RECEIVED

FEB 15 1986

OSTI

**X-Ray Fluorescence Investigation of Surface Lead in the
Pilot Plant Complex, Aberdeen Proving Ground, Maryland**

**Energy Systems Division
Argonne National Laboratory**

Operated by The University of Chicago,
under Contract W-31-109-Eng-38, for the
United States Department of Energy,

Argonne National Laboratory

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States Government, and operated by the University of Chicago under the provisions of a contract with the Department of Energy.

This technical memo is a product of Argonne's Energy Systems (ES) Division. For information on the division's scientific and engineering activities, contact:

Director, Energy Systems Division
Argonne National Laboratory
Argonne, Illinois 60439-4815
Telephone (708) 252-3724

Presented in this technical memo are preliminary results of ongoing work or work that is more limited in scope and depth than that described in formal reports issued by the ES Division.

Publishing support services were provided by Argonne's Information and Publishing Division (for more information, see IPD's home page: <http://www.ipd.anl.gov/>).

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (423) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

X-Ray Fluorescence Investigation of Surface Lead in the Pilot Plant Complex, Aberdeen Proving Ground, Maryland

K.L. Brubaker, H.J. O'Neill, J.E. Parks, J. Rueda, J.F. Schneider, and R.E. Zimmerman

Center for Environmental Restoration Systems, Energy Systems Division,
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

September 1995

Work sponsored by United States Department of Defense, United States Army,
Aberdeen Proving Ground, Maryland

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ple

This report is printed on recycled paper.

Contents

Acknowledgments.....	vii
Notation	viii
Abstract.....	1
1 Introduction.....	1
1.1 Background.....	1
1.2 Objectives	2
1.3 General Approach.....	2
2 Estimates of Structural Parameters	6
2.1 Methodology.....	6
2.2 Summary of Results.....	6
2.3 Evaluation of Uncertainties.....	7
2.4 Paint Color and Substrate Codes.....	7
3 XRF Lead Loading Measurements	9
3.1 Data Quality Objectives	9
3.1.1 Objective Number One.....	9
3.1.2 Objective Number Two	10
3.2 Sampling Strategy.....	11
3.2.1 Overall Strategy.....	11
3.2.2 Sampling Point Density.....	12
3.2.3 Sampling Point Locations	12
3.3 Lead Loading Data Collection	13
3.3.1 Methodology.....	13
3.3.2 Health and Safety.....	15
3.4 Quality Controls	17
3.4.1 Calibration Data.....	18
3.4.2 Calibration Checks and Control Charts.....	20
3.4.3 Detection Limits	21
3.4.4 Duplicate Measurements.....	24
4 Data Reduction and Analysis.....	27
4.1 XRF Data Validation.....	27
4.1.1 Data Comparison and Adjustment	27
4.1.2 XRF Spectra for Selected Samples	27
4.2 Data Description and Summary Statistics	30
4.3 Data Analysis	40
4.3.1 Definition of Strata	40
4.3.2 Analysis	40
4.4 Statistical Analysis and Test Results.....	51
4.4.1 Linearization Approximation.....	52
4.4.2 Direct Computation of the Probability of H_0	56

Contents (Cont.)

5	Summary and Conclusions.....	58
6	References.....	60
	Appendix A: XRF Lead Calibration Data.....	61
	Appendix B: Lead Loading Databases for PPC Buildings	67
	Appendix C: Stratified Random Sampling Formulas.....	97
	Appendix D: Analysis of Paint Chip Samples for RCRA Metals	103
	Appendix E: Pilot Plant Complex Lead Content — Alternative Statistical Approach to Hypothesis Testing	109

Figures

1	Current Pilot Plant Complex.....	4
2	Sample Lead Measurement Data Logsheet.....	16
3	Calibration Lines.....	19
4	Variation of K-Shell XRF Standard Deviation with Lead Loading.....	23
5	Duplicate Data Scatterplot.....	25
6	Duplicate Difference Summary Figures.....	26
7	XRF Spectrum 1	28
8	XRF Spectrum 2	29
9	XRF Spectrum 3	29
10	Frequency Distribution of Building E5625 Data by Substrate, and of Combined Outbuilding Data.....	33
11	Lognormal Distributions — Exterior and Interior of Building E5625.....	34
12	Lognormal Distributions — Exterior and Interior of PPC Outbuildings.....	35
13	Lognormal Distributions — Metal vs. Non-Metal	36
E-1	Assumed Frequency Distributions for the Mean Lead Loading — Buildings E5616, E5617, E5625, and E5627.....	121
E-2	Assumed Frequency Distributions for the Mean Lead Loading — Buildings E5618, E5621, E5632, and E5633.....	122

Figures (Cont.)

E-3	Alternative Assumed Lead Loading Distributions for Building E5617	123
E-4	Integration Limits and Approximations.....	125
E-5	Value of ξ at which Cumulative Gamma Distribution Equals 0.9999995.....	128
E-6	Value of X at which Cumulative Student's t Distribution Equals 0.9999995.....	129

Tables

1	Pilot Plant Complex Buildings.....	3
2	Structural Definition Results Required for Lead Problem Evaluation.....	6
3	Codes Used for Paint Color and Substrate Type	8
4	Sample-Specific Information Recorded on Data Logsheets.....	17
5	Regression Parameters for Calibration Lines.....	20
6	Averages and Standard Deviations for Calibration Check Data.....	21
7	Distribution of Quality Control Check Values.....	22
8	Estimated Detection Limits for Measurement of Lead in Paint.....	22
9	Standard Deviation Regression Line Parameters.....	24
10	Lead Loading Distribution Data — Building E5625	31
11	Lead Loading Distribution Data — PPC Outbuildings	32
12	Substrate Data	37
13	Paint Color Data.....	38
14	Color/Substrate Correlation in Lead Loading Data.....	39
15	Stratum Definitions for Building E5625	41
16	Stratum Definitions for PPC Outbuildings	42
17	Unsampled Areas	43
18	Data Analysis Summary for Building E5616.....	44
19	Data Analysis Summary for Building E5617.....	44

Tables (Cont.)

20	Data Analysis Summary for Building E5618.....	45
21	Data Analysis Summary for Building E5621.....	45
22	Data Analysis Summary for Building E5625.....	46
23	Data Analysis Summary for Building E5627.....	47
24	Data Analysis Summary for Building E5632.....	47
25	Data Analysis Summary for Building E5633.....	48
26	Summary of Results	49
27	Stratification Performance	50
28	Relative Variances of A, L, and M.....	54
29	Hypothesis Testing Results — Linearization Approaches	55
30	Estimated Upper-Bound Probability of H_0 Being True	57
A-1	Lead K-Shell XRF Emission Calibration Data — Concrete Substrate Blank.....	63
A-2	Lead K-Shell XRF Emission Calibration Data — Steel Substrate Blank	64
A-3	Lead L-Shell XRF Emission Calibration Data — Concrete Substrate Blank.....	65
A-4	Lead L-Shell XRF Emission Calibration Data — Steel Substrate Blank.....	66
D-1	Results of Paint Chip Analyses for Building E5625	107
E-1	Three Lower Bounds to the Probability that $Q < 0$ for PPC Buildings	126

Acknowledgments

The authors would like to thank Victor Cohut for logistical support; Henry Cobo, Dave O'Reilly, and Marc Smits for providing the field XRF measurements; Marti Hahn for assistance in preparing the final XRF database; and Larry Shepard for developing the Health and Safety Plan for this investigation.

Notation

A	total painted surface area (in ft ²)
ANL	Argonne National Laboratory
APG	Aberdeen Proving Ground
DQO	data quality objective
EPA	U.S. Environmental Protection Agency
ft ²	square feet
g	gram
H ₀	null hypothesis
keV	kilo-electron-volt
L	mean lead loading for paint (in mg Pb/cm ²)
M	mass of rubble expected to be produced upon demolition
mc	millicurie
mg Pb/cm ²	milligrams of lead per square centimeter
NIST	National Institute of Standards and Technology
PPC	Pilot Plant Complex
QC	quality control
RCRA	Resource Conservation and Recovery Act
RSD	relative standard deviation
S	appropriate standard deviation
S ₀	standard deviation at zero lead concentration
S _{meas}	random error of measurement
TCLP	Toxicity Characteristic Leaching Procedure
XRF	x-ray fluorescence
yd ³	cubic yards

X-Ray Fluorescence Investigation of Surface Lead in the Pilot Plant Complex, Aberdeen Proving Ground, Maryland

by

K.L. Brubaker, H.J. O'Neill, J.E. Parks, J. Rueda,
J.F. Schneider, and R.E. Zimmerman

Abstract

This report presents the results and findings from a field measurement program undertaken in the Pilot Plant Complex (PPC) at Aberdeen Proving Ground, Maryland, to address the potential contamination of the PPC structures with lead in paint. A portable x-ray fluorescence device was used to measure the lead loading at approximately 1,000 locations on painted surfaces in the PPC buildings. The device performed well, although external calibration was necessary for accurate results. The principal conclusion is that the amount of lead present in all the buildings examined presents no regulatory waste disposal problems. The analysis showed that the estimated lead concentration in the amount of rubble expected from each building is far below the regulatory limit, even assuming that all the lead present would be leached during the test procedure (Toxicity Characteristic Leaching Procedure). The level of confidence for this conclusion exceeds 95%. The frequency distributions of the data were markedly skewed; the most probable values were quite low, but significant tails were detected. Evidence for at least three different sub-populations of lead loading values was found, and no simple curve is adequate to describe the observed distributions.

1 Introduction

1.1 Background

Demolition, in a controlled, safe, and environmentally acceptable manner, is planned for the buildings that make up the Pilot Plant Complex (PPC) at Aberdeen Proving Ground (APG) in Maryland. Argonne National Laboratory (ANL) has undertaken a program to address environmental issues arising from the planned demolition and to develop a scope of work for the demolition process. One issue that has arisen is the potential for contamination of the demolition rubble with hazardous substances and the implications of that possible contamination for the disposal of the rubble. One contaminant that may be present in significant amounts is lead, potentially present in the paints used to coat the interior and exterior of the buildings; paints were formerly manufactured using lead-containing substances. The primary regulatory question is

whether the amount of lead present in the expected building rubble exceeds the limit set by waste disposal regulations. This report presents the results and findings from a field measurement program undertaken in December 1994 to address the potential lead contamination issue.

The PPC currently comprises nine buildings. The Pilot Plant, Building E5625, is a four-story building constructed of a structural concrete and steel framework with walls constructed mostly of clay tile. The activities carried out in this building consisted primarily of pilot-plant-scale testing of production methods for chemical warfare agents and other substances. The remaining buildings, which are much smaller, provided support for the activities in Building E5625. Table 1 lists these buildings and summarizes their histories. The code letter shown in Table 1 is the letter assigned to each building during this study. Building E5626, the guardhouse, was not included in the sampling program described in this report. Figure 1 shows a current map of the complex.

1.2 Objectives

The objectives of the field study were (1) to estimate the average lead loading (mass of lead per unit surface area) in each of the eight PPC buildings that were examined and (2) to determine the distribution of the lead within each building. The estimated average lead loading was combined with estimates of the total painted area within each building and the mass of rubble that will be generated during the demolition of each building to calculate the lead concentration expected in the building rubble. This concentration was compared with regulatory disposal levels to determine whether disposal of the rubble would be restricted on the basis of its lead concentration. The lead distribution data were intended for use in designing a pre-demolition remediation program. Data quality objectives (DQOs) for these two general goals, developed on the basis of current U.S. Environmental Protection Agency (EPA) guidance (EPA 1993), are described in Section 3.1.

1.3 General Approach

ANL's approach to estimating the average lead loading in paint at the PPC buildings was to conduct a sampling program that involved measurement of the lead loading at randomly selected points in painted areas both inside and outside each building. A portable instrument that uses the principle of X-ray fluorescence (XRF) was used to obtain the lead loading measurements. The XRF measurements were calibrated by using standards obtained from the National Institute of Standards and Technology (NIST). Estimates of the painted surface area and mass of rubble for each building were prepared from detailed structural measurements made by the ANL team. The lead loading measurements were combined with the structural data to produce estimates of the total lead present in each building and to supply information required to conduct the statistical analysis.

The sampling study included the interior and exterior of eight buildings in the PPC. The population of interest was the set of all possible independent XRF sampling units or areas (each

TABLE 1 Pilot Plant Complex Buildings^a

Current Building Designation	Code Letter	Construction Date	Uses
E5616	A	1942	Change house Pipe-fitting supply room Public toilet
E5617	B	1942	Lime house Test equipment laboratory Pilot plant control building Dichloro process hydrogenation control room
E5618	C	1942	Experimental laboratory Pump house Compressed air house Plant neutralization system
E5621	D	1942	Air compressor building Workshop Machine shop Machine, pipe, carpenter shop Inert gas generator facility
E5625	E	1942	Gas compressor building Pilot plant Agent filling GA pilot plant Agent transfer facility Process laboratory Pilot plant — toxics
E5626	F	1983	Guardhouse
E5627	G	1942	Laboratory and office Laboratory First aid station Quality control laboratory
E5632	H	1970	Refrigerator building
E5633	I	1942	Cooling tower Flammable materials storehouse Drum storage

^a Source: Anderson and Kvitek (1995)

FIGURE 1 Current Pilot Plant Complex (Source: Anderson and Kvitek 1995)

approximately one square inch [1 in.²] in area). Each building was divided into strata for sampling and statistical analysis; each stratum consisted of one or more painted surfaces. Each stratum will be considered as a unit for possible remediation purposes.

2 Estimates of Structural Parameters

2.1 Methodology

The mass of rubble that may be generated during the proposed decommissioning of the PPC, and the areas of the painted surfaces were estimated for each of the buildings examined. These estimates were made on the basis of existing-condition surveys and materials inventories of each of the PPC buildings; the surveys were conducted as part individual structural definitions of each building. The structural definitions for each individual building are provided in reports currently in preparation.

Existing condition surveys, conducted for each of the PPC buildings during July and August 1994, included internal and external field measurements along with photographic records. Those field measurements and records were translated into individual building floor plan drawings and building material inventory summaries that were used to estimate the expected mass of rubble and the existing painted surface area for each of the buildings.

2.2 Summary of Results

Table 2 presents a summary of the estimated quantities of rubble and painted surface areas and the estimated in-situ material volumes for each of the buildings.

TABLE 2 Structural Definition Results Required for Lead Problem Evaluation

Building (Code)	In-Situ Material Volume (yd ³)	Material Weight (tons)	Total Painted Surface Area (ft ²)
E5616 (A)	355	692	16,106
E5617 (B)	70	141	3,481
E5618 (C)	111	219	1,412
E5621 (D)	125	238	1,478
E5625 (E)	3,448	6,764	117,352
E5627 (G)	394	758	17,842
E5632 (H)	69	132	834
E5633 (I)	43	88	751

2.3 Evaluation of Uncertainties

In order to carry out the appropriate statistical tests, ANL needed to develop values for the uncertainties, as well as the estimated values of the structural parameters. The uncertainty estimates described below are based on professional engineering judgment and experience.

ANL obtained in-situ measurements of the building materials at the PPC that were as accurate as possible. The predicted tolerance of the basic in-situ material measurements was estimated to be $\pm 10\%$.

In-situ material volumes were estimated on the basis of (1) the in-situ material measurements, (2) field observations, and (3) assumptions established on the basis of engineering practice and published data. The predicted tolerance of the material volume was estimated to be within 20%.

The weights of the building materials were estimated on the basis of in-situ measurements and published material densities, and vary according to specific material manufacturers for which no specific data were available. The uncertainty in the weight estimates was conservatively estimated at $\pm 20\%$.

The painted surface areas were estimated on the basis of the in-situ building material measurements, which included measurements of the length, width, and height of the painted surfaces (as applicable). Painted surface areas excluded unpainted areas larger than one square foot (1 ft^2) per wall. The uncertainty of the painted surface area in each building was conservatively estimated at $\pm 10\%$.

2.4 Paint Color and Substrate Codes

Table 3 shows the letter codes used in this study to designate particular paint colors and underlying substrate types on data logsheets and in databases and tables.

TABLE 3 Codes Used for Paint Color and Substrate Type

Paint Color	Color Code	Substrate Type	Substrate Code
Baby blue	BB	Brick	A
Bright white	BW	Cinder block	B
Cream	CR	Concrete (sealed)	C
Dark blue	DB	Concrete (unsealed)	D
Exterior wall white	EW	Clay tile	E
Gray cream	GC	Caulking/elastomer	F
Light gray	GL	Plaster	G
Green	GN	Steel (columns)	H
Gray	GY	Steel (beams)	I
Light blue	LB	Wood	J
Lime green	LG	Metal plates	K
No paint	NP	Fiberboard	L
Pinky cream	PC	Drywall	M
Pink	PK	Transite	N
White	WH	Steel doors/frames	O
Yellow	YL	Steel windows/frames	P

3 XRF Lead Loading Measurements

3.1 Data Quality Objectives

3.1.1 Objective Number One

Regulations based on the Resource Conservation and Recovery Act (RCRA, Public Law 94-580, as amended) govern the disposal of rubble in a landfill. These regulations require that the total leachable content of various toxic substances, including lead, be below specified levels. The total leachable content of a given substance is determined by conducting the Toxicity Characteristic Leaching Procedure (TCLP) (EPA 1986) on samples of debris and analyzing the leachate for that substance. A typical industrial lead paint loading is 13 mg/cm² (Dewalt 1994); if the average lead loading in PPC buildings was equal to this value and the lead was assumed to be totally leachable, the ratio of the total mass of leachable lead to the total mass of rubble would be significantly higher than that allowed by disposal regulations. Lead sampling and analysis were conducted to determine whether the total lead content in PPC buildings exceeds the levels allowed by RCRA regulations.

The results and findings of the sampling program were intended to support a decision to either (1) remediate the lead contamination or show that the lead would not cause a violation of regulations, or (2) to do nothing further. The latter decision would be made if analysis results revealed, with sufficient confidence, that the rubble could be disposed in compliance with applicable regulations regarding lead content. The required input to the decision (and its sources) included the following:

- The estimated average lead loading within each building, together with its estimated standard deviation (from the field sampling program);
- The estimated painted surface area within each building, together with its estimated standard deviation (from the field measurement program);
- An estimate of the total mass of rubble, together with its estimated standard deviation (from the building structural definition work); and
- The relevant regulatory threshold (from federal and Maryland regulations).

The State of Maryland requires a confidence level of at least 95% in decisions regarding regulatory compliance. This means that, if the true lead loading in a given building is above the regulatory limit, the statistical test procedure that is used should lead to the correct decision with at

least 95% confidence. In accordance with EPA guidelines (EPA 1993), a hypothesis testing approach was adopted in formulating this DQO. The hypothesis (H_0) to be tested is:

H_0 : The total lead content in each building studied is greater than the total mass of rubble generated from that building times 10^{-4}

This hypothesis, if correct, would lead to the most severe consequences if an incorrect decision were made. In other words, if the *actual* lead content is above the action level but, because of random or other errors, the *estimated* content turns out to be less than the action level, the consequences of an incorrect decision error are considered more severe than those associated with the alternative hypothesis — that the lead content is below the action level.

If this hypothesis is rejected at the 95% (or higher) confidence level, no further action will be taken regarding lead contamination in the subject building; otherwise, the lead will be remediated or further studies initiated to examine potential mitigating factors.

The factor 10^{-4} is derived from the TCLP procedure, described in the applicable regulations as follows:

- The minimum amount of sample = 100 grams (g);
- For a 100-g sample, the final leachate volume = 2 liters (L);
- The regulatory limit for lead in the leachate is 5 milligram per liter (mg/L); and
- The maximum concentration of leachable lead in the 100-g sample is:

$$\frac{(5 \text{ mg / L}) \cdot (2\text{L}) \cdot (1 \text{ g / 1,000 mg})}{100 \text{ g}} = 10^{-4} \text{ g(lead) / g(rubble) .} \quad (1)$$

It should be noted that, for statistical analysis and testing purposes, all of the lead present in each building is assumed to be leachable. The statistical procedures used for testing this hypothesis are presented, along with the results, in Section 4.4.

3.1.2 Objective Number Two

The distribution of lead in painted surfaces within the PPC buildings was not expected be uniform because of many factors: the painting schedule, when the building was in use, and the former presence of equipment that would not have been moved for painting. Knowledge of the distribution will be important in selecting a remediation option if remediation of the lead is

necessary. Sampling and analysis for lead were required to determine the lead distribution within the building.

The remediation decision that will be made, if necessary, on the basis of the sampling and analysis results for lead is expected to depend on the distribution of lead within each building. Input to this decision will include the following:

- The estimated total quantities of lead in individually designated areas (strata) within each building (from the field sampling program); and
- The estimated standard deviations of the lead content estimates (from the field sampling program).

Each of the designated strata were sampled, and the number of sampling points was chosen so that the mean lead loading within each stratum would be determined within $\pm 0.5 \text{ mg/cm}^2$ with 95% confidence.

3.2 Sampling Strategy

3.2.1 Overall Strategy

During the planning of the sampling effort, ANL expected that different areas within the study buildings would (in all likelihood) have different lead loadings because of differences in the number of times that each area was painted and in the paint used. ANL hoped that differences in paint color and in the underlying substrate could be used as indicators of differing lead levels. Because one of the project DQOs was to determine the distribution of lead within each building, all significant surfaces were to be sampled. Accordingly, a stratified random sampling approach (Cochran 1977) was identified as the most suitable method for estimating the overall mean lead loading within each building. This method was chosen because the alternative, a simple random sampling approach, might leave some strata unsampled.

In the stratified random sampling approach, the population to be sampled is divided into strata and each stratum is randomly sampled. The overall mean is then computed as a weighted average, with weights given (ideally) in terms of the relative sizes of each stratum. In this case, the weights are proportional to the painted surface areas of each stratum, and each stratum is a collection of one or more painted surfaces that are expected to be approximately homogeneous on the basis of paint color and substrate. The advantage of stratified sampling is that, by identifying homogeneous sub-areas, sampling each, and combining the results, the overall mean may (in principle) be determined with significantly greater precision for a given number of measurements compared with a simple random sampling approach. If only one stratum is used, as was the case

for Buildings E5618, E5621, E5632, and E5633, the approach is equivalent to the simple random sampling method.

3.2.2 Sampling Point Density

The overall sampling point density was determined on the basis of the requirement that the mean lead loading within each stratum be determined to within $\pm 0.5 \text{ mg/cm}^2$ with 95% confidence. Most walls in Building E5625 are divided into segments, each measuring 20 feet long and 13 feet high. The definitions of strata for analysis and possible remediation purposes originally incorporated this segmentation, except for certain situations (such as small foyers that separate laboratories from a central corridor). Based on industrial data, it was expected that the standard deviation of measured lead loadings using XRF techniques within a homogeneous area would be on the order of 0.2 mg/cm^2 ; this value is reasonably consistent with the findings of this study. In order to obtain an estimate of the mean lead loading within each stratum to within $\pm 0.5 \text{ mg/cm}^2$ with 95% confidence, a minimum of three samples were required. (With three samples, the expected standard error of the mean would be $0.2/\sqrt{3} = 0.1155 \text{ mg/cm}^2$. The critical value of Student's t for 95% confidence (two-tailed) and $3 - 1 = 2$ degrees of freedom is 4.303. The 95% confidence limit is therefore expected to be $\pm 0.1155 \times 4.303 = \pm 0.4970 \text{ mg/cm}^2$.)

The number of sampling points used in strata larger than the nominal 260-ft^2 area ($20 \text{ ft} \times 13 \text{ ft}$) was to be proportional to the surface area, using a sampling point density of three points per 260 square feet, or $1.15 \text{ points}/100 \text{ ft}^2$. In practice, data were taken at three randomly selected sampling points on a single randomly chosen wall and at one randomly selected point on each of the other walls in every room that contained walls constructed of similar materials and painted a similar color. On occasion, small adjacent rooms were combined for sampling purposes. At least three sampling points were used, even in strata smaller than the nominal 260 ft^2 . The same nominal point density was used in all the buildings examined. The primary exception to this design was the building exteriors where, for safety and efficiency, fewer points were sampled.

3.2.3 Sampling Point Locations

Each painted surface was approximately rectangular in shape. The spaces were interrupted by smaller areas, such as doors, windows, and pipe and vent holes, that were not included in the sampling effort. The XRF unit that was used views an area of approximately 5 cm^2 , so that the average diameter of the area viewed is approximately 1 in. The total rectangular area for each surface was divided into 1-in.-square cells, and the center of each was regarded as the potential location of an independent X-ray measurement. The required number of sampling locations within a given stratum was obtained by multiplying the number required per unit area, obtained as described above, by the area of the study surface. Each sampling location for a given stratum was selected from the total population of possible cell locations by randomly selecting a row and a column of cells; the cell at the intersection of the selected row and column was chosen for sampling. Prior to the measurement program, the required numbers of randomly selected locations

were marked on each surface to be sampled. Unsuitable locations were identified and dropped from consideration. Locations were excluded from the sampling effort because they fell within doorways, windows, or other openings in the surface, or because they fell within an unpainted area large enough to be accounted for in estimating the total painted surface area. An adequate number of extra random locations were selected to allow ANL to identify the required number.

