, on the recommendation of the lawyers representing the children, at least one group of 18 did not participate in the ILZRO study. In the absence of identification by names of the individuals in the three studies, it has been impossible to evaluate the effects of non-participation.

The ILZRO study was very different; 138 children from Smeltertown agreed to participate in a study. Residence, not blood lead, was the selection criterion. Two control groups were chosen, and were reported to have been matched on age, sex, ethnic background, and income, with one set chosen from El Paso and another set for those 8 years of age or under from a rural area about 12 miles from the smelter. This classification had the effect of grouping together children who, under the CDC criteria, would have been in "lead" and "control" groups.

The criteria used for subclassification of children with regard to lead exposure were based in both studies on the blood lead level. Whereas the CDC study utilized blood lead values obtained at only two points in time, ILZRO, which was faced with the problem that many children had repeated blood lead measurements with marked variations over a period of 18 months (the levels being generally lower after exposure was discontinued), classified children on the basis of the average of the "two highest" recorded values.

This criterion results in a substantial increase in the number of children in the apparently higher blood lead category and a corresponding decrease in the number of those in the apparently lower blood lead level category.

Although it is understandable that this type of selection was used to avoid underestimating the problem of lead intoxication in the population examined, it ultimately resulted in muddling of the separation between groups (and possibly obscuring eventual differences). For example, the selection for analysis of children from the same geographical area, subclassified according to blood lead level, in the ILZRO study, may give the impression that the effects of lead itself are being studied in a homogeneous population. However, since exposure was geographically the same, other factors inherent to each individual child may be responsible for the difference in blood lead level observed.

An additional method of classification could have been the use of free erythrocytic protoporphyrin measurements (FEP) which have been shown to provide an indication of metabolic effects of lead absorption on metabolism, particularly useful in blood lead level ranges (40-60 μg/100 ml) where analytical and biological fluctuation may result in uncertain classification. (The ILZRO study included this test but did not include it as a basis for data analysis.) Absence of elevation of free erythrocytic protoporphyrin may indicate those instances where high blood lead levels were spurious.

The following psychometric tests were employed by the two studies:

1. Wechsler Intelligence Scale for Children, WISC (CDC, ILZRO)
2. McCarthy Scales of Children's Abilities (ILZRO)
3. Wechsler Preschool and Primary Scale of Intelligence, WPPSI (CDC)
4. Lincoln-Oseretsky Motor Development Scale (ILZRO)
5. California Test of Personality Adjustment (ILZRO)
6. Frosting Perceptual Quotient (ILZRO)
7. Bender Visual-Motor Gestalt Test (CDC, ILZRO)
8. Peabody
9. WRAT
10. Wepman
11. Draw-a-person

All of the tests selected by both studies were appropriate for the ages of the children to whom they were administered. Since the common ground for these studies is the WISC test, with the WPPSI used by CDC and the McCarthy Scales by ILZRO for the younger children in their studies, the Committee concentrated on these three tests and the results obtained for them.

E.3 **RESULTS**

The study by CDC reports results for 27 children given the WPPSI (12 with blood lead levels 40-80 μg/100 ml and 15 with blood lead levels less than 40 μg/100 ml) and for 97 children tested with the WISC (34 in the "lead group" and 63 in the "control group"). Statistical analyses were performed on grouped data with one-tailed tests. Significant differences between lead and control groups are reported in this study for the performance IQ's of the WICS and WPPSI. In subtest scores, significant differences were found in Coding on the WISC and Geometric Design on the WPPSI. When data from both tests are combined, a significant difference between lead and control groups on performance IQ is found. No differences were found between groups in verbal IQ's or full-scale IW's of the WISC or WPPSI.

The ILZRO study based on match pairing solely by residences reports no significant differences in scores on the WISC or McCarthy scales between groups with increased lead absorption and pair-matched controls. Statistical analysis was by means of two-way analysis of variance by age and blood lead levels.

The two studies base much of their conclusions upon psychometric and neurological testing of children from El Paso and Smeltertown. The reported significant differences and psychometric and neuromotor functions in the CDC study were clouded by potentially important methodological difficulties. These included

age differences between case and control groups, limited statistical treatment of the psychometric data collected, and, in the ILZRO study, the use of an average of the two highest blood lead levels to categorize lead exposure.

In addition, both the studies shared the following inherent problems:

1. Non-random exclusion of large groups of children
2. Uncertainties as to the selection of control groups
3. Reliance upon blood lead as the indicator of lead exposure and intoxication in analyses of data
4. Measurement of a limited aspect of psychological behavior
5. Lack of consideration of the potentially disruptive influences on test taking of the razing of Smeltertown, closing of its school, resettlement, litigation, and public controversy
6. Inability to rule out possible preexisting conditions

The Committee stressed the last issue, noting the likelihood that any behavioral or genetic factors that predispose an individual child to ingest or absorb more lead than another child equally exposed may itself be correlated to he result of psychometric testing. In other words an increased blood lead level may reflect, rather than cause, a preexisting difference in intelligence or behavior, an issue inherent in virtually all retrospective studies of the effects of low level blood lead.

The opinion of the committee was that no firm conclusions could be drawn from the studies as to whether or not there are subclinical effects of lead on children in El Paso and that the reports and data made available have not clearly demonstrated any psychologic or neurologic effects in the children under study. It noted the absence of major chronic clinical effects, and concluded that these studies therefore do not bear upon the conclusions of other investigations under different conditions and those in which clinical effects have been confirmed. However, because of inherent problems of study design and the limitations in the tests used, this finding should not lead to a conclusion that low levels of lead have no effects on neuropsychological performance.

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