3.3 Lead Loading Data Collection

3.3.1 Methodology

Theory of XRF Operation

A TN Technologies Spectrace Model 9292 Portable Lead Analyzer was used to make the lead loading measurements. This instrument operates on the principle of x-ray fluorescence. In the XRF process, samples are irradiated with gamma rays, which collide with K- and L-shell electrons of metal atoms, dislodging them from their orbits and leaving a hole in the inner electron shell. This hole is immediately filled by an outer-shell electron. This readjustment of the atomic electron distribution is accompanied by the emission of an x-ray. The energy of the emitted x-ray is characteristic of the specific metal, and the intensity of the x-rays emitted is proportional to the concentration of that metal. The unit of energy is the "keV" (kilo-electron-volt). X-ray energy is proportional to the frequency and inversely proportional to the wavelength of the x-rays. An x-ray of energy 12.4 keV has a wavelength of about 1 angstrom (1×10^{-8} cm).

The XRF energy spectrum can be used to identify metals present in the sample by looking for emission lines characteristic of each specific metal of concern. For example, lead produces L-emission lines at 10.5 and 12.6 keV and K-emission lines at 72.5, 74.5, and 84.8 keV. A sample that has emission lines at these energies contains lead. The quantity of lead is determined by comparing the intensity of these emissions to the emission intensity from a standard containing a known quantity of lead.

In the TN Spectrace Model 9292 lead analyzer, gamma rays are produced by a 30-millicurie (mc) ^{109}Cd source. The instrument measures the energy spectrum of the x-rays emitted by the sample using a mercuric iodide detector. This spectrum is recorded, evaluated, saved in memory by the instrument, and used to determine the relative concentration of lead. This spectrum also contains much qualitative information about the sample and allows the analyst to determine the nature of the sample matrix, whether the XRF is operating properly, and whether interferences are affecting the estimate of the element concentration. The estimated lead concentration can be read from the instrument display when the measurement is made. Results and spectra stored in the memory of the unit may be downloaded to a personal computer for archiving and additional analysis.

Procedures

The instrument was used in accordance with the manufacturer's recommendations, the standard operating procedure written for lead measurement, and the requirements of the APG-approved Sampling Plan.

The basic operating procedures followed each day during the sampling program were as follows:

- Instrument setup and internal checks: performed at the start of each sampling day and as the manufacturer recommended during the sampling day. These included the following:
 - Unpack and assemble the instrument, and turn the electronics "on";
 - Verify the time and date, and update these if incorrect;
 - Check the automatic results storage setting;
 - Check "display threshold" setting;
 - Select the "lead in paint" application;
 - Verify that the instrument is set for "real time;"
 - Perform the automated standard operating check;
 - Conduct the automated internal calibration procedure; and
 - Make any required adjustments.
- Quality control (QC) measurements (see Section 3.4 for description):
 - Perform measurements on the blank and high-value standards provided, and plot the results on the quality control charts (if one or more points are out of control, take the required corrective action); and
 - Perform selected duplicate measurements.

- Lead loading measurements:
 - Set the time of sample analysis;
 - Make the measurement (15 seconds per measurement);
 - Label and store the results electronically; and
 - Manually record the results on the data logsheets developed for lead measurements.

Field work for the structural definition phase of ANL's overall program for the PPC was carried out from May to October 1994. Data from this effort were used to prepare data logsheets used during the lead measurement field program to manually record measurements and other observations. Figure 2 shows a sample completed data logsheet. The lead loading field measurement program was initiated on December 12, and was completed on December 16, 1994.

The data were recorded in two ways: manually on the pre-prepared data logsheets and electronically by the Spectrace 9292 instrument. The logsheets contain location information (building, floor, and room), information regarding the structural survey, identification of the analyte of interest (lead), and general information about the lead measurements being made (date, time, sampling team members, logbook number, etc.). Table 4 describes the additional information available on the data logsheets for each specific measurement. The information source column indicates whether the information item was (1) determined during the structural survey and preprinted on the form, (2) entered on the form by the lead loading measurement team, or (3) taken from some other source. Also, the total painted surface area in the room, calculated on the basis of the structural survey data, is pre-printed at the bottom of the form in the box labeled "Total SAC (ft²)." Room numbers correspond with ANL's room numbering scheme.

3.3.2 Health and Safety

Field team members followed the APG-approved Health and Safety Plan at all times during the field program. Special safety considerations regarding radiation exposure are associated with the use of the portable XRF device. All manufacturer's recommendations and specified operating procedures were precisely followed by ANL measurement team members, all of whom had received special training provided by the manufacturer and had been certified as qualified by the manufacturer prior to the start of the field program.

DATA LOG WORKSHEET
Pilot Plant Complex
 Aberdeen Proving Ground, MD

Page 8 of 12Location **A - 1 - 08**Analyte **LEAD**

BLDG FLOOR ROOM
 Total Lead Content _____ (mg)

SURVEY Team VC/AD/JR
 Date 25 JULY 1994 Logbook _____
 Is surface painted? X YES NO (If NO, do not survey.)

Reviewed and Approved by: _____

Site Task Leader _____ Date _____

MONITOR Team D. O'Reilly, H. Cobo, M. Emken
 Date 13 DEC 1994 Logbook # 1
 Instrument 9292 Time 11:55

Sampling & Analysis Coordinator _____ Date _____

QA/QC Coordinator _____ Date _____

Survey Area Information								Monitoring Data		
Surface Number	Sample Number	Random Point ID	Substrate		SA _r (ft ²)	Less (ft ²)	SA _c (ft ²)	Instr Code	Monitoring Data (mg/cm ²) L/K	Substrate Lead Content (mg)
			Code	Color						
01	1	1	E	BB	282.0	0.0	282.0	134	-.004 .3	
01	2	2	E	BB	0.0	0.0	0.0	135	.023 .1	
01	3	3	E	BB	0.0	0.0	0.0	136	.022 .1	
02	1	1	E	BB	190.0	0.0	190.0	137	.012 .4	
03	1	1	E	BB	282.0	78.9	203.1	138	.43 1.1	
04	1	2	E	BB	190.0	55.6	134.4	139	.016 .08	
D-03	1	1	E	BB	0.0	0.0	0.0	140	.48 1.4	
B							0.0	141	-.007 -.1	
I							0.0	142	2.62 3.8	
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
							0.0			
COMMENTS D = Duplicate, B = Blank, I = Standard BB AND OTHERS IN THIS ROOM, CONSIDER AS ONE COLOR. COMBINE.								SUMMARY VALUES		
								Total SA _c (ft ²)	COV Lead Content (%)	Mean Lead Content (mg/cm ²)
								809.5		

FIGURE 2 Sample Lead Measurement Data Logsheet

TABLE 4 Sample-Specific Information Recorded on Data Logsheets

Information Item	Description	Pre-printed	Source
Surface number	Index specifying a particular surface in the room	Y	Structural survey
Sample number	Index labeling the sample number for a given surface	Y	Structural survey
Random point ID	Denotes the random location that was used	Y	List of random locations prepared for a given surface
Substrate code	Code designating the type of underlying substrate for a given surface	Y	Structural survey list of possible codes; see Table 3
Substrate color	Code designating the color of the paint on a given surface	Y	Structural survey list of possible codes; see Table 3
SA _T	Gross painted surface area (ft ²)	Y	Structural survey
Less	Painted area adjustments (ft ²)	Y	Structural survey
SA _C	Net painted surface area; equal to the gross area minus the adjustments (ft ²)	Y	Structural survey
Instrument code	Sequential sample ID number, unique to each measurement	N	Lead measurement team
Monitoring data (mg/cm ²)	L- and K-shell readings taken from the instrument immediately following each measurement	N	Lead measurement team

3.4 Quality Controls

A number of QC provisions were incorporated into this study to ensure that the resulting data would be of known and adequate quality. Although the Spectrace 9292 spectrometer had been factory calibrated prior to its shipment to ANL, and internal automated calibration checks were conducted regularly, an external calibration study was performed to provide a set of data to either confirm the factory and internal calibrations or correct the instrument readouts. Further, external calibration checks were run periodically during the study to ensure consistent instrument performance. Finally, data reproducibility and precision were evaluated by making duplicate measurements at a rate of at least one pair of duplicates for each room within the PPC.

3.4.1 Calibration Data

The accuracy of the data in this study was ensured by using calibration standards for lead in paint films; these standards, obtained from NIST, had the following certified lead content (in mg Pb/cm²): zero (<0.001), 0.29, 1.02, 1.63, and 3.53. A separate external calibration study was performed, in which each standard was placed against a substrate blank and a set of twenty readings was obtained. Calibration sets were obtained using both concrete and steel substrate blanks; both K- and L-shell XRF emission readings were recorded in all cases. The data obtained are presented in Appendix A.

Data from the calibration study were managed as follows. Means and standard deviations were calculated for each set of measurements made using the five calibration standards and two substrate blanks. Then, the five mean values for each substrate blank were subjected to a weighted linear regression against the NIST-certified lead values; the regression weights were inversely proportional to the variances (Draper and Smith 1966) associated with the data for each reference lead loading value. These mean values and the corresponding regression lines for the concrete and steel substrate blanks are shown in Figure 3. The regression line parameters, given in Table 5, show that the instrument readings were generally biased high by about 15% for either substrate. The table reveals an additional offset bias of about +0.2 mg Pb/cm² for metallic substrates, and an offset bias of about -0.04 mg Pb/cm² for non-metallic substrates. The steel and concrete offset biases are statistically significant at approximately the 99.1% and 97.8% confidence levels, respectively. The error bars shown in Figure 3 represent the standard deviation of each associated set of 20 measurements; the standard deviation of the mean of each set is smaller than the error bars shown by a factor of $1/\sqrt{20} \approx 0.2236$.

The raw lead K-shell emission data collected from paint overlying a metallic substrate (substrate codes H, I, K, O, and P) were corrected for calibration using the following equation:

$$\text{Corrected value (mg Pb/cm}^2\text{)} = (\text{raw value} - 0.18413)/1.15095 \quad (2)$$

Data collected from paint overlying all other substrates were corrected using the following equation:

$$\text{Corrected value (mg Pb/cm}^2\text{)} = (\text{raw value} + 0.04438)/1.14965 \quad (3)$$

The standard deviations from the calibration study were used in estimating detection limits, as described in Section 3.4.3, and in adjusting stratum variances to account for the effects of measurement error, as described in Section 4.3.

FIGURE 3 Calibration Lines

TABLE 5 Regression Parameters for Calibration Lines^a

Substrate	y-Intercept	Slope
Concrete	-0.04438±0.0289	1.14965±0.0266
Steel	0.18413±0.0802	1.15095±0.0519

^a Quoted uncertainties represent 95% confidence limits based on three degrees of freedom.

3.4.2 Calibration Checks and Control Charts

The performance of the lead analyzer during the study was monitored by using control charts on the basis of the instrument's K- and L-shell responses to the lead zero and high (3.53 mg Pb/cm²) calibration standards against the concrete substrate blank. These QC data were acquired by the ANL measurement team immediately after making the last set of measurements for each room in the PPC, and were immediately plotted onto the control charts. Thus, the ANL measurement team was able to promptly detect any degradation in performance that might have resulted from contamination of the instrument probe.

On December 12, 1994, prior to initiating the field study, the ANL measurement team set up the control charts. Sets of 20 measurements were made by using the concrete blank and both the lead zero and the lead high calibration standards; both K- and L-shell readings were made in all cases. Averages and standard deviations were calculated for each set. The control charts were set up using these parameters, which are given in Table 6. For the high calibration standard, a notable difference was observed between the variability of the K-shell readings, for which the relative standard deviation (RSD) was 14%, and the L-shell readings, for which the RSD was only 1.9%.

This observation is consistent with the manufacturer's remarks in the instrument operating manual regarding the relative precision obtainable with the K- and L-shell readings. In this study, only the K-shell data were used in the analysis, for reasons discussed in Section 4.1.2.

During the study, 88 sets of calibration check data were obtained and plotted. Averages and standard deviations of these values are also given in Table 6. The table reveals no significant difference between the performance of the instrument prior to and during the study.

In general, the instrument performance during the study, as reflected by the control charts, appeared to be normal in all regards. There was no evidence of the measurement system being out of control at any point. Readings fluctuated normally around the averages, with only a few readings more than two standard deviations from the mean. The distributions of QC values for

TABLE 6 Averages and Standard Deviations for Calibration Check Data

Data Acquired for Setting Up Control Charts prior to Field Measurement

	Zero Standard		High Standard	
	K-Shell	L-Shell	K-Shell	L-Shell
Number	20	20	20	20
Average	-0.0303	-0.00625	3.76	2.62
Standard deviation	0.105	0.00425	0.525	0.049
Relative standard deviation	-	-	14.0%	1.9%

Data Acquired during Field Measurement Program

	Zero Standard		High Standard	
	K-Shell	L-Shell	K-Shell	L-Shell
Number	88	88	88	88
Average	-0.0451	-0.00455	3.90	2.59
Standard deviation	0.111	0.00392	0.548	0.099
Relative standard deviation	-	-	14.1%	3.8%

each measured parameter are shown in Table 7. If the frequency distribution is Gaussian, approximately 5% of the values are expected to fall outside the $\pm 2S$ range, where S denotes the appropriate standard deviation. Although an abnormal number of L-shell values seemed to fall below the $-2S$ limit when using the high calibration standard, these were randomly distributed throughout the study and apparently did not indicate that the measurement system was out of control.

3.4.3 Detection Limits

The detection limits for lead in paint using the Spectrace 9292 instrument were estimated from the data generated in the calibration study described in Section 3.4.1. A standard deviation was calculated for each set of twenty measurements made with the five calibration standards and the concrete and steel substrate blanks. These standard deviations, which represent the random error of measurement (S_{meas}), were used in making two separate estimates of the detection limits. Both estimating methods gave virtually identical results for each substrate, although the detection limit using the concrete blank was slightly lower than that found using the steel blank. Results are summarized in Table 8.

The SW-846 method (EPA 1986) defines the detection limit as the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte

TABLE 7 Distribution of Quality Control Check Values

Range	K-Blank	L-Blank	K-High Calibration	L-High Calibration
> 3S ^a	1	1	0	0
2S to 3S	3	2	1	0
1S to 2S	6	22	22	8
0 to 1S	31	38	35	28
-1S to 0	33	22	24	31
-2S to -1S	12	3	5	11
-3S to -2S	1	0	0	5
< -3S	1	0	1	5
Percent outside $\pm 2S$	6.8%	3.4%	2.3%	11.4%

^a S denotes appropriate standard deviation.

TABLE 8 Estimated Detection Limits for Measurement of Lead in Paint^a

Estimation Method	Concrete (mg Pb/cm ²)	Steel (mg Pb/cm ²)
Extrapolation	0.256	0.360
SW-846 definition ^b	0.256	0.392

^a Based on the use of the Spectrace 9292 Lead Analyzer, K-shell emissions only.

^b From EPA 1986.

concentration is greater than zero. Each SW-846 detection limit was calculated by multiplying the one-tailed Student's t statistic for the 99% confidence level and nineteen degrees of freedom ($t = 2.54$) by the standard deviation obtained by using the 0.29 mg Pb/cm² standard.

In the extrapolation method (American Chemical Society 1983), the standard deviation is plotted against the reference lead levels and extrapolated to zero in order to estimate S_0 , the standard deviation at zero lead concentration. The detection limit then equals three times the value of S_0 obtained. For this study, a linear regression was performed on the five standard deviations obtained with each substrate blank against the corresponding lead levels in the standards; the resulting regression lines are shown in Figure 4. Table 9 presents the regression line parameter values.

FIGURE 4 Variation of K-Shell XRF Standard Deviation with Lead Loading

TABLE 9 Standard Deviation Regression Line
Parameters^a

Parameter ^b	Concrete	Steel
Slope	0.03356 $\pm$ 0.0143	0.01300 $\pm$ 0.0078
Intercept	0.08536 $\pm$ 0.0180	0.13056 $\pm$ 0.0098

^a Quoted uncertainties represent 95% confidence limits based on three degrees of freedom.

^b The intercept has the same units as the standard deviation (mg Pb/cm²). The slope is dimensionless.

3.4.4 Duplicate Measurements

The ANL measurement team made at least one pair of duplicate measurements in each room of the PPC, resulting in 104 pairs of duplicate data. Making a duplicate measurement required the operators to return the probe to the sampling point, so these measurements may contain an additional random error associated with slight inaccuracies in locating the probe. Three of the duplicate pairs were measured on painted steel substrates; the balance of the measurements were taken on the various non-metallic substrates that make up the buildings. A scatterplot of the duplicate data is shown in Figure 5. The slope and intercept of the fitted line, 1.0369 and 0.00919, are not statistically different from one and zero, respectively.

The duplicate differences (first value minus second value) for the study are shown in sequential order in Figure 6(A). The horizontal line shows the position of the mean value; the mean of the 104 values is -0.0382 mg Pb/cm² and the standard deviation is 0.4578 mg Pb/cm². Note that the standard deviation is dominated by a few large values. Figure 6(B) shows the frequency distribution of the differences, along with a Gaussian curve computed from the above values for the mean and standard deviation. The fit is visually poor, and the distribution fails the D'Agostino test for normality by a substantial margin (Gilbert 1987). The test statistic value is -32.1 , compared with the 0.5% and 1% critical values (for 100 points) of -3.58 and -3.15 , respectively. For 63 of the 104 pairs, the average value of the pair was less than 0.25 mg Pb/cm², the approximate detection limit.

The duplicate data provide an independent check on the variability of the measurements. As discussed above, the calibration data show, among other things, that the standard deviation of lead loading measurements increases with lead loading. Such an increase is expected in the duplicate data as well. To test this possibility and to check for the presence of any additional source of random error, the duplicate data were collected into six classes on the basis of the average values of the two measurements in each pair. Each pair may be characterized by the average value and the

FIGURE 5 Duplicate Data Scatterplot

difference between the two values. The average and standard deviation of the differences in each class were computed. The six class standard deviations were then regressed against the six class average lead loading values. In order to compare the results with those shown in Figure 4, the standard deviations, and hence the slope and intercept, were reduced by a factor of $1/\sqrt{2} \approx 0.7071$ because they measure the variability of differences of two measurements rather than the variability inherent in one measurement. When this was done, the 95% confidence limits on the slope and intercept were $(-0.00051 \text{ and } 0.23)$ and $(-0.13 \text{ and } 0.57)$, respectively. The slope and intercept are not statistically different from the values shown in Figure 4, and no evidence exists for any additional source of error in the measurements, such as re-positioning errors.

FIGURE 6 Duplicate Difference Summary Figures

4 Data Reduction and Analysis

4.1 XRF Data Validation

4.1.1 Data Comparison and Adjustment

Reduction of the XRF data from the PPC was carried out in several steps. The lead loading measurements were transferred manually from the original completed logsheets into a database that also contained the remainder of the information that had been pre-printed on the logsheets. The lead data were also downloaded electronically into a similar database. A comparison was made between the two databases and the few discrepancies were resolved. The calibration data were processed as described in Section 3.4.1, and the raw K-shell data were corrected using the calibration equations [Equations (2) and (3) in Section 3.4.1]. A database containing the adjusted data and the remainder of the information contained on the logsheets was then prepared for use in the data analysis phase. This database is reproduced in Appendix B. The XRF spectra associated with selected measurements were also examined, as described in the following section.

4.1.2 XRF Spectra for Selected Samples

Results

Thirty-five selected spectra were examined to evaluate the XRF instrument's performance and to determine whether paint type or substrate surface affected the estimated lead values. As discussed in Section 3.4.1, a set of standards was obtained from NIST to provide a basis for external calibration of the instrument (in addition to the internal calibration completed at the factory by Spectrace). Figure 7 shows the spectrum from the highest standard paint sample used, which had a certified value of 3.53 mg Pb/cm². The large, broad peak on the right side of the spectrum, ranging from approximately 60 to 74 keV, is caused by Compton backscatter, the process whereby a single, high-energy gamma ray produces x-rays and other gamma rays of lower energy by interacting with the materials in the sample. The backscattering power of the sample is directly proportional to the density of the electrons in the sample.

The sharp emission lines on the left side of the spectrum (10.5 and 12.6 keV) are the lead L-shell lines. The lead K-shell lines are on the right side of the spectrum at 72.5, 74.5, and 84.8 keV. Although the K lines are not as well resolved as the L lines, the K lines are used for quantitation of lead in paint because they more accurately measure the lead in multiple layers of paint; the L lines can measure the lead present only in the surface layer. This effect is caused by the

FIGURE 7 XRF Spectrum 1

significant re-absorption of L-shell x-rays within the sample, and the absence of any significant re-absorption of the K-shell x-rays. Thus, the K-shell emissions can penetrate back through the paint to reach the detector, while the L-shell emissions are attenuated by an unknown amount. The four peaks in the region of 20 to 26 keV are source scatter, which is an artifact of the instrument. Barium lines are also present in the standard at 31.2 keV.

Figure 8 is the spectrum of the standard sample obtained from NIST that contained no lead. Figure 9 is the spectrum of the highest lead measurement taken during the PPC study. Here, the K-emission lines are more visible than in the NIST standard (Figure 7). Emissions from zinc and barium are also present.

Conclusions

An examination of 35 selected spectra showed that the instrument was working properly during collection of the data. Other elements (mainly barium and zinc) could be identified in some of the spectra. Generally, no interferences that would affect the results were observed. The Compton backscatter was similar for all spectra except those from paint on metal, where the intensity of the backscatter was less (40 to 50 counts compared with 80 to 90 counts) and the shape of the peak was somewhat flattened. These differences may produce a high bias in the estimate of lead in the paint on metal surfaces, as was observed during the external calibration.

866 XRF Spectrum: NIST Standard for Paint on Concrete

FIGURE 8 XRF Spectrum 2

890 XRF Spectrum: Gray Paint on Clay Tile

FIGURE 9 XRF Spectrum 3

4.2 Data Description and Summary Statistics

The frequency distribution of the calibrated lead loading measurements collected during the study is presented in Tables 10 and 11, and is shown graphically in Figure 10. Table 10 presents the data for Building E5625, and Table 11 presents the combined data for the rest of the PPC buildings (here collectively called the outbuildings). In these tables, the two columns headed by "Range" give the lower and upper limits of each incremental range; the columns marked "Count" give the number of calibrated lead loading values that fell within the given increment; and the columns marked "Average" and "Standard Deviation" give the mean and standard deviation of those values falling within the given increment. The data are segregated according to general substrate type: metallic or non-metallic. No metallic substrates were present in the PPC outbuildings. A total of 507 calibrated lead loading values are available for Building E5625, and 226 values are available for the outbuildings. Of the 507 values for Building E5625, 418 were taken from non-metallic underlying substrates, and 89 from metallic substrates.

These distributions demonstrate several interesting features. All distributions shown are markedly skewed, with the most probable values being quite low but with significant tails at higher values. For Building E5625, 373 out of 507 values (73.6%) are less than or equal to 0.25 mg Pb/cm², the approximate detection limit of the method for non-metallic substrates. For the outbuildings, 156 values out of 226 (69.0%) are less than or equal to 0.25 mg Pb/cm².

There is a very marked difference in the distribution of values measured on metallic substrates compared with the distribution for non-metallic substrates. The metallic substrate data show a much higher relative frequency of "high" values (although "high" is a relative term); the highest values obtained in this study are still significantly below typical values in industrial and other settings. The numbers of values above 3 mg Pb/cm² are 9 out of 89 (10.1 %) for metallic substrates, but only 6 out of 644 (0.93%) for non-metallic substrates (here the non-metallic substrate data from the outbuildings have been combined with those for Building E5625). The numbers of values above 2 mg Pb/cm² are 17 out of 89 (19.1%) for metallic substrates and 19 out of 644 (3.0%) for non-metallic substrates.

As indicated earlier, ANL initially expected that the lead loading might be significantly different in different areas; evidence for this would be the presence of more than one maximum in the frequency distribution of the data. There are hints in the distribution data that this might be the case, although the evidence is not dramatic. The evidence is much more visible in the distributions of the logarithms of the data. Figures 11 and 12 show the frequency distributions for the logarithms of the data divided into exterior and interior data categories. Figure 13 shows the frequency distributions of the logarithms of three classes of data: Building E5625 metallic substrate data; Building E5625 non-metallic substrate data; and outbuilding data. Only those data with natural logarithms greater than -1.5 are shown in Figure 13. This value corresponds to a lead loading value of 0.22 mg Pb/cm², approximately equal to the detection limit for non-metallic substrates. The data shown in Figures 11, 12, and 13 have been smoothed by replacing each count by the average of itself and the two values in adjacent increments. This was done to eliminate

TABLE 10 Lead Loading Distribution Data — Building E5625

Range (mg Pb/cm ²)		Metallic Substrates			Non-Metallic Substrates		
Low	High	Count	Average (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)	Count	Average (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)
-∞ ^a	0.00	11	-0.18	0.078	72	-0.07	0.056
0.00	0.25	24	0.09	0.062	266	0.11	0.064
0.25	0.50	8	0.31	0.065	47	0.34	0.062
0.50	0.75	5	0.59	0.078	2	0.65	0.123
0.75	1.00	8	0.85	0.065	2	0.95	0.062
1.00	1.25	5	1.09	0.048	0		
1.25	1.50	5	1.37	0.048	2	1.39	0.062
1.50	1.75	1	1.66		1	1.60	
1.75	2.00	5	1.87	0.078	9	1.87	0.081
2.00	2.25	0			4	2.13	0.071
2.25	2.50	2	2.32	0.061	6	2.39	0.000
2.50	2.75	4	2.60	0.083	1	2.56	
2.75	3.00	2	2.88	0.123	2	2.91	0.123
3.00	3.25	3	3.17	0.100	1	3.08	
3.25	3.50	2	3.40	0.123	1	3.43	
3.50	3.75	2	3.66	0.000	0		
3.75	4.00	0			0		
4.00	4.25	0			0		
4.25	4.50	1	4.27		0		
4.50	4.75	0			0		
4.75	5.00	1	4.88		0		
5.00	5.25	0			0		
5.25	5.50	0			0		
5.50	5.75	0			1	5.61	
5.75	6.00	0			0		
6.00	6.25	0			1	6.21	
6.25	∞	0			0		

^a The range -∞ to 0.00 includes all values less than or equal to zero; the range 6.25 to ∞ includes all values greater than 6.25.

TABLE 11 Lead Loading Distribution Data — PPC
Outbuildings

Range (mg Pb/cm ²)		Non-Metallic Substrates		
		Count	Average	Standard
Low	High		(mg Pb/cm ²)	Deviation (mg Pb/cm ²)
— ∞ ^a	0.00	31	-0.06	0.047
0.00	0.25	125	0.11	0.062
0.25	0.50	48	0.35	0.065
0.50	0.75	0		
0.75	1.00	9	0.90	0.081
1.00	1.25	3	1.14	0.050
1.25	1.50	4	1.34	0.100
1.50	1.75	4	1.54	0.043
1.75	2.00	0		
2.00	2.25	0		
2.25	2.50	0		
2.50	2.75	0		
2.75	3.00	0		
3.00	3.25	0		
3.25	3.50	1	3.34	
3.50	3.75	0		
3.75	4.00	0		
4.00	4.25	1	4.21	
4.25	∞	0		

^a The range — ∞ to 0.00 includes all values less than or equal to zero; the range 4.25 to ∞ includes all values greater than 4.25.

spurious spiking caused by numerical incompatibilities between the size of the intervals chosen and the resolution of the numerical values, which were recorded generally only to two significant figures.

If the data were lognormally distributed, these plots should show the typical symmetric “bell-shaped” curve of a normal distribution. Although several of the plots do show a peak somewhere near the middle of the range, the peaks are too narrow and the tails too significant for the distributions to be truly lognormal. Note that “central” peaks are only obtained if all the data are plotted, including those that are below the detection limit. There are also strong indications of several subpopulations in these data. The data shown on Figure 13(A), Building E5625 Metallic Substrates, seem to be very approximately lognormal if one ignores the data with logarithms of less than -1.0, which corresponds to a loading of 0.37 mg Pb/cm², approximately equal to the

FIGURE 10 Frequency Distribution of Building E5625 Data by Substrate, and of Combined Outbuilding Data

FIGURE 11 Lognormal Distributions — Exterior and Interior of Building E5625

FIGURE 12 Lognormal Distributions — Exterior and Interior of PPC Outbuildings

FIGURE 13 Lognormal Distributions — Metal vs. Non-Metal

detection limit for metallic substrates. The other plots seem to be generated by heterogeneous subpopulations of lead loading values, presumably corresponding to areas with different numbers of paint layers or different types of paint. It seems plausible, for example, that paints designed for use on different substrates may differ significantly in composition. Figure 11(B) shows a distinct peak at a value of about 0.75, corresponding to a lead loading of about 2.1 mg Pb/cm²; this same peak shows up very clearly in Figure 13(B). Figure 13(A) also shows that the paint on metallic substrates corresponds to a population with a peak at about 0.5, corresponding to a lead loading of 1.6 mg Pb/cm², and that this population is distinct from the one that causes the peak at 2.1 mg Pb/cm². Finally, the remaining data correspond to a third population of very small lead loadings.

Table 12 presents the distribution of measurements over the different substrate types encountered. Shown in the table are the number of measurements made for each substrate type in Building E5625 and in the outbuildings (combined) and the average and standard deviation of the lead loading measurements (in mg Pb/cm²) made for that substrate. The substrates with the highest readings were I and K, both metallic substrates. This confirms the earlier observation that higher lead levels are associated with the metallic substrates. No substrate code was available for 8 of the 733 measurements taken.

TABLE 12 Substrate Data

Substrate Code	Building E5625			PPC Outbuildings		
	Count	Average Loading (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)	Count	Average Loading (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)
A	77	0.16	0.273	1	0.21	
B	107	0.19	0.632	15	0.13	0.125
C	3	0.27	0.138	0	-	-
D	0	-	-	0	-	-
E	124	0.15	0.542	188	0.29	0.505
F	0	-	-	0	-	-
G	96	0.60	0.939	0	-	-
H	0	-	-	0	-	-
I	69	0.69	1.068	0	-	-
J	0	-	-	0	-	-
K	20	2.09	1.120	0	-	-
L	5	0.02	0.046	0	-	-
M	0	-	-	12	0.14	0.123
N	0	-	-	8	0.04	0.117
O	0	-	-	0	-	-
P	0	-	-	0	-	-
Not Specified	6	0.59	0.972	2	0.13	0.246
TOTAL	507			226		

Table 13 presents the distribution of measurements over the different colors of paint encountered. It appears that, in Building E5625, cream, gray-cream, and light gray paints are associated with high lead levels, but this is deceiving. Notice that, in these cases, the standard deviations are unusually high; this indicates a high degree of variability. A total of 17 out of 733 measurements had no paint color associated with them. These 17 measurements did not correspond to non-painted areas, however.

Table 14 presents the distribution of measurements over both substrate type and paint color. If no measurements were made for a particular color/substrate combination, the table entry is left blank. If one or more measurements are available, the number of measurements is given in parentheses and the average lead loading associated with those measurements is also presented.

The association of relatively high lead readings with metallic substrates is confirmed, although the association is not totally consistent. Substrate K (metal plates) is always associated with high readings, but the readings for substrate I (steel beams) were sometimes high and sometimes low. In any given room, the levels were either high or low, however. Similar erratic findings are associated with readings for substrate G (plaster), a non-metallic medium. Wire-mesh backing for the plaster was observed in at least one room, but it is not clear that higher lead

TABLE 13 Paint Color Data

Color Code	Building E5625			PPC Outbuildings		
	Count	Average Loading (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)	Count	Average Loading (mg Pb/cm ²)	Standard Deviation (mg Pb/cm ²)
BB	37	0.06	0.121	90	0.42	0.675
BW	12	0.71	1.070	0		
CR	38	1.01	1.343	50	0.20	0.155
DB	0	-	-	8	0.47	0.487
EW	0	-	-	22	0.08	0.106
GC	24	1.18	1.222	0	-	-
GL	8	1.59	1.314	0	-	-
GN	29	0.21	0.502	0	-	-
GY	115	0.33	0.677	0	-	-
LB	8	0.07	0.079	0	-	-
LG	0	-	-	12	0.10	0.137
PC	0	-	-	16	0.17	0.120
PK	0	-	-	8	0.11	0.148
WH	182	0.29	0.660	18	0.08	0.127
YL	39	0.26	0.992	0	-	-
Not Spec.	15	0.30	0.644	2	0.13	0.246
TOTALS	507			226		

TABLE 14 Color/Substrate Correlation in Lead Loading Data

(A) Building E5625									
Color Code	Substrate Code								
	A	B	C	E	G	I	K	L	Not Specified
BB		(17) 0.022		(3) 0.137		(17) 0.081			
BW	(3) 0.358	(6) 0.146		0	(3) 2.184				
CR		(3) 0.128		(6) 0.053	(12) 0.667	(9) 0.895	(8) 2.696		
GC	(4) 0.687	(3) 0.157		(4) 0.093	(5) 2.196	(8) 1.708			
GL							(8) 1.591		
GN	(4) -0.003	0		(5) 0.138	(20) 0.264				
GY	(23) 0.107	(36) 0.185		(20) 0.375	(14) 0.088	(18) 0.723	(4) 1.860		
LB				(3) 0.146				(5) 0.023	
WH	(34) 0.132	(26) 0.121		(80) 0.110	(37) 0.677	(5) 2.342			
YL	(6) 0.162	(16) 0.530		(3) 0.050	(3) 0.152	(11) 0.000			
Not Specified	(3) 0.099		(3) 0.268		(2) 0.080	(1) -0.247			(6) 0.592

(B) Pilot Plant Complex Outbuildings									
Color Code	Substrate Code								
	A	B	E	M	N	Not Specified			
BB			(85) 0.436	(5) 0.145					
CR		(3) 0.300	(40) 0.200	(7) 0.142					
DB			(8) 0.475						
EW		(6) 0.043	(16) 0.095						
LG			(7) 0.155		(5) 0.032				
PC	(1) 0.213	(6) 0.121	(9) 0.197						
PK			(5) 0.134		(3) 0.062				
WH			(18) 0.075						
Not Specified						(2) 0.126			

readings should be associated with the use of wire mesh. High readings are also not consistently associated with any paint color, according to the data in Table 13. It seems clear that substrate and paint color are of only limited usefulness in locating areas of high lead content. Of course, only the color of the last coat of paint applied is visible. The higher lead readings are likely associated with paint layers that cannot be observed without using intrusive procedures.

4.3 Data Analysis

4.3.1 Definition of Strata

As indicated earlier, a stratified random sampling approach was used as the sampling strategy for XRF measurements of the lead loading. ANL hoped that suitable strata could be identified using paint color and substrate as determining factors. As the discussion above indicates, however, with the exception that higher lead loadings tend to be associated with metallic substrates, there is very little correlation between these variables and the XRF-based lead loadings. Sufficient measurements were taken to allow reasonable strata to be defined after the fact. For the final analysis, strata were somewhat arbitrarily defined as rooms or collections of rooms in which the XRF data distribution seemed similar, based on a visual examination of the data. The degree of success achieved by stratification is discussed in Section 4.3.2. Table 15 presents the definitions used for Building E5625, and Table 16 presents the stratum definitions for the outbuildings. The Building E5625 strata corresponding to mostly metallic substrates are also indicated in Table 15. Room numbering follows ANL's conventions. For example, E-1-15 denotes room number 15 on the first floor of Building E (E5625).

All rooms in Buildings E5616, E5617, and E5627 were sampled. The interiors of Buildings E5618, E5621, E5632, and E5633 are unpainted and were not sampled. Certain rooms in Building E5625 were not sampled because of a physical hazard, lack of access, or because they are unpainted. A total of 5,363 square feet of painted area in Building E5625 was not sampled because of a hazard or lack of access, and was not included in any stratum for that building. Approximately 89% of the planned samples were collected for Building E5625; 100% of the planned samples were collected in all other buildings. The ceilings and floors in the buildings were not sampled. Table 17 summarizes the unsampled areas and compares the unsampled and sampled areas for each building.

4.3.2 Analysis

Tables 18 through 25 summarize the results of the analysis of the XRF lead loading data for the PPC buildings. For each stratum in each building, the following information is given: the number of XRF measurements used; the stratum average lead loading (in mg Pb/cm²); the variance of the stratum average (the stratum sample variance divided by the number of

TABLE 15 Stratum Definitions for Building E5625

Stratum	Rooms or Other Description
1	Rooms E-1-03 and -04
2	Rooms E-1-07, -08, and -10
3	Rooms E-1-11, -12, and -13 (all substrate K)
4	Rooms E-1-15, -16, and -17 (mostly substrate K)
5	Room E-1-18
6	Room E-1-21
7	Rooms E-1-23 and -24
8	Room E-1-26
9	Rooms E-1-27 and -28
10	Rooms E-1-29 and -30
11	Rooms E-1-31 and -32
12	Rooms E-2-03 and -04
13	Rooms E-2-07 and -08
14	Rooms E-2-11, -12, -13, -14, -15, and -16 (mostly substrate I)
15	Rooms E-2-19, -20, and -21
16	Rooms E-3-03, -04, and -05
17	Rooms E-3-07, -08, -09, -10, and -11
18	Room E-3-14
19	Rooms E-3-17, -18, and -19 (mostly substrate I)
20	Rooms E-3-20 and -21
21	Rooms E-4-03, -04, and -05
22	Rooms E-4-07, -08, and -09
23	Room E-4-12
24	Rooms E-4-15, -16, -17, and -18
25	Building exterior — north face
26	Building exterior — east face
27	Building exterior — south face
28	Building exterior — west face

measurements); the total painted area in the stratum that was subject to random sampling (in ft^2); the contribution of the stratum to the overall building average lead loading; and the contribution of the stratum to the variance of the overall building average. The "Totals" line at the bottom for each building gives the total number of values used, the total painted area in the strata for the building, the overall building average lead loading (in mg Pb/cm^2), and the variance of the overall average loading. All quantities were computed using the stratified random sampling formulas in Cochran (1977), Chapters 5 and 5A. These formulas are reproduced in Appendix C.

The tables also show the values of two corrections to the variance of the mean. The first is a correction for measurement error; this correction is based on the regression equations given in Section 3.4.3 for the standard deviations of XRF measurements as functions of lead loading. The

TABLE 16 Stratum Definitions for PPC Outbuildings

Building (Code)	Stratum	Rooms or Other Description
E5616 (A)	1	Building exterior
	2	Rooms A-1-01, -02, -03, -04, and -05
	3	Rooms A-1-06, -07, -08, and -09
	4	Room A-1-10
	5	Room A-1-11
	6	Room A-1-12
E5617 (B)	1	Building exterior
	2	Building interior
E5618 (C)	1	Building exterior
E5621 (D)	1	Building exterior
E5627 (G)	1	Rooms G-1-01, -02, -03, -04, -05, -06, and -07
	2	Rooms G-1-08, -09, -10, -11, -12, -13, -14, and -15
	3	Room G-1-16
	4	Rooms G-1-17, -18, -19, and -20
	5	Building exterior
E5632 (H)	1	Building exterior
E5633 (I)	1	Building exterior

variance of the mean given in the "Totals" row contains one component for the variability of the lead loadings being measured and one for the variability of the XRF instrument reading for the given loadings. The data from Section 3.4.3 can be used to subtract the estimated contribution of instrument variability; the formula used for this purpose is given in Appendix C, and the "correction for measurement error" provides the value found. This correction was only applied for Buildings E5616, E5625, and E5627 because enough measurements were available only for these three buildings for the variance of the mean to be stable enough to make this correction. In other cases, the variance of the mean is subject to sufficient error that this correction, if made, would yield nonsensical or unreasonable results. In the tables, this correction is given in parentheses if it was not actually applied.

The second correction arises from uncertainties in the painted areas associated with each stratum. Because the weights used in computing the overall building average lead loading are proportional to these areas, errors in these values result in errors in the weights used. If these errors have a mean of zero, as assumed here, the computed mean lead loading is not affected, but the variance of the mean is increased because of this additional source of variability. The formula used to compute this correction is given in Appendix C. This correction is zero if only one stratum is used, as was the case for Buildings E5618, E5621, E5632, and E5633. The correction was not applied for Building E5617 for the same reason that the measurement error correction was not applied there.

TABLE 17 Unsamped Areas

Building (Code)	Location/ Reason	Unsamped Area (ft ²)	Total Sampled Area (ft ²)	Unsamped Area (percent)
E5616 (A)	Ceiling	4,753.0	11,352.8	29.5
E5617 (B)	Ceiling	592.1	0.0	
	Floor	592.1	0.0	
	Total	1,184.2	2,296.9	34.0
E5618 (C)	None	0.0	1,411.8	0.0
E5621 (D)	None	0.0	1,477.6	0.0
E5625 (E)	Exterior	0.0	28,145.2	
First floor	Ceiling	8,800.1	0.0	
	Floor	711.5	0.0	
	Hazard	617.6	-	
	No access	1,543.2	-	
	Total	11,672.4	18,122.4	
Second floor	Ceiling	9,121.4	0.0	
	Floor	0.0	0.0	
	Hazard	694.6	-	
	No access	0.0	-	
	Total	9,816.0	11,114.5	
Third floor	Ceiling	6,777.8	0.0	
	Floor	0.0	0.0	
	Hazard	780.4	-	
	No access	243.8	-	
	Total	7,802.0	11,241.1	
Fourth floor	Ceiling	6,777.8	0.0	
	Floor	0.0	0.0	
	Hazard	0.0	-	
	No access	1,483.1	-	
	Total	8,260.9	11,177.8	
	Grand total	37,551.3	79,801.0	32.0
E5627 (G)	Ceiling	4,188.4	0.0	
	Floor	0.0	0.0	
	Total	4,188.4	13,654.0	23.5
E5632 (H)	None	0.0	834.0	0.0
E5633 (I)	Ceiling	247.0	0.0	
	Floor	0.0	0.0	
	Total	247.0	504.4	32.9

TABLE 18 Data Analysis Summary for Building E5616

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	-0.0049	0.0213	2,641.7	-1.138E-03	1.925E-04
2	25	0.1487	0.0292	2,673.7	3.503E-02	6.473E-05
3	22	0.1985	0.1279	4,011.9	7.016E-02	7.258E-04
4	9	1.2003	1.6917	1,202.6	1.272E-01	2.109E-03
5	8	1.0938	1.0135	416.4	4.012E-02	1.704E-04
6	4	1.1911	0.1129	406.5	4.265E-02	3.617E-05
Totals	73			11,352.8	3.140E-01	3.299E-03
Correction for measurement error						-1.622E-04
Correction for uncertainties						2.581E-05
Total painted surface area sampled (ft ²)						11,352.8
Estimated mean lead loading (mg Pb/cm ²)						0.3140
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0562

TABLE 19 Data Analysis Summary for Building E5617

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	0.1067	0.0124	1,216.2	5.652E-02	5.8038E-04
2	6	0.0598	0.0028	1,080.7	2.812E-02	1.0309E-04
Totals	12			2,296.9	8.464E-02	6.8347E-04
Correction for measurement error						(-6.519E-04)
Correction for uncertainties						(2.222E-06)
Total painted surface area sampled (ft ²)						2,296.9
Estimated mean lead loading (mg Pb/cm ²)						0.0846
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0261

TABLE 20 Data Analysis Summary for Building E5618

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	0.0415	0.0032	1,411.8	4.152E-02	5.3297E-04
Totals	6			1,411.8	4.152E-02	5.3297E-04
Correction for measurement error						(-1.255E-03)
Correction for uncertainties						0
Total painted surface area sampled (ft ²)						1,411.8
Estimated mean lead loading (mg Pb/cm ²)						0.0415
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0231

TABLE 21 Data Analysis Summary for Building E5621

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	0.1705	0.0338	1,477.6	1.705E-02	5.631E-03
Totals	6			1,477.6	1.705E-02	5.631E-03
Correction for measurement error						(-1.388E-03)
Correction for uncertainties						0
Total painted surface area sampled (ft ²)						1,477.6
Estimated mean lead loading (mg Pb/cm ²)						0.1705
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0750

TABLE 22 Data Analysis Summary for Building E5625

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	15	0.1447	0.0128	3,178.6	5.762E-03	1.356E-06
2	29	0.1927	0.1908	4,181.6	1.010E-02	1.807E-05
3	7	2.1859	0.8857	379.2	1.039E-02	2.857E-06
4	15	2.0250	1.1588	1,478.3	3.751E-02	2.651E-05
5	10	0.7677	1.3811	1,043.0	1.003E-02	2.359E-05
6	8	0.0690	0.0062	497.3	4.303E-04	3.011E-08
7	8	0.0712	0.0295	1,887.6	1.685E-03	2.063E-06
8	17	0.2110	0.3808	1,670.2	4.417E-03	9.810E-06
9	11	0.6643	2.8431	398.8	3.320E-03	6.454E-06
10	17	0.0710	0.0178	730.9	6.507E-04	8.774E-08
11	30	0.2661	0.2494	2,676.9	8.925E-03	9.352E-06
12	21	0.1465	0.0196	3,238.5	5.947E-03	1.537E-06
13	25	0.1209	0.0179	2,983.4	4.518E-03	9.998E-07
14	34	0.8586	1.1238	2,669.9	2.873E-02	3.700E-05
15	18	0.0316	0.0156	2,222.7	8.800E-04	6.726E-07
16	19	0.0484	0.0209	1,865.3	1.130E-03	6.006E-07
17	41	0.2130	0.9498	4,184.3	1.117E-02	6.368E-05
18	13	0.2487	0.3025	2,581.6	8.046E-03	2.435E-05
19	11	1.5159	1.3629	1,138.6	2.163E-02	2.522E-05
20	14	0.5227	0.5544	1,471.3	9.638E-03	1.346E-05
21	25	0.1308	0.0256	2,427.4	3.978E-03	9.487E-07
22	24	0.1009	0.0093	3,080.1	3.895E-03	5.799E-07
23	13	0.1350	0.0157	2,744.9	4.642E-03	1.433E-06
24	36	1.0206	1.3908	2,925.4	3.741E-02	5.191E-05
25	18	0.1025	0.0128	8,382.9	1.077E-02	7.854E-06
26	9	-0.0146	0.0121	5,342.1	-9.807E-04	6.016E-06
27	6	0.1053	0.0090	4,150.0	5.476E-03	4.047E-06
28	13	0.0811	0.0084	10,270.2	1.044E-02	1.070E-05
Totals	507			79,801.0	2.605E-01	3.512E-04
Correction for measurement error						-3.192E-05
Correction for uncertainties						5.653E-06
Total painted surface area sampled (ft ²)						85,163.7
Estimated mean lead loading (mg Pb/cm ²)						0.2605
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0180

TABLE 23 Data Analysis Summary for Building E5627

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	38	0.1816	0.0187	4,207.6	5.595E-02	4.6679E-05
2	45	0.1702	0.0304	3,893.8	4.853E-02	5.4887E-05
3	4	1.0172	0.0372	410.9	3.061E-02	8.4218E-06
4	23	0.2137	0.0159	2,544.1	3.982E-02	2.4047E-05
5	6	0.1241	0.0091	2,597.6	2.362E-02	5.4843E-05
Totals	116			13,654.0	1.985E-01	1.8888E-04
Correction for measurement error						-1.006E-04
Correction for uncertainties						8.064E-06
Total painted surface area sampled (ft ²)						13,654.0
Estimated mean lead loading (mg Pb/cm ²)						0.1985
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0098

TABLE 24 Data Analysis Summary for Building E5632

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	0.0430	0.0057	834.0	4.295E-02	9.520E-04
Totals	6			834.0	4.295E-02	9.520E-04
Correction for measurement error						(-1.257E-03)
Correction for uncertainties						0
Total painted surface area sampled (ft ²)						834.0
Estimated mean lead loading (mg Pb/cm ²)						0.0430
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0309

TABLE 25 Data Analysis Summary for Building E5633

Stratum	Number of Values	Stratum Average (mg Pb/cm ²)	Variance of Stratum Average	Area (ft ²)	Contribution to Overall Average	Contribution of Average to Variance
1	6	0.0821	0.0044	504.4	8.209E-02	7.414E-04
Totals	6			504.4	8.209E-02	7.414E-04
Correction for measurement error						(-1.295E-03)
Correction for uncertainties						0
Total painted surface area sampled (ft ²)						504.4
Estimated mean lead loading (mg Pb/cm ²)						0.0821
Estimated standard deviation of the mean lead loading (mg Pb/cm ²)						0.0272

Table 26 provides a summary of the final results. The mean lead loading, its standard deviation, and the total painted surface area for each building are obtained from the previous tables. The total lead present is given by $0.002048 \times L \times A$ pounds, where L is the mean lead loading (in mg Pb/cm²), and A is the total painted surface area (in ft²). The projected rubble mass is taken from Table 26. The column labeled "Degrees of Freedom" gives the number of statistical degrees of freedom associated with the variance of the mean lead loading.

The quantity R in Table 26 is defined by the following equation:

$$R = 97.65 \times \frac{M}{A \times L} \quad (4)$$

where M is the rubble mass in tons. The factor 97.65 converts units to a consistent set and incorporates the factor 10^{-4} , derived from the regulatory limit for lead (see Section 3.1.1); R is then dimensionless. For a given total surface area and mean lead loading, a critical value exists for the rubble mass below which the building demolition debris would be classified as hazardous waste because of the presence of lead. R is the factor by which the actual rubble mass exceeds this critical value. A value of R that is less than 1 indicates that a waste disposal problem will be encountered. In terms of the hypothesis H_0 described in Section 3.1.1, if R were less than 1, H_0 would be determined to be true and further studies or remediation procedures would be initiated. (Actually, further work would be initiated in response to an R value somewhat greater than 1 because of the requirement of 95% confidence.) The R values given in Table 26 are all more than an order of magnitude greater than 1. On the basis of this finding, the amounts of lead present in all the buildings examined are too low by at least an order of magnitude to cause a waste disposal problem. This finding is verified by the details of the statistical hypothesis testing described in the next section.

TABLE 26 Summary of Results

Building (Code)	Mean Lead Loading (mg/cm ²)	Standard Deviation of the Mean (mg/cm ²)	Total Painted Surface Area (ft ²)	Total Lead Present (lb)	Projected Rubble Mass (tons)	R ^a	Degrees of Freedom
E5616 (A)	0.3140	0.0562	16105.8	10.36	692	13.36	18.34
E5617 (B)	0.0846	0.0261	3481.1	0.60	141	46.73	6.71
E5618 (C)	0.0415	0.0231	1411.8	0.12	219	364.98	4.99
E5621 (D)	0.1705	0.0750	1477.6	0.52	238	92.24	5.00
E5625 (E)	0.2605	0.0180	117352.3	62.62	6764	21.60	203.12
E5627 (G)	0.1985	0.0098	17842.4	7.25	758	20.90	40.59
E5632 (H)	0.0430	0.0309	834.0	0.07	132	359.83	5.00
E5633 (I)	0.0821	0.0272	751.4	0.13	88	139.31	5.00

^a R is defined as $97.65 \times M/(A \times L)$, where M is the rubble mass in tons, A the painted surface area in ft², and L the mean lead loading (in mg Pb/cm²). See text for a discussion.

The sampling program and the analysis of the data could each have been carried out in several ways, and it is of interest to investigate how successful the approach that was adopted here has been in comparison with possible alternatives. To do this, the results for the strata (as defined) were combined to emphasize the differences between the interior and exterior measurements and to produce estimates of population variances in addition to the variances of the mean loadings being considered. Table 27 summarizes the results. The "exteriors" combination consists of treating all the building exteriors together. The three "interior" combinations treat the interiors of the three buildings involved separately from their exteriors. The remaining combinations correspond to the analyses already described, and Table 27 entries for quantities already reported in Table 26 reproduce the entries given there. For each of the combinations of strata defined in the table, the mean lead loading, the variance of the mean, and the effective number of degrees of freedom were computed using the stratified random sample formulas. The estimated population variance was also computed (the standard deviations are the square roots of the respective variances). The "Stratification Performance Factor" measures the gain in precision that resulted from using a stratified random sampling approach instead of simple random sampling. This quantity is the ratio of the population variance divided by the number of measurements to the estimated variance of the mean (computed according to the stratified random sampling formulas). A value greater than 1 indicates that stratification has been successful; the greater the number, the higher the degree of success. A value of two, for example, indicates that, to achieve the same level of precision, approximately twice as many measurements would have been required if simple random sampling had been used.

Only one stratum was used for Buildings E5618, E5621, E5632, and E5633, and for these buildings there is no difference between stratified and simple random sampling. Only two strata were used for E5617; the stratum means were rather similar, and their individual variances were

TABLE 27 Stratification Performance

Building Combination	Number of Values	Mean Lead Loading (mg/cm ²)	Standard Deviation of the Mean (mg/cm ²)	Population Standard Deviation (mg/cm ²)	Degrees of Freedom	Stratification Performance Factor
Exteriors	88	0.074	0.007	0.113	53.6	1.02
E5625 (Interior)	461	0.363	0.028	0.339	214.0	0.32
E5616 (Interior)	68	0.411	0.062	0.708	16.5	0.14
E5627 (Interior)	110	0.216	0.012	0.213	101.3	2.13
E5616 (A)	74	0.314	0.056	0.667	18.3	1.82
E5617 (B)	12	0.085	0.026	0.092	6.7	1.03
E5618 (C)	6	0.042	0.023	0.057	5.0	1.00
E5621 (D)	6	0.171	0.075	0.184	5.0	1.00
E5625 (E)	507	0.261	0.018	0.655	203.1	2.41
E5627 (G)	116	0.199	0.010	0.204	40.6	1.91
E5632 (H)	6	0.043	0.031	0.075	5.0	1.00
E5633 (I)	6	0.082	0.027	0.066	5.0	1.00

not large — indicating that the strata were approximately homogeneous. For these reasons, stratification produced no significant improvement over simple random sampling for this building. For similar reasons, no significant improvement in precision was obtained by stratifying the building exteriors compared with what would have been found by simple random sampling.

The table shows that if the interior of Building E5627 were treated separately from its exterior, stratification would produce a significant improvement in precision based on these numbers. The reason is that one stratum has a significantly higher mean lead loading than the rest, but the stratum variances are all approximately uniform and are relatively low, indicating that the strata (as defined) do represent approximately homogeneous areas and that significantly different lead loadings have been isolated into different strata. Because the same stratum definitions were used in the basic analysis that incorporated the building exterior, the stratification was successful. If the interiors of Buildings E5625 and E5616 had been considered separately from their exteriors, however, a significant loss of precision would have resulted from the use of stratification. In each case, the reason is that several strata exist that have large mean lead loadings and that also are quite heterogeneous, as indicated by their large variances. Stratification works well only when significantly different measured values are associated with different strata. In the basic analysis described earlier, however, each building was considered in its entirety and its external surfaces were incorporated as distinct strata. Because of the large difference between exterior and interior measured values, on the average, and the large surface area associated with building exteriors, stratification was successful overall for Buildings E5616 and E5625, even though it was not successful in the interiors alone. Defining only two strata per building, exterior and interior, would have been a more efficient approach. No effective way of defining strata for building interiors prior to a field measurement program is apparent from the results of this study, and care must be used in their definition, even with the measurements available.

Given the very detailed data available, greater precision in the results might be expected if strata were defined as individually sampled surfaces or rooms. This approach was considered, but would have involved well over 100 strata. If an increase in the precision of the mean lead loading values were needed — for example to sharpen the statistical tests in an attempt to just barely reject (at the 95% confidence level) the hypothesis that there is too much lead present — then the analysis could have been re-done in this way. The next section discusses why there is no need of such an increase in precision. Also, it is not clear just how great a difference it would make; in many rooms in Building E5625, the measurements were highly variable, and would have resulted in heterogeneous strata in any event. With a smaller number of samples per stratum, the individual stratum variances might not decrease as much as expected from increased homogeneity.

In June 1994, 22 paint chip samples were collected in Building E5625 and analyzed for RCRA-regulated metals, including lead. The objectives of this preliminary work were to gain insight into the general levels of these metals in paint in Building E5625 and to obtain data that might be useful in planning the more detailed investigation described in this report. The analyses indicated that lead concentrations in paint from the PPC range up to 27.9% by weight; these results are not useful, in themselves, for estimating the overall lead loading in the building. The results are discussed further in Appendix D.

4.4 Statistical Analysis and Test Results

As described in Section 3.1, a hypothesis testing approach was adopted in this study as the methodology for deciding whether the lead content of the PPC buildings was likely to be too high or whether it could be ignored for waste disposal purposes. This approach follows current EPA guidance (EPA 1993). Standard statistical procedures for conducting such tests are designed, for the most part, to test hypotheses about a single unknown parameter; for example, the value of the mean of some population of interest. Related standard procedures for providing a range of values (in the form of confidence limits) in which an unknown parameter value lies with a specified probability are also designed to address only a single parameter. For each building considered in this study, however, three different parameters are involved and some level of uncertainty is associated with each. The three parameters are the mean lead loading (L) for the painted surfaces, the total painted surface area (A), and the mass of rubble (M) expected to be produced upon demolition. The hypothesis to be tested must be formulated in terms of these parameters and a suitable method found to allow all three uncertainties to contribute to the overall measure of uncertainty involved in the statistical test.

Various assumptions are involved in making any statistical test, depending on the way in which the hypothesis has been formulated and the specific test used. For example, many classical statistical tests are based on the assumption that the underlying probability distribution of the observations used in the test is a Gaussian or normal distribution. If the parameter of interest is the mean of some population, the Central Limit Theorem of statistics supports the assumption that the usual estimates of the mean are approximately normally distributed. However, this assumption is rarely verified in practice and, if the underlying distribution of the observations being averaged is far from normal, the validity of this assumption is questionable unless a very large number of

observations is involved. The data presented earlier show that, in this study, the distributions of the lead loading measurements for each building are indeed very far from normal.

Three general approaches were considered for testing the hypothesis that, for a given building, the amount of lead present in paint exceeds the regulatory threshold for waste disposal. In conformance with standard statistical terminology, this hypothesis, denoted by H_0 in Section 3.1, will be called the null hypothesis. The first general approach is to assume that the error in estimating each of the three parameters involved is small compared with the numerical value of the estimate. This allows the problem to be linearized and standard statistical methods to be used. The second approach considered is to use a generalization of the standard methods to more than three parameters; this method was quickly found to be infeasible for reasons discussed in Appendix E. The third general approach was to adopt a Bayesian methodology that allows the direct computation of the probability that H_0 is true. A significant advantage of this approach is that, although some assumptions must be made about the distributions of the three parameters, more physically reasonable assumptions can be made than standard statistical methods allow. Statistical tests were completed using both the first and the third approaches; the results are described in the next two sections.

4.4.1 Linearization Approximation

Within this general approach, the actual test used depends on how the hypothesis is formulated. One possible formulation is to consider the quantity R , defined in Section 4.1.2. R is defined as the ratio [see Equation (4)]:

$$R = \frac{cM}{A \times L} . \quad (5)$$

where c is a numerical constant that corrects for the use of different units of measure and also incorporates the factor 10^{-4} , derived from the waste disposal regulations. R is a dimensionless quantity representing the factor by which the expected rubble mass exceeds the amount that would cause the rubble to be considered hazardous waste on the basis of its lead content, assuming also that all the lead present is leachable. The null hypothesis can be formulated by assuming that R is less than 1 and constructing a test of this inequality. It turns out that, because of the estimated magnitudes of the values of R for the buildings considered, it is better to consider linearizing the quantity T , defined as the inverse of R :

$$T = \frac{A \times L}{cM} . \quad (6)$$

The null hypothesis is then that T is greater than 1.

The standard assumption is now made that independent determinations of the value of T are normally distributed. Then an appropriate test of the null hypothesis is to compute the following quantity:

$$z_1 = T - 1 + 1.645 \times T \times S_1 \quad (7)$$

and to accept H_0 if z_1 turns out to be positive, and reject H_0 if z_1 is negative. The factor 1.645 is just the critical one-tailed 95% value for the normal distribution, and its use associates 95% confidence with the test procedure if the true value of T is unity (and greater than 95% confidence if T is less than unity). S_1 is an estimate of the relative standard error of T (the standard error of T divided by T); in order to obtain a value for S_1 , an expression for the total differential of T , in terms of differential elements of A , L , and M , is obtained from Equation (6) by the usual rules of calculus. By treating each element as an independent random variable and using the usual statistical formula for the variance of a sum of terms gives an expression for the variance of T (the square of the standard error) in terms of T and the relative variances of A , L , and M (Mandel 1984). S_1 is thus computed from the following equation:

$$S_1 = \left[\frac{\text{Var}(A)}{A^2} + \frac{\text{Var}(L)}{L^2} + \frac{\text{Var}(M)}{M^2} \right]^{1/2} \quad (8)$$

This approach involves the assumption that the relative errors of A , L , and M are small. Values for the variances of A , L , and M are required in order to use Equations (7) and (8). The assumption of normality for T is highly questionable, however, because even if the estimates of A , L , and M were normally distributed, neither the product nor the ratio of normally distributed random variables is normally distributed. In fact, the ratio of two normally distributed variables has a Cauchy distribution (Lupton 1993), a distribution which is so delocalized that its variance (defined as the second moment about the mean) is mathematically undefined.

An alternative formulation of the null hypothesis that avoids this difficulty is to consider not the ratio but the difference (q) between $A \times L$ and cM :

$$q = A \times L - cM \quad (9)$$

The null hypothesis then states that q is positive. A suitable test is to compute $q + 1.645S_q$, and to accept H_0 if it is positive. An equivalent alternative is to compute z_2 :

$$z_2 = 1 - R + 1.645 \times S_2 \quad (10)$$

and to accept H_0 if z_2 turns out to be positive, and reject H_0 if z_2 is negative. S_2 is computed from the following equation:

$$S_2 = \left[\frac{\text{Var}(A)}{A^2} + \frac{\text{Var}(L)}{L^2} + \left(\frac{\text{Var}(A)}{A^2} \right) \left(\frac{\text{Var}(L)}{L^2} \right) + R^2 \frac{\text{Var}(M)}{M^2} \right]^{1/2} \quad (11)$$

In deriving Equation (11), the exact expression for the variance of a product of random variables has been used, and results in the first three terms inside the square root. This test still requires the assumption that q , in this case, is normally distributed. Now even though the product of two normal random variables is not normally distributed, the sum or difference of two are, and if the relative error in A is much smaller than that of L , their product will be approximately normal if L itself is. In this case, then, if L and M are approximately normally distributed, so is q and the test is suitable. The difficulty with this assumption is that the distribution of L is almost certainly not normal. Evidence for this is the set of markedly skewed distributions of lead loading values shown in Section 4.1. It is unlikely that the sample mean estimated from such distributions would be close to normally distributed. Additional evidence is found in the relative magnitudes of the standard deviations of the mean lead loading compared with the mean itself. In some cases, especially for the smaller buildings, the relative standard deviation of the mean lead loading is too large to be compatible with a normal distribution for a quantity that is inherently positive. In other words, the means are too close to zero and the assumption of a normal distribution assigns a non-negligible probability of an unphysical negative value.

Table 28 shows the relative variances of A , L , and M for the eight buildings in this study. The relative variance of the total painted area in each building was obtained as follows. The estimated error in the area associated with each stratum was quoted to be $\pm 10\%$ (see Section 2.3). The estimate was assumed to be normally distributed, and 10% of the mean value was assumed to be equal to three standard deviations. With this assumption, the $\pm 10\%$ range covers all but about 0.26% of a hypothetical infinite number of repeat estimates. Then the relative standard deviation of

TABLE 28 Relative Variances of A , L , and M

Building (Code)	$\text{Var}(A)/A^2$	$\text{Var}(L)/L^2$	$\text{Var}(M)/M^2$
E5616 (A)	0.00028	0.03208	0.00444
E5617 (B)	0.00056	0.09540	0.00444
E5618 (C)	0.00111	0.30942	0.00444
E5621 (D)	0.00111	0.19364	0.00444
E5625 (E)	0.00006	0.00479	0.00444
E5627 (G)	0.00028	0.00245	0.00444
E5632 (H)	0.00111	0.51603	0.00444
E5633 (I)	0.00111	0.11001	0.00444

a stratum area is 0.0333. The variance of the estimated total painted surface area in a building is $(0.0333)^2$ or 0.001111 times the sum of the squares of the stratum areas, and the relative variance is just this value divided by the square of the estimated total. For buildings with only one stratum, the relative variance of A is just 0.001111.

The relative variance of the rubble mass was obtained in a similar manner, except that the distribution of estimated values was taken to be parabolic (see Appendix E). The quoted uncertainty is $\pm 20\%$, and this was assumed to correspond to a range of ± 3 standard deviations. With the assumed distribution, the relative variance of M is then equal to 0.004444 for all buildings.

The relative variance of L was obtained from the results cited in Section 4.1.2, specifically the mean lead loading values and their estimated standard deviations (see Table 26).

Table 29 shows the results of the two tests described above. For each test, the corresponding value of S is given, along with the value of the test statistic (z_1 or z_2). The quantity $t(\text{crit})$ is that number which, if substituted into Equations (7) or (10) for the factor 1.645, would make the test statistic equal to zero. The larger these values are, the smaller the probability that the null hypothesis is true.

The important point about the results in Table 29 is that all the test statistic values (z_1 and z_2) are negative. According to both these tests, the hypothesis that the amount of lead present in paint in a building is large enough to cause the building demolition rubble to be classified as hazardous waste can be rejected with greater than 95% confidence for all buildings considered.

Three additional comments are in order. First, the test statistic (z_1) is, in all cases, nearly equal to -1. This is just what is expected when T is much less than 1, as Equation (7) shows. Second, the critical multiplier $t_2(\text{crit})$ is close to but less than 15 in all cases. This is because the relative variance of M in Equation (11) is multiplied by R^2 , which (in these cases) is always a large

TABLE 29 Hypothesis Testing Results — Linearization Approaches

Building	$T=1/R$	S_1	z_1	$t_1(\text{crit})$	S_2	z_2	$t_2(\text{crit})$
E5616 (A)	0.192	0.0748	-0.902	64.4	0.909	-10.9	13.60
E5617 (B)	0.317	0.0214	-0.967	144.3	3.131	-40.6	14.61
E5618 (C)	0.561	0.0027	-0.995	648.5	24.338	-323.9	14.95
E5621 (D)	0.446	0.0108	-0.981	204.4	6.165	-81.1	14.80
E5625 (E)	0.096	0.0463	-0.946	213.7	1.442	-18.2	14.29
E5627 (G)	0.085	0.0479	-0.946	235.1	1.394	-17.6	14.27
E5632 (H)	0.722	0.0028	-0.994	496.8	23.999	-319.4	14.95
E5633 (I)	0.340	0.0072	-0.989	406.8	9.293	-123.0	14.88

number. This means that, for this test and in these cases, the relative error of M dominates the relative errors of A and L . This is understandable, because if R is large, then cM is much larger than $A \times L$, and for a given relative error, the overall uncertainty will be caused mostly by uncertainty in the value of M . If the errors in A and L were totally negligible, the particular value of the relative variance of M would give a value of 15 for $t_2(\text{crit})$ for all buildings. Finally, the results shown in Table 28 indicate that, in fact, the errors in estimating the painted surface area are small compared with other errors in the study buildings, and the product term in Equation (11) is indeed negligible compared with the lead loading term.

4.4.2 Direct Computation of the Probability of H_0

In view of the assumptions and approximations made in formulating the two tests just described, a third approach was also used. Appendix E provides the detailed formulation and description of this approach. This third approach is fundamentally Bayesian in nature, in that the probability of the true value of some parameter, say L , lying in a specified range is given meaning and conceptually represents the uncertainty associated with the statement that L is in the specified range. In the same way, meaning is attached to statements about the probability of the null hypothesis being true or false. Once this concept is accepted, standard mathematical manipulations fairly directly yield a formula for the probability that the null hypothesis is false. This formula involves only known quantities, and can be evaluated in the cases of interest. Evaluation of the formula involves the computation of a double integral, which must (in general) be computed numerically. The formulation does, however, allow an obvious conservative approximation to be made in non-critical cases such as those in this study. This approximation involves the relatively easy computation of a lower bound to the probability that H_0 is false, or, equivalently, an upper bound to the probability that H_0 is true. The great advantage of this approach is that, although some assumption must be made about the distributions of A , L , and M (as must also be done with more traditional methods), any physically reasonable distributions may be assumed as long as the parameters involved can be determined completely from the data, and no further assumption is required for the distribution of a combined quantity such as R or q .

In all cases considered, the distribution of A was assumed to be normal and that of M parabolic (see Appendix E). The choice of the distribution to represent L depended on the size of the relative standard deviation of L and the number of degrees of freedom associated with L . If the relative standard deviation was too large to assume a normal or a Student's t distribution without causing too high a probability of an unphysical negative value, a Gamma distribution (Mood and Graybill 1963) was assumed. The Gamma distribution is defined only for positive values of the variable and can be characterized entirely by its mean and standard deviation. In addition, for small values of the relative standard deviation of the random variable, the Gamma distribution approximates a normal distribution, so that as the relative standard deviation decreases, a smooth transition occurs between a highly skewed distribution and a normal distribution. These properties all make this choice a reasonable one. Figures E-1 and E-2 in Appendix E show graphs of the assumed distributions for all buildings.

Table 30 gives the upper-bound probabilities ($P_{\max}$) that H_0 is true as estimated by this approach, along with the type of distribution assumed for the mean lead loading. For symmetric distributions such as the normal or Student's t , the fraction of the area under the curve that corresponds to negative lead loadings is also given as the quantity $1-W$. In practice, the distribution at $L=0$ would be truncated and $1/W$ used as a re-normalization constant for the truncated distribution. For some buildings, several distributions are plausible candidates, and the results of calculations using each are presented for comparison. Additional details are given in Appendix E. Finally, for cases in which a normal or Student's t distribution has been assumed for the mean lead loading, the value of the "Studentized" deviate corresponding to the computed probability is given. For example, for Building E5616, the value of the random variable above which the integrated probability is equal to $P_{\max}$ is 54.1 standard deviations above the mean.

The conclusion to be drawn from this table is that, for any reasonable distribution that is assumed for the mean lead loading on the basis of the field measurement results, the probability that enough lead is present in paint to cause a regulatory waste disposal problem is so small as to be virtually indistinguishable from zero.

TABLE 30 Estimated Upper-Bound Probability of H_0 Being True^a

Building (Code)	Distribution of L	$P_{\max}$	$1-W$	Effective t
E5616 (A)	Normal	1.6×10^{-238}	1×10^{-8}	54.1
	Student's t	1.7×10^{-20}	1×10^{-5}	54.1
	Gamma	4.0×10^{-72}	—	—
E5617 (B)	Student's t	4.8×10^{-12}	8×10^{-3}	117.8
	Gamma	6.2×10^{-117}	—	—
E5618 (C)	Gamma	1.6×10^{-199}	—	—
E5621 (D)	Gamma	4.7×10^{-91}	—	—
E5625 (E)	Normal	2.8×10^{-2910}	1×10^{-47}	235.3
	Student's t	4.4×10^{-228}	3×10^{-33}	235.3
E5627 (G)	Normal	5.2×10^{-2349}	2×10^{-91}	318.2
	Student's t	5.6×10^{-66}	4×10^{-23}	318.2
E5632 (H)	Gamma	8.1×10^{-132}	—	—
E5633 (I)	Gamma	3.5×10^{-202}	—	—

^a See Appendix E.

5 Summary and Conclusions

A field measurement program was conducted in December 1994 to address the possibility of significant lead contamination caused by the presence of lead-based paint in the buildings that make up the PPC at APG. A portable XRF device was used to make approximately 1,000 measurements of the lead loading on painted surfaces in the PPC buildings. External calibration of this device was completed by using standards obtained from NIST, and the measurement process was always in control (on the basis of the results of an extensive set of quality control measurements). Data quality objectives were developed in accordance with current EPA guidance. Analysis of the data allows several significant conclusions to be drawn.

The principal conclusion is that the amount of lead present in all the buildings examined is far too low to present any regulatory waste disposal problems. The analysis shows that the estimated lead concentration in the expected amount of rubble from each building is far below the RCRA regulatory limit based on the TCLP — even assuming that all the lead present would be leached out by the test procedure. The level of confidence with which this conclusion was reached far exceeds the 95% level required by regulatory agencies and, in fact, is virtually indistinguishable from 100%.

The high level of quality control employed in this study was necessary to ensure the adequacy of the data for their intended use. In addition, several conclusions can be drawn regarding the use of XRF for this purpose. The calibration data show that the XRF measurements were approximately 15% too high, that small but statistically significant offsets also occur, that these offsets differ depending on the substrate, and that the standard deviation of XRF measurements increases approximately linearly with lead loading (with a slope that is substrate-dependent). These conclusions are based on data collected over a range of lead loadings — from less than 0.001 mg Pb/cm² to 3.53 mg Pb/cm². Analysis of the duplicate measurements indicated that the variability of the field measurements was consistent with that of the calibration measurements.

The portable XRF device performed well. The means and standard deviations of the calibration check data collected during the field program agree with those from data collected to establish control charts prior to collecting the field measurements. The control chart data indicated no period of abnormal XRF instrument performance. Examination of 35 selected XRF spectra indicated no anomalies in the XRF instrument performance and no interferences that could affect the determination of the lead loading by this technique.

The detection limits of the XRF technique, determined on the basis of the calibration data, were 0.256 mg Pb/cm² for a concrete substrate blank and 0.376 mg Pb/cm² for a steel substrate blank. These values are the average of two values obtained using two different definitions of the term "detection limit."

The distributions of the XRF data collected in the different buildings were markedly skewed; the most probable values were quite low, but significant tails exist. The distribution of

data from metallic substrates is noticeably different from that for other substrates, with a significantly larger fraction of higher lead values. Evidence was found for at least three different sub-populations of lead loading values, and no simple curve (for example, that of a lognormal distribution) is adequate to describe the observed distributions. No significant correlation was observed between lead loading values and paint color and, except for the metallic substrates, no significant correlation was observed between substrate type and lead loading. Also, the correlation for metallic substrates was not totally consistent. No clear way to define strata for use in a stratified random sampling approach based on visual characteristics was found. The highest value observed (corrected for calibration) was 6.21 mg Pb/cm².

Stratification (the use of a stratified random sampling approach instead of simple random sampling) was successful in increasing the precision of the average lead loading estimates for each building in which more than two strata were used, primarily because exterior and interior data were separated into different strata. For interior measurements only, stratification was not uniformly successful because sufficiently homogeneous areas could not be identified on the basis of visible characteristics.

Standard statistical tests and procedures based on linearization, although they incorporate assumptions that are questionable for this study, reject the hypothesis that lead is present in amounts that present regulatory problems with a very high formal level of confidence. The statistical test designed for use in this study that avoids the difficulties of linearization methods also rejects that hypothesis with a very high level of confidence.

The data collection and analysis procedures used in this study were successful in resolving the potential lead contamination issue with a high level of confidence and efficiency.

6 References

American Chemical Society, 1983, "Principles of Environmental Measurement," *Anal. Chem.* 55, 2210-2218.

Anderson, R.W., and T.C. Kvitek, 1995, unpublished information.

Dewalt, G., 1994, Midwest Research Institute, personal communication.

Draper, N.R., and H. Smith, 1966, *Applied Regression Analysis*, John Wiley and Sons, Inc., New York, N.Y.

Cochran, W.G., 1977, *Sampling Techniques* (Third Edition), John Wiley and Sons, Inc., New York, N.Y.

EPA, 1986, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods* (Third Edition), Manual SW-846, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

EPA, 1993, *Data Quality Objectives Process for Superfund*, Report EPA540-R-93-071, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.

Gilbert, R.O., 1987, *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold, New York, N.Y.

Lupton, R., 1993, *Statistics in Theory and Practice*, Princeton University Press, Princeton, N.J.

Mandel, J., 1984, *The Statistical Analysis of Experimental Data*, Dover Publications, Inc., New York, N.Y.

Mood, A.M., and F.A. Graybill, 1963, *Introduction to the Theory of Statistics* (Second Edition), McGraw-Hill Book Co., Inc., New York, N.Y.

U.S. Environmental Protection Agency: see EPA.

Appendix A:
XRF Lead Calibration Data

Appendix A: XRF Lead Calibration Data

Tables A-1 through A-4 give the K- and L-shell XRF calibration measurements made using concrete and steel substrate blanks. Twenty readings were taken for each combination of a NIST-calibrated paint film and a substrate blank. These data are discussed in Section 3.1.

TABLE A-1 Lead K-Shell XRF Emission Calibration Data — Concrete Substrate Blank

Measurement Number	NIST Reference Lead Loading (mg Pb/cm ²)				
	<0.001	0.29	1.02	1.63	3.53
1	0.01	0.31	1.1	2.2	3.7
2	0.03	0.20	1.2	1.9	4.1
3	-0.02	0.30	1.0	1.7	3.9
4	-0.003	0.44	1.1	1.8	4.1
5	-0.06	0.36	1.1	1.9	3.9
6	-0.16	0.13	1.2	1.9	3.9
7	-0.05	0.25	1.5	1.8	3.6
8	-0.17	0.30	1.2	1.9	4.1
9	-0.13	0.38	1.0	1.9	3.6
10	0.03	0.50	1.0	1.7	4.0
11	0.04	0.28	1.1	1.9	3.8
12	-0.06	0.10	1.0	1.7	3.9
13	-0.06	0.34	1.4	1.8	3.9
14	-0.12	0.15	1.0	2.1	4.2
15	-0.04	0.32	1.1	2.1	4.2
16	0.07	0.38	1.1	1.9	4.0
17	-0.09	0.34	1.2	1.7	4.1
18	-0.14	0.31	1.2	2.0	4.2
19	-0.07	0.31	1.1	1.7	3.9
20	-0.09	0.21	1.1	1.8	4.3
Average	-0.054	0.296	1.14	1.87	3.97
Std. Dev.	0.0694	0.101	0.131	0.146	0.198

TABLE A-2 Lead K-Shell XRF Emission Calibration Data — Steel
Substrate Blank

Measurement Number	NIST Reference Lead Loading (mg Pb/cm ²)				
	<0.001	0.29	1.02	1.63	3.53
1	0.1	0.4	1.3	2.2	4.1
2	0.3	0.4	1.2	1.8	4.0
3	0.3	0.3	1.4	2.2	4.5
4	0.2	0.6	1.1	2.0	4.36
5	0.3	0.5	1.7	2.1	4.4
6	0.1	0.5	1.4	2.0	4.4
7	0.05	0.2	1.3	2.0	4.3
8	0.2	0.5	1.5	1.9	4.2
9	0.1	0.4	1.4	1.9	4.3
10	0.03	0.5	1.4	2.1	4.1
11	0.3	0.5	1.5	2.2	4.3
12	-0.007	0.3	1.2	2.1	4.1
13	0.2	0.8	1.5	2.3	4.6
14	0.08	0.4	1.3	2.0	4.2
15	0.4	0.6	1.6	2.2	4.1
16	0.3	0.6	1.5	2.2	4.2
17	0.4	0.4	1.4	1.9	3.9
18	0.3	0.6	1.4	2.2	4.0
19	0.2	0.3	1.5	2.3	4.1
20	-0.007	0.6	1.4	2.0	4.4
Average	0.192	0.470	1.40	2.08	4.23
Std. Dev.	0.130	0.142	0.141	0.144	0.180

TABLE A-3 Lead L-Shell XRF Emission Calibration Data — Concrete Substrate Blank

Measurement Number	NIST Reference Lead Loading (mg Pb/cm ²)				
	<0.001	0.29	1.02	1.63	3.53
1	-0.007	0.302	1.01	1.54	2.58
2	-0.003	0.297	1.04	1.54	2.60
3	-0.009	0.309	1.03	1.52	2.63
4	-0.003	0.311	1.01	1.53	2.63
5	-0.002	0.328	1.02	1.52	2.61
6	-0.007	0.317	1.04	1.52	2.63
7	-0.005	0.303	1.03	1.53	2.60
8	-0.004	0.308	1.03	1.55	2.68
9	-0.008	0.305	1.05	1.57	2.65
10	-0.008	0.328	1.01	1.56	2.67
11	-0.004	0.311	1.05	1.54	2.64
12	-0.006	0.312	1.04	1.51	2.65
13	-0.0005	0.323	1.03	1.55	2.61
14	-0.006	0.316	1.00	1.53	2.66
15	-0.007	0.313	1.03	1.56	2.63
16	-0.008	0.320	1.00	1.53	2.68
17	-0.007	0.321	1.03	1.52	2.64
18	-0.006	0.295	1.04	1.54	2.63
19	-0.005	0.308	1.03	1.53	2.60
20	-0.003	0.318	1.02	1.53	2.61
Average	-0.0054	0.3123	1.027	1.536	2.632
Std. Dev.	0.00231	0.009296	0.01490	0.01569	0.02796

TABLE A-4 Lead L-Shell XRF Emission Calibration Data — Steel Substrate Blank

Measurement Number	NIST Reference Lead Loading (mg Pb/cm ²)				
	<0.001	0.29	1.02	1.63	3.53
1	-0.004	0.316	1.03	1.57	2.67
2	-0.0006	0.311	1.02	1.52	2.63
3	0.002	0.309	1.01	1.54	2.64
4	0.002	0.326	1.05	1.57	2.60
5	-0.003	0.317	1.02	1.53	2.65
6	-0.0007	0.323	1.05	1.58	2.64
7	-0.001	0.307	1.04	1.59	2.62
8	0.002	0.327	1.04	1.53	2.66
9	-0.007	0.321	1.00	1.55	2.63
10	-0.002	0.325	1.03	1.55	2.61
11	-0.002	0.317	1.06	1.54	2.68
12	-0.003	0.314	1.06	1.54	2.64
13	-0.004	0.308	1.05	1.54	2.62
14	-0.001	0.319	1.05	1.57	2.66
15	-0.001	0.312	1.02	1.53	2.64
16	-0.001	0.316	1.04	1.54	2.66
17	0.0002	0.319	1.01	1.54	2.69
18	-0.003	0.319	1.03	1.56	2.66
19	-0.003	0.316	1.04	1.56	2.66
20	-0.002	0.314	1.03	1.53	2.62
Average	-0.0016	0.3168	1.034	1.549	2.644
Std. Dev.	0.00222	0.005782	0.01698	0.01917	0.02371

Appendix B:

Lead Loading Databases for PPC Buildings

Appendix B: Lead Loading Databases for PPC Buildings

This appendix presents the databases used in this study. In each database, the first column gives the building code and the floor, and the second gives the room number; the room number follows ANL's room-numbering convention as discussed in Section 2. The room number is given as "EXT" for exterior data. The "SURFACE" column labels the surface on which the measurement was made, and the "SAMPLE" column numbers the measurements made on that surface. The "SUBST" and "COLOR" columns give the substrate type code and the color code that indicate the type of substrate and the color of the paint at the point where the measurement was made. The substrate type and paint color codes are described in Table 3 in the main body of the text. The "AREA" column gives the surface area in square feet associated with that surface; the area is associated only with the first measurement made on the surface so that the total surface area in the room may be obtained by adding the given areas. The "SEQNO" column gives the sequential number for the measurement; this number uniquely identifies the measurement. The columns labeled "L" and "K" give the L-shell and K-shell lead XRF emission readings taken directly from the instrument; these data are the raw data and are not corrected for calibration. The "VALUE" column gives the K-shell measurement corrected for calibration as described in Section 3.1. The data in the "VALUE" column are the data used in the analysis discussed in the main body of the text.

BUILDING E5616 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
A1	EXT	E	WH	998	0.004	-0.100	-0.048
A1	EXT	E	WH	999	0.003	-0.110	-0.057
A1	EXT	E	WH	1001	-0.003	0.070	0.099
A1	EXT	E	WH	1002	0.000	0.200	0.213
A1	EXT	E	WH	1000	0.005	-0.070	-0.022
A1	EXT	E	WH	1003	0.007	-0.290	-0.214

BUILDING E5616 — INTERIOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
A1	01	E	BB	45	-0.004	-0.200	-0.135
A1	01	E	BB	41	0.054	0.300	0.300
A1	01	E	BB	42	0.017	-0.040	0.004
A1	01	E	BB	43	0.017	0.060	0.091
A1	01	E	BB	44	0.022	-0.030	0.013
A1	01	E	BB	47	0.038	0.090	0.117
A1	01	E	BB	48	0.381	0.300	0.300
A1	01	E	BB	49	0.002	0.300	0.300
A1	01	E	BB	50	0.006	0.070	0.099
A1	01	E	BB	51	0.018	-0.020	0.021
A1	02	E	BB	126	0.002	-0.100	-0.048
A1	02	E	DB	125	0.035	0.100	0.126
A1	02	E	BB	127	0.010	0.070	0.099
A1	02	E	DB	128	0.078	0.500	0.474
A1	02	E	BB	129	0.012	0.300	0.300
A1	02	E	DB	130	0.054	0.500	0.474
A1	03	E	DB	118	0.051	0.005	0.043
A1	03	E	BB	119	0.016	0.200	0.213
A1	03	E	BB	120	0.038	0.500	0.474
A1	03	E	BB	121	0.028	0.050	0.082
A1	04	E	BB	117	-0.005	-0.170	-0.109
A1	05	E	BB	55	0.033	0.100	0.126
A1	05	E	BB	56	0.004	-0.020	0.021
A1	05	E	BB	57	0.027	0.200	0.213
A1	05	E	BB	58	0.062	0.100	0.126
A1	06	E	BB	67	0.008	0.300	0.300
A1	06	E	BB	62	0.001	-0.020	0.021
A1	06	E	BB	63	0.010	0.200	0.213
A1	06	E	BB	65	0.017	-0.040	0.004
A1	06	E	BB	66	0.008	-0.200	-0.135
A1	06	E	BB	64	0.021	-0.020	0.021
A1	07	E	BB	74	0.009	0.080	0.108
A1	07	E	BB	76	-0.007	-0.050	-0.005
A1	07	E	BB	73	0.007	-0.080	-0.031
A1	07	E	BB	71	0.001	0.030	0.065
A1	07	E	BB	72	0.008	-0.040	0.004
A1	07	E	BB	75	0.009	0.090	0.117
A1	08	E	BB	134	-0.004	0.300	0.300
A1	08	E	BB	135	0.023	0.100	0.126
A1	08	E	BB	136	0.022	0.100	0.126
A1	08	E	BB	137	0.012	0.400	0.387
A1	08	E	BB	138	0.430	1.100	0.995
A1	08	E	BB	139	0.016	0.080	0.108
A1	09	E	BB	92	0.007	0.005	0.043
A1	09	E	BB	93	0.150	1.600	1.430

BUILDING E5616 — INTERIOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
A1	09	E	BB	94	0.046	-0.090	-0.040
A1	09	E	BB	95	0.066	0.200	0.213
A1	10	E	BB	80	0.032	0.020	0.056
A1	10	E	BB	83	0.059	0.100	0.126
A1	10	E	BB	82	0.160	0.300	0.300
A1	10	E	BB	84	0.410	1.700	1.517
A1	10	E	BB	85	0.620	4.800	4.214
A1	10	E	BB	86	0.250	1.800	1.604
A1	10	E	BB	87	0.092	0.300	0.300
A1	10	E	BB	88	0.280	1.700	1.517
A1	10	E	BB	81	0.320	1.300	1.169
A1	11	E	BB	100	0.078	1.100	0.995
A1	11	E	DB	99	0.068	0.200	0.213
A1	11	E	BB	101	0.450	3.800	3.344
A1	11	E	DB	102	0.036	0.005	0.043
A1	11	E	DB	104	0.170	1.400	1.256
A1	11	E	BB	103	0.091	1.000	0.908
A1	11	E	DB	106	0.230	1.300	1.169
A1	11	E	BB	105	0.220	0.900	0.821
A1	12	E	BB	110	0.190	0.900	0.821
A1	12	E	BB	111	0.220	1.700	1.517
A1	12	E	BB	113	0.310	1.600	1.430
A1	12	E	BB	112	0.240	1.100	0.995

BUILDING E5617 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
B1	EXT	E	WH	1007	0.150	0.050	0.082
B1	EXT	E	WH	1008	0.008	0.080	0.108
B1	EXT	E	WH	1009	0.007	0.060	0.091
B1	EXT	E	WH	1010	-0.003	0.080	0.108
B1	EXT	E	WH	1011	0.130	0.300	0.300
B1	EXT	E	WH	1012	-0.002	-0.100	-0.048

BUILDING E5617 — INTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
B1	01	E	CR	146	0.011	-0.040	0.004
B1	01	E	CR	144	0.035	0.003	0.041
B1	01	E	CR	145	0.013	0.003	0.041
B1	01	E	CR	143	0.005	0.100	0.126
B1	01	E	CR	147	0.026	-0.020	0.021
B1	01	E	CR	148	0.051	0.100	0.126

BUILDING E5618 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
C1	EXT	E	EW	155	0.009	0.050	0.082
C1	EXT	E	EW	156	-0.003	0.010	0.047
C1	EXT	E	EW	157	0.009	-0.070	-0.022
C1	EXT	E	EW	152	-0.002	-0.060	-0.014
C1	EXT	E	EW	153	0.003	0.100	0.126
C1	EXT	E	EW	154	-0.002	-0.010	0.030

BUILDING E5621 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
D1	EXT	-	-	164	0.020	0.300	0.300
D1	EXT	-	-	165	0.005	-0.100	-0.048
D1	EXT	E	EW	161	0.014	0.080	0.108
D1	EXT	E	EW	162	0.076	0.400	0.387
D1	EXT	E	EW	163	0.005	0.300	0.300
D1	EXT	E	EW	166	0.001	-0.070	-0.022

BUILDING E5625 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E1	EXT	E	WH	1028	0.004	-0.05	-0.005
E1	EXT	E	WH	1027	-0.01	0.04	0.073
E1	EXT	E	WH	1025	0.011	0.02	0.056
E1	EXT	E	WH	1029	-0	-0.1	-0.048
E1	EXT	E	WH	1031	-0	0.3	0.300
E1	EXT	E	WH	1030	-0	-0.06	-0.014
E1	EXT	E	WH	1020	0.019	0.1	0.126
E1	EXT	E	WH	1019	0.002	-0.01	0.032
E1	EXT	E	WH	1021	0.011	0.07	0.099
E1	EXT	E	WH	1024	-0	0.1	0.126
E1	EXT	E	WH	1023	0.002	0.2	0.213
E1	EXT	E	WH	1022	0.006	-0.03	0.013
E1	EXT	E	WH	994	0.002	0.4	0.387
E1	EXT	E	WH	1032	0.031	0.2	0.213
E1	EXT	E	WH	1034	0.002	-0.03	0.013
E1	EXT	E	WH	1037	0.002	0.07	0.099
E1	EXT	E	WH	1017	0.008	0.04	0.073
E1	EXT	E	WH	1018	0.005	0.06	0.091
E2	EXT	E	WH	1042	2E-04	-0.2	-0.135
E2	EXT	E	WH	1041	0.009	-0.1	-0.048
E2	EXT	E	WH	1035	0.002	-0.24	-0.170
E2	EXT	E	WH	1033	0.012	-0.05	-0.005
E2	EXT	E	WH	1036	-0.01	-0.09	-0.040
E2	EXT	E	WH	1016	0.039	0.2	0.213
E2	EXT	E	WH	1043	0.003	-0.04	0.004
E2	EXT	E	WH	1045	0.001	0.009	0.046
E2	EXT	E	WH	1047	0.009	-0.04	0.004
E3	EXT	E	WH	1050	-0	0.2	0.213
E3	EXT	E	WH	1049	0.01	0.03	0.065
E3	EXT	E	WH	1051	0.008	-0.01	0.030
E3	EXT	E	WH	1048	0.01	0.1	0.126
E3	EXT	E	WH	1044	-0	-0.06	-0.014
E3	EXT	E	WH	1046	-0	0.2	0.213
E4	EXT	E	WH	489	0.011	0.09	0.117
E4	EXT	E	WH	490	0.015	0.09	0.117
E4	EXT	E	WH	491	0.005	-0.01	0.030
E4	EXT	E	WH	486	0.004	0.2	0.213
E4	EXT	E	WH	487	0.014	-0.2	-0.135
E4	EXT	E	WH	488	0.006	-0.03	0.013
E4	EXT	E	WH	492	0.033	0.09	0.117
E4	EXT	E	WH	493	0.013	0.2	0.213
E4	EXT	E	WH	494	0.011	0.06	0.091
E4	EXT	E	WH	495	0.011	0.1	0.126
E4	EXT	E	WH	496	0.007	0.07	0.099
E4	EXT	E	WH	497	0.06	-0.02	0.021
E5	EXT	E	WH	500	0.014	-0.01	0.034

BUILDING E5625 — INTERIOR - FIRST FLOOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E1	03	B	GY	860	0.058	0.2	0.213
E1	03	B	GY	859	0.062	0.1	0.126
E1	03	B	GY	861	0.062	0.2	0.213
E1	03	B	GY	862	0.035	-0.06	-0.014
E1	03	B	GY	863	0.045	0.3	0.300
E1	04	E	GY	871	0.005	0.01	0.047
E1	04	A	GY	868	0.3	0.1	0.126
E1	04	A	GY	869	0.036	0.004	0.042
E1	04	A	GY	870	0.008	0.04	0.073
E1	04	E	GY	873	0.038	0.2	0.213
E1	04	G	GY	874	0.055	0.3	0.300
E1	04	G	GY	875	0.052	-0.07	-0.022
E1	04	G	GY	876	0.062	0.005	0.043
E1	04	G	GY	877	0.049	0.3	0.300
E1	04	E	GY	872	0.014	0.2	0.213
E1	07	B	GY	792	0.016	0.3	0.300
E1	07	B	GY	793	0.021	-0.1	-0.048
E1	07	E	GY	795	0.14	0.5	0.474
E1	07	B	GY	796	0.004	-0.04	0.004
E1	08	G	GY	766	-0.01	-0.06	-0.014
E1	08	E	GY	769	0.022	-0.2	-0.135
E1	08	G	GY	767	-0	0.1	0.126
E1	08	G	GY	768	-0	0.02	0.056
E1	08	A	GY	770	0.012	0.2	0.213
E1	08	A	GY	771	0.019	0.08	0.108
E1	08	A	GY	772	0.008	0.2	0.213
E1	08	B	GY	773	0.026	0.3	0.300
E1	08	B	GY	775	0.015	-0.05	-0.005
E1	08	B	GY	776	0.023	0.06	0.091
E1	08	B	GY	774	0.021	0.02	0.056
E1	08	B	GY	777	0.002	0.05	0.082
E1	08	B	GY	778	0.018	0.04	0.073
E1	08	A	GY	782	0.023	-0.1	-0.048
E1	08	E	GY	779	0.005	0.05	0.082
E1	08	E	GY	781	0.03	-0.02	0.021
E1	08	E	GY	780	0.02	0.2	0.213
E1	08	B	GY	783	0.019	0.3	0.300
E1	08	A	GY	784	0.014	0.3	0.300
E1	08	A	GY	785	0.008	0.04	0.073
E1	08	A	GY	786	0.013	0.01	0.047
E1	10	A	WH	995	0.033	0.07	0.099
E1	10	A	WH	997	-0	0.1	0.126
E1	10	E	WH	996	0.008	0.1	0.126

BUILDING E5625 — INTERIOR - FIRST FLOOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E1	15	G	CR	803	0.27	2.2	1.952
E1	15	G	CR	802	0.34	2.1	1.865
E1	15	G	CR	801	0.23	2.2	1.952
E1	15	A	WH	805	0.013	0.3	0.300
E1	18	A	WH	834	0.027	0.1	0.126
E1	18	A	WH	835	0.041	0.2	0.213
E1	18	A	WH	837	0.062	0.02	0.056
E1	18	G	WH	838	0.83	3.4	2.996
E1	18	G	WH	836	0.42	2.1	1.865
E1	18	G	WH	849	0.65	2.7	2.387
E1	18	E	WH	841	0.028	-0.08	-0.031
E1	18	E	WH	842	0.016	0.2	0.213
E1	18	E	WH	843	0.013	0.05	0.082
E1	21	L	LB	848	-0.05	0.07	0.099
E1	21	E	LB	849	-0.01	0.2	0.213
E1	21	E	LB	850	0.006	0.08	0.108
E1	21	E	LB	851	0.007	0.09	0.117
E1	21	L	LB	852	-0.04	-0.02	0.021
E1	21	L	LB	853	-0.05	-0.07	-0.022
E1	21	L	LB	854	-0.05	-0.04	0.004
E1	21	L	LB	855	-0.05	-0.03	0.013
E1	22	G	GY	983	0.01	0.1	0.126
E1	22	G	GY	984	0.026	-0.19	-0.127
E1	22	G	GY	985	0.023	0.09	0.117
E1	22	G	GY	986	0.011	-0.1	-0.048
E1	22	G	GY	987	0.011	0.1	0.126
E1	22	G	GY	988	0.005	-0.2	-0.135
E1	22	G		989	-0.01	0.1	0.126
E1	24	G	GY	990	0.017	0.4	0.387
E1	26	G	WH	904	0.007	-0.03	0.013
E1	26	G	GN	903	0.049	0.1	0.126
E1	26	A	WH	893	0.008	-0.06	-0.014
E1	26	A	GN	896	0.049	0.1	0.126
E1	26	A	WH	894	0.054	0.05	0.082
E1	26	A	GN	897	0.012	-0.13	-0.074
E1	26	A	GN	898	0.016	0.04	0.073
E1	26	A	WH	895	0.006	0.1	0.126
E1	26	G	GN	900	0.092	0.09	0.117
E1	26	G	WH	899	0.002	0.1	0.126
E1	26	G	WH	901	0.004	-0.1	-0.048
E1	26	G	GN	902	0.052	0.02	0.056
E1	26	G	GN	906	0.048	-0.07	-0.022
E1	26	G	WH	905	0.006	-0.23	-0.161
E1	26	-	-	907	0.12	0.4	0.387
E1	26	-	-	908	0.49	2.9	2.561
E1	26	-	-	909	0.097	0.09	0.117

BUILDING E5625 — INTERIOR - FIRST FLOOR p. 3

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E1	27	G	CR	915	0.015	-0.07	-0.022
E1	27	G	CR	916	0.018	0.02	0.056
E1	27	G	CR	917	0.55	1.5	1.343
E1	28	B	GY	882	0.005	0.003	0.041
E1	28	E	GY	883	0.023	0.2	0.213
E1	28	E	GY	884	0.73	6.4	5.606
E1	28	E	GY	885	0.015	0.04	0.073
E1	28	B	GY	886	-0.01	-0.03	0.013
E1	28	B	GY	887	0.009	-0.02	0.021
E1	28	B	GY	888	0.003	-0.03	0.013
E1	28	B	GY	889	0.027	-0.1	-0.048
E1	29	G	GN	960	0.006	-0.15	-0.092
E1	29	G	WH	959	0.007	0.1	0.126
E1	29	G	GN	961	0.009	-0.1	-0.048
E1	29	G	WH	962	0.005	0.1	0.126
E1	29	G	WH	963	-0	-0.04	0.004
E1	29	G	GN	964	0.017	0.05	0.082
E1	29	G	WH	966	0.003	0.2	0.213
E1	29	G	GN	965	0.011	-0.1	-0.048
E1	29	G	WH	967	-0	0.2	0.213
E1	29	G	GN	972	0.013	-0.23	-0.161
E1	29	G	WH	971	-0	0.3	0.300
E1	29	G	GN	970	0.02	-0.01	0.030
E1	29	G	WH	969	0.01	-0.1	-0.048
E1	29	G	GN	968	0.052	0.01	0.047
E1	30	G	CR	977	0.013	0.004	0.042
E1	30	G	CR	978	0.017	0.3	0.300
E1	30	G	CR	979	0.014	0.1	0.126
E1	31	E	WH	937	0.009	0.1	0.126
E1	31	G	WH	922	0.015	0.1	0.126
E1	31	G	GN	921	0.01	0.005	0.043
E1	31	A	WH	924	0.041	1	0.908
E1	31	G	GN	925	0.034	0.2	0.213
E1	31	G	WH	926	0.007	0.1	0.126
E1	31	A	GN	923	0.003	-0.2	-0.135
E1	31	G	WH	927	0.022	0.3	0.300
E1	31	G	GN	928	0.032	0.09	0.117
E1	31	G	WH	929	0.007	0.03	0.065
E1	31	G	GN	932	0.3	1.1	0.995
E1	31	G	WH	933	0.028	0.07	0.099
E1	31	G	GN	934	0.93	2.2	1.952
E1	31	G	GN	931	0.025	-0.01	0.030
E1	31	G	WH	930	0.017	0.02	0.056
E1	31	G	GN	935	0.63	2	1.778
E1	31	G	WH	936	0.002	-0.05	-0.005
E1	31	E	WH	941	0.016	-0.3	-0.222

BUILDING E5625 — INTERIOR - FIRST FLOOR p. 4

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E1	31	E	WH	939	0.019	0.02	0.056
E1	31	E	GN	940	0.065	0.1	0.126
E1	31	E	GN	938	0.038	0.08	0.108
E1	31	E	GN	942	0.014	0.1	0.126
E1	32	G	WH	948	0.008	0.01	0.047
E1	32	G	GN	949	0.021	0.06	0.091
E1	32	G	WH	951	-0	0.08	0.108
E1	32	G	GN	950	-0.01	-0.08	-0.031
E1	32	E	GN	953	0.008	0.09	0.117
E1	32	E	WH	952	0.015	0.03	0.065
E1	32	E	GN	954	0.005	0.2	0.213
E1	32	E	WH	955	0.01	0.4	0.387
E1	07	K	GY	794	0.93	2.9	2.360
E1	11	K	GY	810	1.07	1.5	1.143
E1	11	K	GY	811	0.99	2.1	1.665
E1	11	K	GY	809	1.27	2.8	2.273
E1	12	K	GL	814	1.81	4.4	3.663
E1	12	K	GL	813	1.19	2.4	1.925
E1	12	K	GL	812	1.97	3.9	3.229
E1	13	K	GL	815	0.9	1.8	1.404
E1	15	K	CR	800	0.99	2.4	1.925
E1	15	K	CR	804	0.51	1.3	0.970
E1	16	K	CR	821	1.09	4	3.315
E1	16	K	CR	819	0.78	3.1	2.533
E1	16	K	CR	822	1.25	4.2	3.489
E1	16	K	CR	824	0.64	3.6	2.968
E1	16	K	CR	820	0.62	3.3	2.707
E1	16	K	CR	823	0.86	4.4	3.663
E1	17	K	GL	828	0.96	1.7	1.317
E1	17	K	GL	829	0.65	1.1	0.796
E1	17	K	GL	830	0.54	0.9	0.622
E1	18	K	GL	841	0.028	-0.08	-0.229

BUILDING E5625 — INTERIOR - SECOND FLOOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E2	03	B	GY	682	0.051	0.6	0.561
E2	03	B	GY	680	0.043	0.2	0.213
E2	03	A	GY	681	0.041	-0.2	-0.135
E2	03	B	GY	683	0.037	0.1	0.126
E2	03	B	GY	684	0.046	0.05	0.082
E2	03	B	GY	685	0.055	0.4	0.387
E2	03	B	GY	686	0.042	0.2	0.213
E2	04	A	GY	690	0.045	0.1	0.126
E2	04	A	WH	693	0.006	0.04	0.073
E2	04	A	WH	694	0.013	0.07	0.099
E2	04	A	GY	691	0.012	0.07	0.099
E2	04	A	GY	692	0.051	0.04	0.073
E2	04	A	WH	695	-0.01	0.09	0.117
E2	04	E	WH	698	0.007	0.2	0.213
E2	04	E	WH	697	0.018	0.05	0.082
E2	04	E	WH	696	-0.01	0.06	0.091
E2	04	G	WH	699	0.094	0.04	0.073
E2	04	G	WH	700	0.065	0.1	0.126
E2	04	G	WH	701	0.046	0.1	0.126
E2	04	G	WH	703	0.059	-0	0.035
E2	04	G	WH	702	0.055	0.3	0.300
E2	07	B	WH	711	0.077	0.3	0.300
E2	07	B	WH	708	0.013	0.05	0.082
E2	07	B	WH	709	0.14	0.3	0.300
E2	07	B	WH	710	0.28	0.4	0.387
E2	07	E	WH	712	0.024	-0.02	0.021
E2	07	E	WH	713	0.045	0.1	0.126
E2	07	E	WH	714	0.14	0.5	0.474
E2	07	B	WH	715	0.01	0.2	0.213
E2	08	B	WH	636	0.008	0.02	0.056
E2	08	E	WH	637	0.005	-0.1	-0.048
E2	08	A	WH	638	0.037	0.07	0.099
E2	08	B	WH	639	0.004	0.1	0.126
E2	08	B	WH	641	0.015	0.2	0.213
E2	08	B	WH	642	0.01	0.004	0.042
E2	08	B	WH	643	0.008	0.05	0.082
E2	08	B	WH	644	0.015	0.03	0.065
E2	08	E	WH	645	0.013	-0.21	-0.144
E2	08	E	WH	646	0.004	0.08	0.108
E2	08	E	WH	647	0.028	0.1	0.126
E2	08	B	WH	648	0.02	0.03	0.065
E2	08	A	WH	650	0.02	-0.02	0.021
E2	08	B	WH	649	0.015	0.04	0.073
E2	08	A	WH	651	0.019	0.07	0.099
E2	08	A	WH	652	0.022	0.1	0.126
E2	08	A	WH	653	0.033	-0.03	0.013

BUILDING E5625 — INTERIOR - SECOND FLOOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E2	11	I	GY	759	0.64	1.4	1.056
E2	11	G	WH	758	0.29	2.2	1.952
E2	11	A	WH	760	0.016	0.08	0.108
E2	11	I	GY	761	0.27	0.8	0.535
E2	12	I	GY	757	0.41	0.7	0.448
E2	13	I	GY	751	0.39	1	0.709
E2	13	I	GY	752	0.32	0.8	0.535
E2	13	I	GY	753	0.48	1.2	0.883
E2	13	I	GY	755	0.67	1.1	0.796
E2	13	I	GY	756	1.02	1.8	1.404
E2	13	I	GY	754	0.49	0.2	0.014
E2	14	E	CR	747	0.003	0.1	0.126
E2	14	I	CR	740	0.03	0.3	0.101
E2	14	I	CR	742	0.88	3.7	3.055
E2	14	I	CR	744	0.016	0.08	-0.090
E2	14	I	CR	743	1.68	5.1	4.271
E2	14	I	CR	745	0.025	1.1	0.796
E2	14	E	CR	746	0.006	0.01	0.047
E2	14	E	CR	741	-0	0.01	0.047
E2	15	A	WH	731	0.13	0.2	0.213
E2	15	I	GY	735	0.126	0.5	0.274
E2	15	I	GY	736	0.41	1.4	1.056
E2	15	E	WH	732	0.017	0.2	0.213
E2	15	E	WH	733	0.015	0.1	0.126
E2	15	E	WH	734	0.011	-0	0.038
E2	16	A	WH	719	0.038	0.09	0.117
E2	16	A	WH	720	0.022	0.05	0.082
E2	16	A	WH	722	0.018	0.1	0.126
E2	16	G	WH	724	0.35	2.7	2.387
E2	16	G	WH	723	0.39	2.7	2.387
E2	16	G	WH	721	0.46	3.5	3.083
E2	16	I	GY	725	0.53	1.1	0.796
E2	16	I	GY	726	0.46	0.6	0.361
E2	16	I	GY	727	0.56	1.5	1.143
E2	19	B	WH	679	0.009	-0.11	-0.057
E2	20	G	-	673	0.003	-0.01	0.034
E2	20	E	WH	658	0.007	0.07	0.099
E2	20	A	WH	659	0.016	-0.1	-0.048
E2	20	A	WH	660	0.013	-0.1	-0.048
E2	20	E	WH	661	0.004	0.2	0.213
E2	20	B	WH	662	0.012	0.1	0.126
E2	20	A	WH	665	0.026	0.3	0.300
E2	20	B	WH	663	0.005	-0.2	-0.135
E2	20	A	WH	667	0.008	0.1	0.126
E2	20	A	WH	666	0.035	-0.03	0.013

BUILDING E5625 — INTERIOR - SECOND FLOOR p. 3

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E2	20	B	WH	664	0.014	-0.1	-0.048
E2	20	E	WH	668	8E-04	-0.11	-0.057
E2	20	E	WH	669	0.019	0.1	0.126
E2	20	E	WH	670	-0	-0.28	-0.205
E2	20	G	WH	671	0.004	0.1	0.126
E2	20	G	WH	672	-0	-0.05	-0.005
E2	21	B	WH	674	0.004	-0.03	0.013

BUILDING E5625 — INTERIOR - THIRD FLOOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E3	03	B	YL	520	0.027	0.1	0.126
E3	03	A	YL	521	0.02	-0.1	-0.048
E3	03	A	YL	522	0.027	-0	0.038
E3	03	A	YL	524	0.028	0.2	0.213
E3	03	I	YL	525	0.005	0.3	0.101
E3	03	B	YL	523	-0.01	-0.14	-0.083
E3	03	B	YL	526	-0	-0.02	0.021
E3	03	B	YL	527	0.021	0.3	0.300
E3	04	B	BB	544	0.004	0.05	0.082
E3	05	B	BB	531	-0	-0.27	-0.196
E3	05	B	BB	532	0.001	-0.01	0.030
E3	05	E	BB	533	7E-05	0.04	0.073
E3	05	E	BB	534	-0	0.2	0.213
E3	05	E	BB	535	-0	0.1	0.126
E3	05	I	BB	537	-0	3E-04	-0.160
E3	05	B	BB	536	-0.01	-0.1	-0.048
E3	05	I	BB	538	0.003	-0.02	-0.177
E3	05	B	BB	539	-0.01	-0	0.037
E3	05	I	BB	540	0.01	0.5	0.274
E3	07	I	CR	552	0.004	0.1	-0.073
E3	07	I	CR	553	-0.01	0.2	0.014
E3	07	I	CR	554	0.004	0.4	0.188
E3	07	I	CR	548	0.003	-0.05	-0.203
E3	07	E	CR	546	0.028	0.02	0.056
E3	07	E	CR	547	0.02	-0.24	-0.170
E3	07	E	CR	545	0.013	0.2	0.213
E3	07	G	CR	549	0.026	0.2	0.213
E3	07	G	CR	550	0.016	0.01	0.047
E3	07	G	CR	551	0.009	0.1	0.126
E3	08	B	BB	558	0.004	-0.14	-0.083
E3	08	B	BB	559	0.008	-0.11	-0.057
E3	08	B	BB	560	-0	-0.06	-0.014
E3	08	B	BB	561	0.007	-0.1	-0.048
E3	08	I	BB	562	0.003	0.2	0.014
E3	08	I	BB	563	0.006	0.2	0.014
E3	08	I	BB	566	0.002	0.3	0.101
E3	08	I	BB	565	0.006	0.04	-0.125
E3	08	I	BB	564	0.004	0.3	0.101
E3	08	I	BB	567	0.005	0.3	0.101
E3	09	B	YL	571	1.79	7.1	6.214
E3	09	I	YL	572	0.008	-0.1	-0.247
E3	09	I	YL	573	-0	-0.2	-0.334
E3	09	I	YL	574	0.002	0.3	0.101
E3	09	B	YL	575	-0	-0.1	-0.048
E3	09	B	YL	576	0.021	0.06	0.091

BUILDING E5625 — INTERIOR - THIRD FLOOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E3	09	B	YL	577	0.015	0.3	0.300
E3	09	B	YL	578	0.014	0.3	0.300
E3	09	B	YL	579	0.02	0.1	0.126
E3	10	-	-	583	-0	0.03	0.065
E3	10	-	-	584	0.019	0.1	0.126
E3	10	-	-	585	0.027	0.3	0.300
E3	11	B	CR	586	0.023	0.2	0.213
E3	11	B	CR	587	0.029	0.3	0.300
E3	11	B	CR	588	6E-04	-0.19	-0.127
E3	11	B	WH	589	0.044	0.1	0.126
E3	11	B	WH	590	0.107	0.5	0.474
E3	11	B	WH	591	0.032	0.08	0.108
E3	11	B	WH	592	0.047	-0.08	-0.031
E3	11	B	WH	593	0.016	0.02	0.056
E3	11	E	WH	594	0.12	0.2	0.213
E3	14	E	GY	503	-0	-0.2	-0.135
E3	14	E	GY	504	0.01	-0.02	0.021
E3	14	E	GY	505	-0	0.2	0.213
E3	14	A	GY	506	0.006	0.02	0.056
E3	14	B	GY	507	0.002	-0.03	0.013
E3	14	B	WH	508	0.006	0.2	0.213
E3	14	B	WH	509	0.03	0.2	0.213
E3	14	B	WH	510	0.004	0.07	0.099
E3	14	E	GY	511	0.031	0.2	0.213
E3	14	A	GY	513	0.026	0.2	0.213
E3	14	B	GY	512	0.049	2.3	2.039
E3	14	A	GY	514	0.018	0.1	0.126
E3	14	A	GY	515	0.025	-0.1	-0.048
E3	17	I	GY	631	1.03	1.4	1.056
E3	17	A	GY	632	-0	0.2	0.213
E3	17	I	GY	629	0.47	1.2	0.883
E3	17	I	GY	630	0.97	1.2	0.883
E3	18	I	WH	626	1.23	3.2	2.620
E3	18	I	WH	627	0.98	3.1	2.533
E3	18	I	WH	628	1.31	3.9	3.229
E3	18	I	WH	625	1.1	3.4	2.794
E3	19	E	WH	621	0.113	2.4	2.126
E3	19	E	WH	619	0.013	-0.1	-0.048
E3	19	E	WH	620	0.046	0.4	0.387
E3	20	A	WH	612	0.08	0.5	0.474
E3	20	E	WH	613	0.021	0.3	0.300
E3	20	E	WH	614	0.019	-0.01	0.030
E3	20	E	WH	615	0.031	-0.05	-0.005
E3	21	A	WH	599	0.09	0.04	0.073
E3	21	A	WH	600	0.018	0.1	0.126
E3	21	A	WH	601	0.01	0.2	0.213

BUILDING E5625 — INTERIOR - THIRD FLOOR p. 3

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E3	21	G	WH	603	0.31	2.7	2.387
E3	21	G	WH	604	0.53	1.8	1.604
E3	21	G	WH	602	0.28	1.6	1.430
E3	21	A	WH	605	0.008	0.02	0.056
E3	21	A	WH	606	0.007	-0.15	-0.092
E3	21	I	WH	607	0.28	0.8	0.535
E3	21	I	GY	608	0.05	0.4	0.188

BUILDING E5625 — INTERIOR - FOURTH FLOOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E4	03	B	YL	370	0.023	0.08	0.108
E4	03	A	YL	369	0.014	0.2	0.213
E4	03	A	YL	371	0.04	0.5	0.474
E4	03	A	YL	372	0.018	0.05	0.082
E4	03	B	YL	376	-0.01	0.05	0.082
E4	03	I	YL	373	0.002	0.4	0.188
E4	03	I	YL	374	0.007	0.2	0.014
E4	03	I	YL	375	0.004	0.03	-0.134
E4	03	B	YL	377	0.016	0.1	0.126
E4	03	B	YL	379	0.037	0.5	0.474
E4	03	B	YL	380	0.023	0.2	0.213
E4	03	B	YL	378	0.032	0.1	0.126
E4	04	B	BB	414	0.002	0.07	0.099
E4	04	B	BB	415	-0	0.1	0.126
E4	05	I	-	389	0.007	-0.1	-0.247
E4	05	B	BB	385	0.01	-0.04	0.004
E4	05	A	-	386	0.008	0.1	0.126
E4	05	A	-	387	-0	0.1	0.126
E4	05	A	-	388	3E-05	0.01	0.047
E4	05	B	BB	391	-0.01	-0.02	0.021
E4	05	I	BB	390	0.005	0.3	0.101
E4	05	I	BB	392	0.009	0.3	0.101
E4	05	C	-	393	0.059	0.09	0.117
E4	05	C	-	394	0.041	0.3	0.300
E4	05	C	-	395	0.047	0.4	0.387
E4	07	I	YL	407	0.001	0.3	0.101
E4	07	I	YL	408	5E-04	0.3	0.101
E4	07	I	YL	409	0.002	0.3	0.101
E4	07	I	YL	403	-0	0.2	0.014
E4	07	E	YL	400	0.034	0.1	0.126
E4	07	E	YL	401	-0	-0.07	-0.022
E4	07	E	YL	402	0.025	0.01	0.047
E4	07	G	YL	404	0.036	0.1	0.126
E4	07	G	YL	405	0.014	0.3	0.3
E4	07	G	YL	406	-0.01	-0.01	0.032
E4	08	B	BB	416	6E-05	-0.05	-0.005
E4	08	B	BB	417	-0	0.09	0.117
E4	08	B	BB	418	-0	0.2	0.213
E4	08	B	BB	419	0.001	0.07	0.099
E4	08	I	BB	420	0.003	0.4	0.188
E4	08	I	BB	421	0.009	0.2	0.014
E4	08	I	BB	422	0.006	0.5	0.274
E4	08	I	BB	423	0.005	0.5	0.274
E4	08	I	BB	424	0.008	0.3	0.101
E4	08	I	BB	425	0.008	0.4	0.188

BUILDING E5625 — INTERIOR - FOURTH FLOOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E4	09	B	GY	479	0.006	-0.01	0.033
E4	09	B	GY	480	0.032	-0.09	-0.04
E4	09	E	GY	481	0.009	-0.02	0.021
E4	09	B	GY	482	0.013	-0.02	0.021
E4	12	E	GY	353	0.007	-0.13	-0.074
E4	12	A	GY	354	0.003	0.2	0.213
E4	12	B	GY	355	0.017	0.06	0.091
E4	12	B	GY	356	0.016	0.2	0.213
E4	12	B	GY	358	0.03	0.2	0.213
E4	12	B	GY	357	0.035	0.4	0.387
E4	12	E	GY	359	0.009	0.2	0.213
E4	12	E	GY	360	0.001	-0.11	-0.057
E4	12	E	GY	361	0.006	0.04	0.073
E4	12	B	GY	362	0.004	0.07	0.099
E4	12	A	GY	363	0.033	0.1	0.126
E4	12	A	GY	364	0.032	0.2	0.213
E4	12	A	GY	365	0.019	0.01	0.047
E4	15	I	GC	460	0.8	2.3	1.838
E4	15	I	GC	459	0.85	1.8	1.404
E4	15	I	GC	461	0.59	2.2	1.751
E4	15	I	GC	462	0.93	1.7	1.317
E4	15	I	GC	463	1.81	5.8	4.879
E4	15	A	GC	464	0.018	0.3	0.3
E4	15	A	GC	465	0.035	0.2	0.213
E4	15	A	GC	466	0.018	0.09	0.117
E4	15	E	GC	467	0.012	0.3	0.3
E4	16	A	GC	473	1.2	2.4	2.126
E4	16	G	GC	471	0.71	2	1.778
E4	16	G	GC	472	0.84	2	1.778
E4	16	I	GC	474	1.04	2.4	1.925
E4	16	I	GC	475	0.038	0.5	0.274
E4	17	B	GC	446	-0	0.07	0.099
E4	17	B	GC	447	0.013	0.04	0.073
E4	17	B	GC	448	-0	0.3	0.3
E4	17	G	GC	449	0.39	2.5	2.213
E4	17	G	GC	450	0.58	2.7	2.387
E4	17	G	GC	451	0.5	3.2	2.822
E4	17	I	GC	452	0.01	0.5	0.274
E4	17	E	GC	453	0.011	-0.06	-0.014
E4	17	E	GC	454	0.011	0.01	0.047
E4	17	E	GC	455	0.02	-0	0.037
E4	18	G	BW	433	0.17	0.8	0.734
E4	18	G	BW	434	0.37	3.9	3.431
E4	18	G	BW	435	0.29	2.7	2.387

BUILDING E5625 — INTERIOR - FOURTH FLOOR p. 3

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
E4	18	A	BW	430	0.21	0.4	0.387
E4	18	A	BW	431	0.002	0.4	0.387
E4	18	A	BW	432	0.017	0.3	0.3
E4	18	B	BW	436	0.005	-0.01	0.03
E4	18	B	BW	437	0.024	0.1	0.126
E4	18	B	BW	438	0.012	0.3	0.3
E4	18	B	BW	439	0.013	0.3	0.3
E4	18	B	BW	440	0.023	0.07	0.099
E4	18	B	BW	441	0.022	-0.02	0.021

BUILDING E5627 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
G1	EXT	E	WH	1058	0.028	0.200	0.213
G1	EXT	E	WH	1057	0.004	0.200	0.213
G1	EXT	E	WH	1060	-0.003	0.100	0.126
G1	EXT	E	WH	1055	-0.004	-0.100	-0.048
G1	EXT	E	WH	1056	0.007	0.100	0.126
G1	EXT	E	WH	1059	0.001	0.090	0.117

BUILDING E5627 — INTERIOR p. 1

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
G1	01	A	PC	326	0.032	0.200	0.213
G1	01	B	PC	327	0.041	0.030	0.065
G1	01	B	PC	328	0.046	0.006	0.044
G1	01	B	PC	329	-0.003	0.080	0.108
G1	01	B	PC	330	0.033	0.080	0.108
G1	01	E	PC	331	0.044	0.200	0.213
G1	02	E	PC	307	0.041	0.050	0.082
G1	02	E	PC	306	0.046	0.100	0.126
G1	02	E	PC	309	0.046	0.090	0.117
G1	02	B	PC	310	0.040	0.300	0.300
G1	02	B	PC	311	0.046	0.070	0.099
G1	02	E	PC	308	0.055	0.100	0.126
G1	03	E	BB	290	0.051	0.200	0.213
G1	03	E	BB	291	0.039	-0.050	-0.005
G1	03	E	BB	292	0.071	-0.070	-0.022
G1	03	E	BB	293	0.055	0.400	0.387
G1	03	E	BB	294	0.038	-0.001	0.038
G1	03	E	BB	295	0.048	0.100	0.126
G1	04	E	PC	264	0.051	0.400	0.387
G1	04	E	PC	265	0.057	0.500	0.474
G1	04	E	PC	266	0.000	0.100	0.126
G1	04	E	PC	267	0.033	0.100	0.126
G1	05	E	BB	257	0.068	0.500	0.474
G1	05	E	BB	258	0.035	0.030	0.065
G1	05	E	BB	259	0.048	0.500	0.474
G1	05	E	BB	260	0.042	0.300	0.300
G1	06	E	CR	241	0.024	0.100	0.126
G1	06	E	CR	239	0.120	0.300	0.300
G1	06	E	CR	240	0.013	0.080	0.108
G1	06	E	CR	242	0.020	0.050	0.082
G1	06	E	CR	243	0.026	0.200	0.213
G1	06	E	CR	244	0.033	0.200	0.213
G1	07	E	CR	226	0.077	0.030	0.065
G1	07	E	CR	221	0.039	0.400	0.387
G1	07	M	CR	222	0.043	0.300	0.300
G1	07	M	CR	223	0.025	0.030	0.065
G1	07	M	CR	224	0.039	0.040	0.073
G1	07	E	CR	225	0.039	0.200	0.213
G1	08	E	BB	199	0.052	0.200	0.213
G1	08	E	BB	200	0.047	0.300	0.300
G1	08	E	BB	201	0.043	0.060	0.091
G1	08	M	BB	203	0.030	0.080	0.108
G1	08	M	BB	202	0.025	0.300	0.300
G1	08	M	BB	204	0.023	0.070	0.099
G1	09	E	CR	179	0.027	0.100	0.126
G1	09	E	CR	180	0.037	0.300	0.300
G1	09	E	CR	181	0.002	-0.200	-0.135

BUILDING E5627 — INTERIOR p. 2

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
G1	09	E	CR	182	0.044	0.300	0.300
G1	10	E	CR	170	0.016	0.200	0.213
G1	10	E	CR	171	0.036	0.200	0.213
G1	10	E	CR	172	0.019	-0.030	0.013
G1	10	E	CR	173	0.050	0.300	0.300
G1	10	E	CR	174	0.120	0.900	0.821
G1	10	E	CR	175	0.041	0.300	0.300
G1	11	E	PK	211	0.042	0.090	0.117
G1	11	E	PK	210	0.026	0.400	0.387
G1	11	E	PK	212	0.028	-0.050	-0.005
G1	11	E	PK	213	0.037	-0.090	-0.040
G1	11	E	PK	214	0.041	0.200	0.213
G1	11	N	PK	215	0.003	-0.120	-0.066
G1	11	N	PK	216	0.015	0.100	0.126
G1	11	N	PK	217	0.006	0.100	0.126
G1	12	E	LG	230	0.028	0.030	0.065
G1	12	N	LG	231	0.011	-0.110	-0.057
G1	12	E	LG	232	0.023	0.300	0.300
G1	12	N	LG	233	0.010	-0.070	-0.022
G1	12	N	LG	234	0.007	0.100	0.126
G1	12	N	LG	235	0.001	0.200	0.213
G1	13	E	LG	248	0.027	0.300	0.300
G1	13	N	LG	249	0.005	-0.160	-0.101
G1	13	E	LG	250	0.020	0.200	0.213
G1	13	E	LG	251	0.022	0.100	0.126
G1	13	E	LG	252	0.033	-0.090	-0.040
G1	13	E	LG	253	0.039	0.100	0.126
G1	14	E	CR	196	0.050	0.200	0.213
G1	14	E	CR	197	0.050	0.100	0.126
G1	14	E	CR	198	0.047	0.400	0.387
G1	15	E	BB	278	0.039	0.040	0.073
G1	15	E	BB	279	0.065	0.200	0.213
G1	15	E	BB	280	0.055	-0.004	0.035
G1	15	E	BB	281	0.034	0.500	0.474
G1	16	E	BB	283	0.120	1.000	0.908
G1	16	E	BB	284	0.113	1.200	1.082
G1	16	E	BB	285	0.107	0.900	0.821
G1	16	E	BB	286	0.058	1.400	1.256
G1	17	M	BB	299	0.019	0.100	0.126
G1	17	E	BB	300	0.001	0.090	0.117
G1	17	E	BB	301	0.031	0.400	0.387
G1	17	E	BB	302	0.038	0.030	0.065
G1	18	B	CR	315	0.032	0.300	0.300
G1	18	B	CR	316	0.043	0.200	0.213
G1	18	B	CR	317	0.044	0.400	0.387
G1	18	E	CR	318	0.040	0.400	0.387
G1	18	M	CR	319	0.039	0.400	0.387

BUILDING E5627 — INTERIOR p. 3

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
G1	18	M	CR	320	0.016	0.110	0.134
G1	18	M	CR	321	0.032	0.050	0.082
G1	18	E	CR	322	0.048	0.100	0.126
G1	19	E	CR	271	0.035	0.010	0.047
G1	19	M	CR	272	0.009	-0.100	-0.048
G1	19	E	CR	273	0.044	0.300	0.300
G1	19	E	CR	274	0.073	0.200	0.213
G1	20	E	CR	188	0.018	0.040	0.073
G1	20	E	CR	186	0.046	0.300	0.300
G1	20	E	CR	187	0.024	0.200	0.213
G1	20	E	CR	189	0.036	0.200	0.213
G1	20	E	CR	190	0.038	0.300	0.300
G1	20	E	CR	191	0.074	0.300	0.300
G1	20	E	CR	192	0.031	0.300	0.300
G1	8A	E	BB	207	0.063	0.400	0.387
G1	8A	M	BB	206	0.014	0.060	0.091

BUILDING E5632 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
H1	EXT	B	EW	335	-0.002	0.030	0.065
H1	EXT	B	EW	336	0.014	0.060	0.091
H1	EXT	B	EW	337	-0.002	-0.130	-0.074
H1	EXT	B	EW	338	0.002	-0.070	-0.022
H1	EXT	B	EW	339	-0.001	0.100	0.126
H1	EXT	B	EW	340	-0.004	0.040	0.073

BUILDING E5633 — EXTERIOR

BLDG	ROOM	SUBST	COLOR	SEQNO	L	K	VALUE
I1	EXT	E1	EW	344	0.005	0.080	0.108
I1	EXT	E1	EW	345	0.001	0.100	0.126
I1	EXT	E1	EW	346	0.005	-0.100	-0.048
I1	EXT	E2	EW	348	0.008	0.100	0.126
I1	EXT	E3	EW	347	0.001	0.080	0.108
I1	EXT	E4	EW	349	0.004	0.040	0.073

Appendix C:
Stratified Random Sampling Formulas

Appendix C: Stratified Random Sampling Formulas

This appendix reproduces formulas given in Chapters 5 and 5A of Cochran (1977) for use in the analysis of data collected using a stratified random sampling approach. In addition, other formulas referred to in Section 4.2 are provided.

This appendix will use Cochran's notation. L denotes the number of strata that are defined, and the subscript h denotes a particular stratum. Each stratum consists of sampling units, each of which has an equal chance of being included in the sample actually drawn from that stratum. Cochran's notation then is:

N_h	Total number of units in the stratum
n_h	Number of units in the sample
y_{hi}	Value obtained for the i -th unit in the sample
$W_h = \frac{N_h}{N}$	Stratum weight
$N = \sum_{h=1}^L N_h$	Total number of units in all strata
$f_h = \frac{n_h}{N_h}$	Sampling fraction in the stratum
$\bar{Y}_h = \frac{1}{N_h} \sum_{i=1}^{N_h} y_{hi}$	True mean for the stratum
$\bar{y}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} y_{hi}$	Sample mean for the stratum
$S_h^2 = \frac{1}{N_h - 1} \sum_{i=1}^{N_h} (y_{hi} - \bar{Y}_h)^2$	True variance for the stratum
$s_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2$	Sample variance for the stratum

The following formulas implement a stratified random sampling approach:

$$\bar{y} = \frac{1}{N} \sum_{h=1}^L \bar{y}_h = \sum_{h=1}^L W_h \bar{y}_h \quad \text{Estimated population mean}$$

$$s^2(\bar{y}) = \sum_{h=1}^L \frac{W_h^2 s_h^2}{n_h} - \sum_{h=1}^L \frac{W_h s_h^2}{N} \quad \text{Estimated variance of the population mean}$$

$$n_e = \frac{\left(\sum g_h s_h^2 \right)^2}{\sum \frac{g_h^2 s_h^4}{n_h - 1}} \quad \text{Effective number of degrees of freedom}$$

$$g_h = \frac{N_h (N_h - n_h)}{n_h} \quad \text{Used in previous formula}$$

$$s^2 = \frac{N}{N-1} \sum_{h=1}^L \left[s_h^2 + (\bar{y}_h - \bar{y})^2 \right] \quad \text{Estimated population variance}$$

An approximate correction for instrument error can be made to the sample variance using data on the variability of XRF measurements. The sample variance for a stratum consists of two contributions, one from the variability of the quantity being measured and one from the variability of individual measurements for the measurement technique being used. The correction for instrument error consists of subtracting an estimate of the variance due to instrument variability from the sample variance s_h^2 . The contribution of instrument variability to the sample variance for a stratum can be computed from

$$s_h^2(\text{inst}) = (c + d\bar{y}_h)^2 + d^2 \left(1 - \frac{1}{n_h} \right) s_h^2 \quad (\text{C.1})$$

where c and d are the intercept and slope of the regression line of instrument standard deviation against lead loading; these values are obtained from Table 9 in the main text. Note that the second term should really contain the corrected variance rather than s_h^2 , but the second term is much smaller than the first for the cases considered in this work, and this minor correction was ignored.

A correction for errors in the weights W_h can be added to the estimated variance of the mean using estimates of the errors of stratum areas. If these errors have zero mean, the estimated

The following formulas implement a stratified random sampling approach:

$$\bar{y} = \frac{1}{N} \sum_{h=1}^L \bar{y}_h = \sum_{h=1}^L W_h \bar{y}_h$$

Estimated population mean

$$s^2(\bar{y}) = \sum_{h=1}^L \frac{W_h^2 s_h^2}{n_h} - \sum_{h=1}^L \frac{W_h s_h^2}{N}$$

Estimated variance of the population mean

$$n_e = \frac{\left(\sum_{h=1}^L g_h s_h^2 \right)^2}{\sum_{h=1}^L \frac{g_h^2 s_h^4}{n_h - 1}}$$

Effective number of degrees of freedom

$$g_h = \frac{N_h(N_h - n_h)}{n_h}$$

Used in previous formula

$$s^2 = \frac{N}{N-1} \sum_{h=1}^L \left[s_h^2 + (\bar{y}_h - \bar{y})^2 \right]$$

Estimated population variance

An approximate correction for instrument error can be made to the sample variance using data on the variability of XRF measurements. The sample variance for a stratum consists of two contributions, one from the variability of the quantity being measured and one from the variability of individual measurements for the measurement technique being used. The correction for instrument error consists of subtracting an estimate of the variance due to instrument variability from the sample variance s_h^2 . The contribution of instrument variability to the sample variance for a stratum can be computed from

$$s_h^2(\text{inst}) = (c + d\bar{y}_h)^2 + d^2 \left(1 - \frac{1}{n_h} \right) s_h^2 \quad (\text{C.1})$$

where c and d are the intercept and slope of the regression line of instrument standard deviation against lead loading; these values are obtained from Table 9 in the main text. Note that the second term should really contain the corrected variance rather than s_h^2 , but the second term is much smaller than the first for the cases considered in this work, and this minor correction was ignored.

A correction for errors in the weights W_h can be added to the estimated variance of the mean using estimates of the errors of stratum areas. If these errors have zero mean, the estimated

Reference

Cochran, W.G. (1977) *Sampling Techniques* (Third Edition), John Wiley and Sons, New York, N.Y.

Appendix D:

Analysis of Paint Chip Samples for RCRA Metals

Appendix D: Analysis of Paint Chip Samples for RCRA Metals

D.1 Background

The Data Quality Objective (DQO) for conducting lead analyses on the painted surfaces within the PPC was identified in Section 3.1. Paint chips were collected in June 1994 from various locations within the PPC to (1) obtain preliminary information on the potential lead burden within the PPC, (2) acquire some initial insight into the possibility that the lead content of the PPC might exceed the RCRA regulatory level, (3) survey the paint within the PPC for all eight metals (Ag, As, Ba, Cd, Cr, Hg, Se, and Pb) regulated by RCRA, and (4) identify any metals other than lead that would pose a potential problem. This approach appeared attractive as an initial screening technique, because it would be considered non-invasive and could be performed immediately and, in addition, might help define the magnitude of the field XRF investigation to follow.

D.2 Sample Selection

Members of the ANL field sampling team were accompanied by ERDEC personnel in acquiring the paint chips from the various locations within the Pilot Plant (Building E5625). The selection of sampling sites was governed by the desire to sample as many different types of painted surfaces as possible. This meant collecting paint chips from a variety of substrates, such as cinder block, metal railings, and structural steel beams. It also involved acquiring samples from as many different colored surfaces as possible to determine whether paint color was related to metal content. Because the results were to be used in planning the subsequent XRF investigation of lead in the painted surfaces in the PPC, the broadest spectrum of sample types was desired. In all, a total of 22 individual paint chip samples were collected.

Because Army regulations require that the removal of paint chips be non-invasive (due to the possible presence of chemical warfare agents), it was not possible to scrape the paint from the various substrates. Therefore, the samples obtained for these analyses were paint chips that were already in the process of flaking off from the substrate. Sampling consisted of lightly brushing the painted surfaces with a thin bristled brush and collecting the paint chips in a metal tray. Each sample was then divided into two sub-samples and each sub-sample bagged in Zip-loc plastic containers, double contained in metal cans, and transported to the ERDEC Monitoring Branch for chemical agent screening. Once chemical agent clearance was obtained, the samples were transported to the ANL analytical laboratory for analysis. A chain-of-custody procedure was used for tracking the samples throughout this process.

D.3 Sample Analysis

Upon clearance by the ERDEC Monitoring Branch, the paint chip samples were logged into the ANL analytical laboratory log and assigned ANL sample numbers. All samples appeared non-uniform with respect to size and thickness; many of the paint chips exhibited traces of the substrate from which they were removed.

The paint chips were analyzed for all metals except mercury by using a method involving the digestion of 0.2 g of paint chips in hot nitric acid and hydrogen peroxide, followed by analysis of the digestate using inductively coupled plasma atomic emission spectroscopy (ICP-AES). Mercury concentrations were measured by using EPA SW-846 Method 7471, which involved digesting (oxidizing) 0.2 g of paint chips in potassium permanganate and potassium persulfate. The sample was then reduced with stannous chloride and the mercury vapor was measured using conventional cold vapor atomic absorption on an automated mercury analyzer.

D.4 Results and Conclusions

The results of the analyses are presented in Table D-1. The metal concentrations for all the paint chips surveyed are very low and, based on preliminary calculations, there does not appear to be a potential rubble disposal problem with any of the RCRA metals. This does not mean that all the painted surfaces were low in lead content. For example, lead concentrations of 17.8% and 27.9% were measured. However, both these samples were collected from steel surfaces that can be easily removed from the demolition rubble, if necessary. Also, their contribution to the total mass of the demolition rubble would be insignificant.

TABLE D-1 Results of Paint Chip Analysis

Building E5625^a

Sample Location					RCRA-Regulated Metal Concentration (percent by weight)							
Floor	Room	Surface ^b	Substrate Code ^c	Color	Ag	As	Ba	Cd	Cr	Hg	Pb	Se
1	32	2	B	GN	<0.001	<0.007	0.234	<0.001	0.005	0.0003	0.79	<0.007
1	31	C	C	WH	0.001	<0.007	0.200	0.001	0.013	0.0010	1.26	<0.007
1	26	1	I	GN	<0.001	<0.007	0.189	<0.001	0.009	0.0228	0.08	<0.007
1	26	—	(steel)	GY	0.001	<0.007	0.022	0.015	0.002	0.0011	0.02	<0.007
1	3	4	B	WH	<0.001	<0.007	0.079	<0.001	0.004	0.0000	0.07	<0.007
1	8	10	A	WH	<0.002	<0.007	0.358	<0.01	0.003	0.0009	0.04	<0.007
2	8	10	O	WH	0.001	<0.007	0.030	<0.001	0.015	0.0025	0.28	<0.007
2	23	C	(steel)	GY	<0.001	<0.007	0.073	<0.001	0.046	0.0007	0.24	<0.007
2	19	—	(sr)	YL	0.002	<0.007	0.053	0.004	3.87	0.0017	17.76	<0.007
2	20	1	A	WH	<0.001	<0.007	0.106	<0.001	0.008	0.0002	0.03	<0.007
2	8	1	(steel)	WH	<0.001	<0.007	0.011	0.002	1.97	0.0001	0.87	<0.007
3	14	4	A	WH	<0.001	<0.007	0.037	<0.001	0.011	0.0002	0.20	<0.007
3	7	3	A	WH	<0.001	<0.007	0.025	<0.001	0.004	0.0010	0.09	<0.007
3	21	F	C	black	0.001	<0.007	0.186	0.002	0.105	0.0005	1.00	<0.007
3	19	4	A	WH	<0.001	0.013	0.174	<0.001	0.004	0.0067	0.84	<0.007
3	3	1	B	YL	<0.001	<0.007	0.172	0.002	0.008	0.0002	27.91	<0.007
3	5	—	I	—	<0.001	<0.007	0.004	<0.001	0.002	0.0001	0.12	<0.007
3	7	2	A	WH	<0.001	<0.007	0.256	<0.001	0.003	0.0004	0.13	<0.007
3	11	7	A	WH	<0.001	<0.007	0.015	0.001	0.017	0.0004	2.22	<0.007
4	17	2	B	GY	<0.001	<0.007	0.187	0.002	0.005	0.0014	0.64	<0.007
4	3	4	B	YL	<0.001	<0.007	0.011	<0.001	0.002	0.0000	0.01	<0.007
4	12	4	I	WH	0.001	<0.007	0.046	<0.001	0.003	0.0001	0.09	<0.007
Maximum TCLP leachate concentration (mg/L) =					5	5	100	1	5	0.2	5	1

^a Major elemental components of paint chip samples: Ca (0.2-13.5%), Fe (0.09-8.05%), Mg (0.02-2.47%), Zn (0.01-5.79%).
 Other elemental components present include: Be (2-5 ppm), Co (12-284 ppm), Cu (32-582 ppm), Mn (12-555 ppm), Ni (12-310 ppm),
 Sb (<0.72-718 ppm), Tl (<72-105 ppm), V (6-116 ppm).

TABLE D-1 (Cont.)

- ^b Denotes the specific surface in each room, using the ANL identification code, from which the sample was collected. C denotes the ceiling, F the floor, and — denotes samples for which the location was not determined (loose chips may have been collected from the floor).
- ^c See Table 3 in the main text: (steel) denotes a steel substrate not otherwise specified; (sr) denotes a steel railing.
- ^d See Table 3 in the main text: "black" denotes black paint, for which no color code was assigned; — denotes a sample for which the paint color was not recorded.

Appendix E:

**Pilot Plant Complex Lead Content —
Alternative Statistical Approach to Hypothesis Testing**

Appendix E: Pilot Plant Complex Lead Content — Alternative Statistical Approach to Hypothesis Testing

E.1 Introduction

This appendix presents the statistical basis of the alternative approach developed for use in testing the hypothesis that the lead content in each Aberdeen Proving Ground Pilot Plant Complex building is less than the threshold amount that would result in non-compliance with the RCRA waste disposal regulations for lead in building debris. Only lead in lead-based paint is considered. The approach described here gives directly a value for the probability that the threshold is not exceeded; if this probability is greater than 95%, the requirement of 95% confidence is considered to be satisfied.

This introductory section gives the background for the approach described in later sections. The general formula for the desired probability is derived in Section E.2. Assumptions regarding the probability distribution functions needed in this approach are discussed in Section E.3. The final specific expression for the desired probability is given in Section E.4. An approximate conservative expression for the desired probability is derived in Section E.5. Results from the application of this method to PPC buildings are presented also in Section E.5.

Three quantities must be estimated in order to evaluate the lead content in a building and the possibility of non-compliance with waste disposal regulations: the total painted surface area (A) in the building, the average lead loading (L , mass per unit surface area) in the painted area, and the total mass of debris (M) that will be generated during building demolition. Estimates of each of these quantities are considered random variables, and the problem at hand is to determine with a specified level of confidence that the product $A_t \times L_t$ is less than $10^{-4} M_t$, where the factor 10^{-4} arises from the waste disposal regulations for lead. The subscript t denotes the true (unknown) value of the parameter. Equivalently, we wish to test the hypothesis H_0 :

$$H_0: A_t \times L_t - 10^{-4} M_t < 0 \quad . \quad (E.1)$$

(Note that this hypothesis is the reverse of that considered in the main body of the text.)

Although this hypothesis involves the *true* values of the three parameters, only *estimated* values are available. According to the "classical" approach to hypothesis testing, the quantity $Q = A_t \times L_t - 10^{-4} M_t$ is either truly less than or greater than zero (ignoring the zero probability case $Q = 0$), and is not a random variable. When we state that H_0 is true with 95% confidence, this is to be interpreted as meaning that if an indefinitely large number of sets of measurements of A , L , and M were made, 95% of the associated estimates of Q would be negative. According to the classical approach, developed in the 1920s and taught in most statistics textbooks today, this is not the same thing as saying that the "probability" that H_0 is true is 0.95. When we speak informally of the probability that H_0 is true, we make a statement about our "subjective" belief that H_0 is true,

rather than a statement about the true numerical value of the quantity Q . Classical statistics does not recognize the concept of “subjective” probability as being valid, although it is at the heart of the Bayesian approach to statistics (Lee 1989).

A large part of classical statistics deals with the question of evaluating parameters, like means and variances, that characterize the probability distribution functions (pdfs) of populations from which random samples of some size are drawn. The present problem is not this simple, however. Three random variables and their associated pdfs are involved, and the main focus of concern is another random variable defined as a nonlinear function of the first three. Let A , L , and M denote measurement-based estimates of the quantities A_t , L_t , and M_t , and let q denote the associated estimate of Q : $q = A \times L - 10^{-4}M$; q is a random variable since A , L , and M are. The difficulties in constructing a suitable test of the null hypothesis H_0 according to classical statistical principles are due to at least three factors: (1) only one estimate q of the true value of Q is available (the sample size is unity), (2) the probability distribution function for q is complicated and must be computed numerically, and (3) the pdf for q depends not only on q and Q but also on the values of parameters that characterize the pdfs for A , L , and M . These factors make it infeasible to construct a test of H_0 using classical statistical principles without making additional and unacceptable approximations and assumptions.

The approach adopted here is to utilize a formula derived below for the value of the (Bayesian) cumulative distribution function for Q at $Q = 0$, given reasonable assumptions about the distributions of the estimates A , L , and M , together with the results of X-ray fluorescence (XRF) measurements of the lead loading and other physical measurements in and about each building. The Bayesian probability that H_0 is true is obtained directly by evaluating the given formula. The great advantages of using a Bayesian approach are that the final formula for the desired probability contains only known quantities and that additional assumptions and approximations regarding the distribution of q are unnecessary. In addition, it should be noted that the estimated uncertainties in the painted area A and the rubble mass M are not based on results from sampling some population, but rather on engineering judgment — in other words, on professional engineers’ subjective evaluation of the accuracy of the estimates. They are already Bayesian probabilities.

E.2 Derivation of a Formula for the Probability that $Q < 0$

The classical approach in problems like this is to find the distribution function of q (an estimator of Q based on measurements) in terms of only Q and known quantities, and to use it to derive confidence limits for Q . This is very difficult to do in practice except for the simplest estimators, and a different approach is needed here. A Bayesian approach that uses probability distribution functions (pdfs) for the quantities A_t , L_t , and cM_t , where $c = 10^{-4}$, is adopted. These are definite physical quantities with definite and specific but unknown values, and the concept of pdfs for them is characteristic of the Bayesian approach to statistics. The term “probability” as used here is essentially synonymous with “uncertainty;” the pdf for L_t , for example, describes the uncertainty with which the value of L_t is known, given that an estimate L of that value is available from XRF data.

To illustrate the point further, suppose that an estimator (m) for some parameter has a normal distribution with mean μ and standard deviation σ . The pdf for the estimator is then given by:

$$f(m) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{m-\mu}{\sigma}\right)^2\right\} . \quad (\text{E.2})$$

The classical interpretation of this equation is that $f(m)$ describes the probability distribution of the random variable m in terms of the population parameters μ and σ . Suppose, however, that a specific value for m has been obtained from a set of measurements, and suppose that the value of σ is known independently. Then this equation can be interpreted as describing our *uncertainty* regarding the true mean μ , given the known values of m and σ . The Bayesian probability that μ lies in the range from μ to $\mu+d\mu$, given the estimate m and the known value of σ , is then $f(\mu)d\mu$ where $f(\mu)$ is given by:

$$f(\mu) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(\frac{\mu-m}{\sigma}\right)^2\right\} . \quad (\text{E.3})$$

Both classical and Bayesian statistics recognize this expression as describing the probability that m and μ differ by the specified amount. Classical statisticians regard m as the result of a set of measurements that, in principle, could be repeated indefinitely so that the frequency with which m takes on a value in any specified range can be determined. Equation (E.2) then describes the resulting distribution. Bayesian statisticians view the algebraically equivalent Equation (E.3) as describing our uncertainty regarding the value of μ , given the actual measurement m that has been made.

A quantity that has a definite but unknown (uncertain) value will be called an “uncertain variable” in the rest of this discussion. A random variable is a quantity that takes different values as a result of different but similar measurements. An uncertain variable or parameter is a definite physical quantity with a specific but unknown value, and measurements lead to an estimate of that value; the estimate itself is a random variable. The probability distribution function for an uncertain variable is the usual Bayesian a’posteriori pdf (Lee 1989). Uniform Bayesian prior pdfs are assumed.

To continue the example, the Bayesian probability that μ is less than some given value u is given by:

$$p(\mu < u) = \int_{-\infty}^u f(\mu) d\mu . \quad (\text{E.4})$$

This equation can be used to derive confidence limits on μ that are equivalent (in this case) to those derived by classical methods.

The objective in the rest of this section is to derive an expression for the Bayesian probability (or level of uncertainty) that the product of two uncertain variables (x and y) is less than the value of a third (z). The first step is to compute the probability that the product xy is less than a specified number v . Given that y lies in the range $[u, u+du]$, the product xy will be less than v if x is less than v/u . The desired probability, conditional on y being in the specified range, is therefore equal to the probability of x being less than v/u , which is given by $F(v/u)$ where $F(x)$ is the cumulative distribution function for the variable x :

$$p(xy < v : y \in [u, u + du]) = p(x < v / u) = F(v / u) \quad (\text{E.5})$$

where

$$F(x) = \int_0^x f(\xi) d\xi \quad (\text{E.6})$$

Here $f(x)$ denotes the pdf for the uncertain variable x . The lower limit on this integral was taken to be zero in recognition of the fact that all the variables in the specific problem of interest here are physically non-negative. The total probability that xy is less than z , for z in the range $[v, v+dv]$, is then obtained by multiplying the conditional probability in Equation (E.5) by the probability that y is in the given range and integrating over u . The result is:

$$p(xy < z : z = v) = \int_0^\infty F(v / u) g(u) du \quad (\text{E.7})$$

Here $g(y)$ is the pdf for y .

Equation (E.7) is valid for a given value of z . If z is itself uncertain, as is the case of interest here, the total desired probability is obtained by multiplying this expression by the probability that z lies in the range $[v, v+dv]$ and integrating over v :

$$p(xy < z) = \int_0^\infty \int_0^\infty F(v / u) g(u) h(v) dv du \quad (\text{E.8})$$

Here $h(z)$ is the pdf for z . Equation (E.8) is the desired result for the probability that $Q < 0$, after we identify x as A_t , y as L_t , and z as $10^{-4}M_t$.

E.3 Probability Distribution Functions for A, L, and M

In order to compute the value of the integral in Equation (E.8), expressions for the probability distribution functions for x, y, and z must be available. In the specific problem at hand, assumptions must be made because the distribution functions are not known.

Total Painted Surface Area

It is assumed that the probability distribution of the estimate of the total painted surface in the building is normal with mean A (unknown) and standard deviation σ_A (assumed known). Since the area is inherently positive, only positive values will be considered and slight adjustments made to the normal pdf to take this into account. The assumed pdf for the uncertain quantity $x = A_t$ is:

$$f(x) = \frac{1}{W_A \sigma_A \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{x-A}{\sigma_A} \right)^2 \right] . \quad (\text{E.9})$$

Here A denotes the value of the available estimate. The range of the variable is truncated to $(0 \leq x < \infty)$, and the normalization constant W_A is then chosen so that the pdf is properly normalized to unity. The resulting value of W_A is :

$$W_A = 1 - \frac{1}{2} \operatorname{erfc} \left(\frac{A}{\sigma_A \sqrt{2}} \right) = 1 - \frac{1}{2} \operatorname{erfc}(\lambda_A) . \quad (\text{E.10})$$

In Equation (E.10), $\operatorname{erfc}(b)$ denotes the complementary error function (Abramowitz and Stegun, 1965). The associated cumulative distribution function $F(w)$ is then given by:

$$F(w) = p(x < w) = 1 - \frac{1}{2W_A} \operatorname{erfc}(r) \quad (\text{E.11})$$

with
$$r = \lambda_A \left(\frac{w}{A} - 1 \right) . \quad (\text{E.12})$$

Note that the equations can be written so that $F(w)$ depends only on the quantities A/σ_A and w/A .

The use of a truncated normal distribution avoids possible problems with non-physical negative values and is essentially indistinguishable from a true normal distribution if A/σ_A is greater than about 5. In the analysis described in the main text, three times σ_A was assumed equal to the quoted uncertainty of $\pm 10\%$ of the estimated value A, so that A/σ_A was equal to 30. Then the quantity $1 - W_A$ equals 5×10^{-198} ; in this case, the effect of restricting the distribution to

positive values of A only is quite negligible and W_A may be replaced by unity in the above equations.

Mass of Building Debris

The value for the total mass of debris to be generated on demolition is based on engineering estimates and associated computations. In addition, upper and lower bounds can be set on the actual value based on the professional judgment of the engineers involved in making the estimate. The value itself is considered to be fairly uncertain, but the level of uncertainty drops to zero at those bounds. The model that is assumed for the distribution of the uncertain parameter M_t is a simple parabolic function:

$$h(M_t) = \frac{3}{4d} \left[1 - \left(\frac{M_t - M}{d} \right)^2 \right] . \quad (\text{E.13})$$

Here M denotes the value of the estimate, and the physical bounds on the value of M_t are assumed to be $M - d$ and $M + d$, thereby defining d . The pdf for M_t goes to zero as M_t approaches either $M - d$ or $M + d$, as required. The value of d used in this study was $0.2M$, and is regarded as conservative. The parameter M_t enters into the computations only in combination with the factor $c = 10^{-4}$. A change of variable gives the corresponding distribution of the uncertain quantity $z = cM_t$ in terms of the estimate M and the parameter d :

$$h(z) = \frac{3}{4cd} \left[1 - \left(\frac{z - cM}{cd} \right)^2 \right] . \quad (\text{E.14})$$

It is convenient for future use to define $\psi(\eta)$ to be:

$$\psi(\eta) = \frac{3}{4} (1 - \eta^2) \quad (\text{E.15})$$

with η defined as

$$\eta = \frac{z - cM}{cd} . \quad (\text{E.16})$$

Average Lead Loading

The mean lead loading for each building is estimated using XRF measurements and a stratified random sampling approach. Cochran (1977, pp. 95-96) prescribes the use of the Student's t distribution for the computation of confidence limits for the mean in such cases. In classical statistics, the Student's t distribution arises in problems where neither the mean nor the variance of an assumed normally distributed population being sampled are initially known. In Bayesian statistics the t distribution arises naturally in the same situations (Lee 1989, pp. 68-71).

As discussed in the main text, there is evidence that this assumption may not be appropriate for some buildings and in those cases, principally those in which the ratio of the standard deviation of the mean to the mean itself (the relative standard deviation or RSD) was not small compared to unity, a different distribution was assumed for the mean lead loading. In cases where the RSD was small and the effective number of degrees of freedom was greater than about 10, either a Student's *t* or a Normal distribution was a suitable choice.

The normal distribution is discussed above, but for future use it is convenient to transform variables by defining

$$\xi = \frac{y}{S\sqrt{2}} \quad (\text{E.17})$$

and

$$\lambda = \frac{L}{S\sqrt{2}} . \quad (\text{E.18})$$

S is the estimated standard error of the mean *L* and *y* is the uncertain true value *L_t*. Then the normalized distribution function for ξ is

$$\phi(\xi) = \frac{1}{W\sqrt{\pi}} e^{-(\xi-\lambda)^2} \quad (\text{E.19})$$

where, as in the case of the painted area, the distribution is restricted to positive values of the lead loading. The use of the normal distribution must therefore be restricted to cases in which *S/L* is sufficiently small. The associated renormalization factor *W* is given by

$$W = 1 - \frac{1}{2} \text{erfc}(\lambda) . \quad (\text{E.20})$$

The cumulative distribution $\Phi(\xi)$ is defined by

$$\Phi(\xi) = \int_0^{\xi} \phi(x) dx \quad (\text{E.21})$$

and is given for the normal distribution by

$$\Phi(\xi) = 1 - \frac{1}{2W} \text{erfc}(\xi - \lambda) . \quad (\text{E.22})$$

The Student's t distribution is given by (Mood and Graybill 1963, p. 233 and 252):

$$p(t) = \frac{1}{\sqrt{k\pi}} \frac{\Gamma(\frac{k+1}{2})}{\Gamma(\frac{k}{2})} \left(1 + \frac{t^2}{k}\right)^{-\frac{1}{2}(k+1)} \quad (\text{E.23})$$

where k is the number of degrees of freedom and the variable t is defined by:

$$t = \frac{y - L}{S} . \quad (\text{E.24})$$

Since the same expression arises in Bayesian statistics, the same dichotomy of interpretations as in the normal distribution case also exists, and we may interpret Equation (E.23) as describing our uncertainty regarding the true value L_t , given a measured value L .

As usual, the range of the variable is restricted to positive values only and the distribution renormalized. The resulting expression for the distribution $g(y)$, where y is identified as the true mean lead loading L_t , is:

$$g(y) = \frac{1}{WS\sqrt{k}B(\frac{k}{2}, \frac{1}{2})} \left[1 + \left(\frac{y-L}{S\sqrt{k}}\right)^2\right]^{-\frac{1}{2}(k+1)} \quad (\text{E.25})$$

where W is the renormalization factor and B is a Beta function (Abramowitz and Stegun 1965, Chap. 6). For future use, it is convenient to transform variables by defining

$$\xi = \frac{y}{S\sqrt{k}} \quad (\text{E.26})$$

and

$$\lambda = \frac{L}{S\sqrt{k}} . \quad (\text{E.27})$$

Then the normalized distribution for ξ is:

$$\phi(\xi) = \frac{1}{WB(\frac{k}{2}, \frac{1}{2})} \left[1 + (\xi - \lambda)^2\right]^{-\frac{1}{2}(k+1)} . \quad (\text{E.28})$$

The renormalization factor W is given by:

$$W = 1 - \frac{1}{2} I_{\delta} \left(\frac{k}{2}, \frac{1}{2} \right) \quad (\text{E.29})$$

where $I_{\delta} \left(\frac{k}{2}, \frac{1}{2} \right)$ is an Incomplete Beta function and δ is given by:

$$\delta = \frac{1}{1 + \lambda^2} \quad (\text{E.30})$$

The associated cumulative distribution function $F(x)$ is given by

$$\Phi(\xi) = 1 - \frac{1}{2W} I_x \left(\frac{k}{2}, \frac{1}{2} \right) \quad (\text{E.31})$$

where X denotes the following quantity:

$$X = \frac{1}{1 + (\xi - \lambda)^2} \quad (\text{E.32})$$

The Beta and Incomplete Beta functions are discussed in Abramowitz and Stegun (1965, Chapters 6 and 26) and formulas presented for their computation are given there and by Press et al. (1992).

In those cases in which neither the normal or the Student's t distributions were acceptable because the RSD was too large, the mean lead loading was assumed to be described adequately by a Gamma distribution (Mood and Graybill 1963):

$$g(y) = \frac{1}{\Gamma(\alpha + 1)\beta} \left(\frac{y}{\beta} \right)^{\alpha} e^{-y/\beta} \quad (\text{E.33})$$

This distribution is normalized and is defined only for positive values of y . The parameters α and β are given in terms of the mean L and standard deviation S by:

$$\alpha = \left(\frac{L}{S} \right)^2 - 1 \quad (\text{E.34})$$

and

$$\beta = \frac{S^2}{L} \quad (\text{E.35})$$

For large values of α , the Gamma distribution approaches a normal distribution. It is convenient to transform variables as before by defining:

$$\xi = \frac{y}{\beta} \quad (E.36)$$

Then the normalized distribution function for ξ is:

$$\phi(\xi) = \frac{1}{\Gamma(\alpha + 1)} \xi^\alpha e^{-\xi} \quad (E.37)$$

and the associated cumulative distribution function is:

$$\Phi(\xi) = \frac{1}{\Gamma(\alpha + 1)} \int_0^\xi x^\alpha \exp(-x) dx = P(\alpha + 1, \xi) \quad (E.38)$$

where $P(\alpha+1, \xi)$ is an Incomplete Gamma function (Abramowitz and Stegun 1965; Press et al. 1992).

Figures E-1 and E-2 show the distributions assumed for the mean lead loading in the PPC buildings. Figure E-3 shows how two possible alternative distributions for E5617 compare: a Gamma distribution and a Student's t distribution.

E.4 Final Expression for the Desired Probability

Inserting the above expressions for the three probability distributions into Equation (E.8) yields the following result for the probability that $Q = A_t \times L_t - 10^{-4}M_t$ is less than zero:

$$p(Q < 0) = \int_{-1}^1 \int_0^\infty F\left(\frac{v(\eta)}{u(\xi)}\right) \phi(\xi) \psi(\eta) d\xi d\eta \quad (E.39)$$

$$\text{where} \quad v(\eta) = c(M + d\eta) \quad (E.40)$$

$$\text{and} \quad u(\xi) = \left(\frac{L}{\gamma}\right) \xi \quad (E.41)$$

FIGURE E-1 Assumed Frequency Distributions for the Mean Lead Loading — Buildings E5616, E5617, E5625, and E5627

FIGURE E-2 Assumed Frequency Distributions for the Mean Lead Loading — Buildings E5618, E5621, E5632, and E5633

FIGURE E-3 Alternative Assumed Lead Loading Distributions for Building E5617

where γ is a known parameter depending on the distribution assumed to describe the mean lead loading. For a normal or a Student's t distribution, $\gamma = \lambda$ where λ is defined in Equations (E.18) or (E.27), respectively. For a Gamma distribution, $\gamma = \alpha + 1 = (L/S)^2$. $F(w)$ is given by Equations (E.11) and (E.12). From those equations, it is clear that $F(w)$ is actually a function of r only, where r is given by Equation (E.12). Substituting $w = v/u$ into Equation (E.12) gives:

$$r = \lambda_A \left[\gamma R \left(\frac{1 + \left(\frac{d}{M}\right)\eta}{\xi} \right) - 1 \right] \quad (\text{E.42})$$

where, as usual,

$$R = \frac{10^{-4} M}{A \times L} \quad (\text{E.43})$$

The desired probability as given by Equation (E.39) is thus a function only of the ratio R and of the relative error ratios:

$$\frac{\sigma_A}{A}, \frac{S}{L}, \text{ and } \frac{d}{M}$$

Recall that $R > 1$ corresponds to an estimated lead loading insufficient to cause regulatory problems, while $R < 1$ corresponds to too much lead in the building.

E.5 A Simpler Approximate Method

The double integral in Equation (E.39) must in general be evaluated numerically. However, the function $F(r)$ is essentially a rounded step function; $F(r)$ is close to unity for r much greater than $1/\lambda_A$ and to zero for r less than $1/\lambda_A$. If σ_A is vanishingly small, $F(r)$ equals one for positive r , and zero for negative r . This suggests an approximate method for finding a lower bound for the probability that $Q < 0$. If this bound is greater than the required 0.95, the true probability is guaranteed to also be greater than 0.95.

The desired probability is defined as an integral over the infinite rectangle $[-1 < \eta < +1, 0 < \xi < \infty]$. Figure E-4 shows the $\eta - \xi$ plane and the integration limits. The contours of constant $F(r)$ are straight lines through the point $\xi = 0, \eta = -M/d$; the $r = 0$ line is shown in the figure as well as a line for a value of r greater than zero. $F(r)$ equals 0.5 along the $r = 0$ line, and $F(r)$ approaches unity rapidly for values of r greater than zero, which, on the figure, lie above and to the left of the $r = 0$ line. Similarly, $F(r)$ approaches zero rapidly as r decreases from zero, corresponding to points below and to the right of the $r = 0$ line. The desired approximation consists of restricting the integration in Equation (E.39) to the hatched area in the figure, defined by η between -1 and $+1$, and ξ between zero and the value ξ^* , which is defined by the intersection of the lines $r = r^*$ and $\eta = -1$. In addition, the smallest value of $F(r)$ anywhere in the hatched area occurs at the point $(\xi = \xi^*, \eta = -1)$ and equals $F(r^*)$. If the function $F(r)$ in the integral is replaced everywhere in the hatched area by this minimum value, this constant can be removed from the integral. The integral then factors, since the integrand consists of a product of two functions, one a function of η and one of ξ . The integral over η can be done immediately, and equals unity. The remaining integral is just the cumulative distribution function of ξ evaluated at ξ^* , and the final result is:

$$p(Q < 0) > F(r^*)\Phi(\xi^*) \equiv F^* \Phi^* \quad . \quad (\text{E.44})$$

As r^* increases from zero, F^* increases monotonically from one-half to very nearly one and Φ^* decreases monotonically from the value $\Phi(\xi_{\min})$, where $\xi_{\min}$ is defined by the intersection of the lines $r = 0$ and $\eta = -1$; if $\xi_{\min}$ is large enough, the value of $\Phi(\xi_{\min})$ will be very nearly one. Equation (E.44) thus represents the product of two factors acting in opposite directions such that

FIGURE E-4 Integration Limits and Approximations

for small enough or large enough values of r^* , the given lower bound to $p(Q < 0)$ would be less than the required value. The expectation is, however, that for at least one intermediate value, the lower bound will be high enough. The important point is that *every* value of r^* generates a lower bound on the desired probability, and it only takes one that results in a value of $F^*\Phi^*$ greater than 0.95 to prove the case. For the buildings studied in this work, it turns out that the desired probability is extremely close to unity over a wide range of values of r^* .

The value of $\xi_{\min}$ is given by:

$$\xi_{\min} = \gamma \left(1 - \frac{d}{M} \right) R \quad (\text{E.45})$$

and ξ^* and r^* are related by:

$$\xi^* = \frac{\xi_{\min}}{1 + \left(\frac{r^*}{\lambda_A} \right)} \quad (\text{E.46})$$

or

$$r^* = \lambda_A \left(\frac{\xi_{\min}}{\xi^*} - 1 \right) . \quad (\text{E.47})$$

To implement this approximation for the buildings considered in this study, three values of r^* were considered for each building. The first is the value 3.4589, which is the value at which F^* equals 0.9999995. The second is the value which corresponds to ξ^* at which Φ^* equals 0.9999995, and the third is the value at which the two factors in Equation (E.44) are equal. If a normal distribution is used for the lead loading, the third value of r^* is that which gives the largest value of the desired probability. If another distribution is used, however, this property is only very approximately true. Table E-1 summarizes the results.

TABLE E-1 Three Lower Bounds to the Probability that $Q < 0$ for PPC Buildings^a

Building	Distribution	$r^*(1)$	$1-p(1)$	$r^*(2)$	$1-p(2)$	$r^*(3)$	$1-p(3)$
E5616	Normal	3.4589	5×10^{-7}	200.09	5×10^{-7}	23.32	1.6×10^{-238}
	Student's t	3.4589	5×10^{-7}	156.66	5×10^{-7}	6.60	1.7×10^{-20}
	Gamma	3.4589	5×10^{-7}	170.92	5×10^{-7}	12.70	4.0×10^{-72}
E5617	Student's t	3.4589	5×10^{-7}	302.66	5×10^{-7}	4.87	4.8×10^{-12}
	Gamma	3.4589	5×10^{-7}	620.65	5×10^{-7}	16.25	6.2×10^{-117}
E5618	Gamma	3.4589	5×10^{-7}	957.76	5×10^{-7}	21.31	1.6×10^{-199}
E5621	Gamma	3.4589	5×10^{-7}	307.31	5×10^{-7}	14.30	4.7×10^{-91}
E5625	Normal	3.4589	5×10^{-7}	1061.16	5×10^{-7}	81.82	2.8×10^{-2910}
	Student's t	3.4589	5×10^{-7}	1052.05	5×10^{-7}	22.80	4.4×10^{-228}
E5627	Normal	3.4589	5×10^{-7}	531.05	5×10^{-7}	73.50	5.2×10^{-2349}
	Student's t	3.4589	5×10^{-7}	512.02	5×10^{-7}	12.15	5.6×10^{-66}
E5632	Gamma	3.4589	5×10^{-7}	664.07	5×10^{-7}	17.27	8.1×10^{-132}
E5633	Gamma	3.4589	5×10^{-7}	649.21	5×10^{-7}	21.45	3.5×10^{-202}

^a The actual lower bounds are given by one minus the values given in the $1-p(i)$ columns.

The table shows the values of r^* and one minus the probability that $Q < 0$ for the three values of r^* considered and for the different possible choices of distribution for the mean lead loading in each building. For each of the first two choices of r^* , the probability is at least as large as $1 - 5 \times 10^{-7}$ or 0.9999995, because one factor equals this value and the other is even closer to one. The true probability value is in all cases much closer to one than even 0.9999995, however, as is shown by the third lower bound, given by one minus the value given in the 1-p(3) column. For example, if the mean lead loading for Building E5617 is described by a Student's t distribution, the value of $r^* = 4.87$ results in a lower bound to $p(Q < 0)$ of $1 - 4.8 \times 10^{-12}$, or approximately 0.99999999995.

Of course, once one lower bound greater than 0.95 is established, no further work is necessary. The calculation of the probabilities involved requires the ability to evaluate several special functions; the algorithms in Press et al. (1992) were used in this work. Setting up and debugging a program or spreadsheet to evaluate these functions takes time and may be inconvenient. In order to provide a method that can be used easily, the value of ξ for which the cumulative Gamma distribution equals 0.9999995 was computed as a function of the parameter $\alpha + 1$ and is plotted in Figure E-5. Similarly, the quantity X , defined in Equation (E.32), for which the cumulative Student's t distribution equals 0.9999995 was computed as a function of the number of degrees of freedom, and is plotted in Figure E-6. It should also be recalled that the cumulative normal distribution $\Phi(\xi)$ equals 0.9999995 at $\xi = 3.4589$.

An example will illustrate the use of these figures. Consider Building E5616 and suppose that the uncertainty mean lead loading is modeled using a Student's t distribution; the RSD is $0.0562/0.3140 = 0.179$ and the effective number of degrees of freedom is $k = 18.34$ from Table 26 in the main text. This value of the RSD is about the largest that would still allow the use of a normal or Student's t distribution. From Figure E-6, the value of X such that the cumulative Student's t distribution equals 0.9999995 is about 0.26. The parameter λ is computed from Equation (E.27) to be 1.3039, and the value of $\xi_{\min}$ is computed from Equation (E.45) to be 13.94; recall that for a Student's t distribution $\gamma = \lambda$, and that d/M equals 0.2. The value of R is obtained from Table 26 in the main text. The value of ξ^* corresponding to the above value of X is computed from Equation (E.48):

$$\xi^* = \lambda + \left(\frac{1-X}{X} \right)^{1/2} \quad (\text{E.48})$$

to be 2.99. For this building, λ_A is approximately 42.3; this value is obtained by using the definition of λ_A in Equation (E.10) together with the value for the ratio σ_A/A obtainable as the square root of the value given for the relative variance of A for this building in Table 28 in the main text. Now compute the corresponding value of r^* from Equation (E.47); the result is $r^* = 155$. Since this value is greater than the value 3.4589 at which F^* equals 0.9999995, all values between them also result in a lower bound greater than $(0.9999995)^2 = 0.999999$ for the probability that $Q < 0$. If the second value of r^* had been less than 3.4589, then the best lower

FIGURE E-5 Value of ξ at which Cumulative Gamma Distribution Equals 0.9999995

bound would have been less than 0.999999 and more detailed calculations would need to be made to establish that an acceptable lower bound exists. Figures such as E-5 and E-6 could be developed corresponding to any specified target lower bound, such as 0.95, instead of 0.999999.

FIGURE E-6 Value of X at which Cumulative Student's t Distribution Equals 0.9999995

References

Abramowitz, M., and I.A. Stegun, 1965, *Handbook of Mathematical Functions*, Dover Publications, Inc., New York, N.Y.

Cochran, W.G., 1977, *Sampling Techniques* (Third Edition), John Wiley and Sons, New York, N.Y.

Lee, P.M., 1989, *Bayesian Statistics: An Introduction*, Halstead Press, John Wiley and Sons, New York, N.Y.

Mood, A.W., and F.A. Graybill, 1963, *Introduction to the Theory of Statistics* (Second Edition), McGraw-Hill Book Co., New York, N.Y.

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, 1992, *Numerical Recipes in C* (Second Edition), Cambridge University Press, New York, N.Y.