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A Preliminary Evaluation of the Scitec MAP-3, Warrington Microlead I, and Princeton Gamma-Tech XK-3 Portable X-Ray Fluorescence Spectrometers
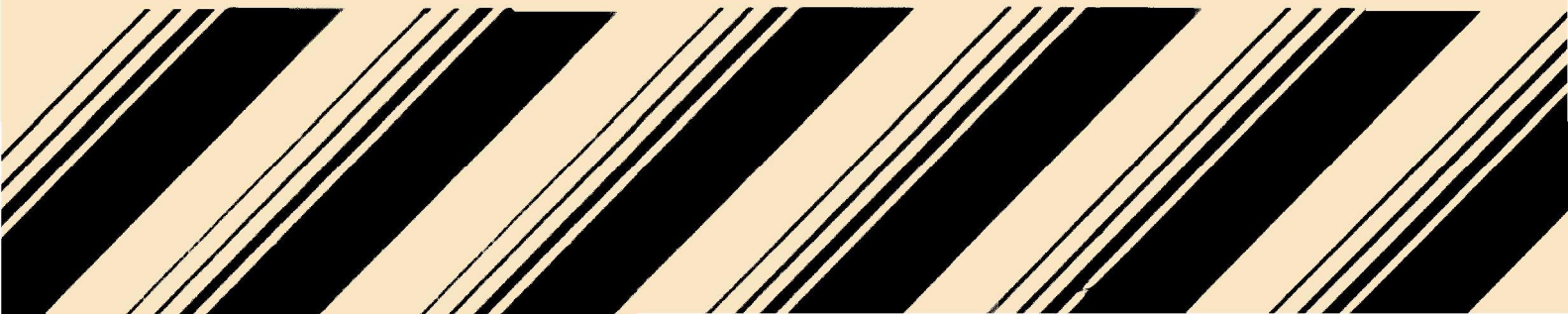
A Preliminary Evaluation of the Scitec MAP-3, Warrington Microlead I, and Princeton Gamma-Tech XK-3 Portable X-Ray Fluorescence Spectrometers

Prepared by

E. D. Estes
D. L. Hardison
C. O. Whitaker
J. D. Neefus
W. F. Gutknecht

Center for Environmental Measurements and Quality Assurance
Research Triangle Institute
Research Triangle Park, North Carolina 27709-2194

Prepared for

Ms. Sharon Harper, Work Assignment Manager

Atmospheric Research and Exposure Assessment Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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EXECUTIVE SUMMARY

The potential impact on health from environmental lead has resulted in increased interest in lead exposure by Federal, State and local government agencies. As a result, programs committed to sampling and analysis of lead are increasing nationwide. Public housing authorities are required, by 1994, to randomly inspect all their housing projects for lead-based paint. Currently, the most common approach to screening housing for the presence of lead in paint is the use of the portable X-ray fluorescence (XRF) detector, which is relatively inexpensive (0.1 - 0.2 hours/test for labor), gives rapid results, and can be used with minimal damage. Inconclusive XRF measurements must be confirmed with field-collected samples back in the laboratory using a more accurate analytical method such as atomic absorption spectrometry (AAS) or inductively coupled plasma emission spectrometry (ICP).

The accuracies and precisions of portable XRF instruments for measurements of lead-in-paint concentrations near the U.S. Department of Housing and Urban Development (HUD) action level for abatement (1.0 mg/cm^2) have not been well established. Therefore, at the request of the U.S. Environmental Protection Agency (USEPA), the Research Triangle Institute (RTI) performed a limited evaluation of three portable XRFs currently being used for field measurements: the Scitec MAP-3, the Warrington Microlead I, and the Princeton Gamma-Tech (PGT) XK-3. The purpose of the evaluation was to compare these very different, commercially available portable XRFs, on as equal a basis as possible, for their biases and precisions when measuring lead in paint films at concentrations ranging from 0 to 7.16 mg/cm^2.

Each instrument was used to make a series of measurements in order to determine the effects of sample concentration and substrate on the precision and bias. The samples chosen for the study were standard latex and oil-based paint films prepared by RTI. The lead concentrations of the seven paint films ranged from nominally 0 to 7.16 mg/cm^2 as confirmed by digestion using a modification of NIOSH Method 7082 and analysis by inductively coupled plasma emission spectrometry. Eight different substrates of varying densities were chosen to represent the types of building materials likely to be encountered in the field. The measurement plan called for triplicate

measurements of each paint film on each substrate using each of the three portable XRF instruments according to the manufacturer's instructions. The order of measurement for the Warrington and PGT instruments followed a randomized test matrix. Because of the availability of the instrument, the measurements for the Scitec XRF were completed before the test matrix was developed and therefore were not performed in the same order.

Based upon the data collected during this limited evaluation, it appears that all three instruments measure lead in paint more accurately (as determined by inspection of bias) on 1/2" plasterboard than on the other substrates tested. Predicted biases for the Scitec XRF across the test sample concentration range varied from -0.6 mg/cm^2 at 1.6 mg/cm^2 for 5" concrete to 3.3 mg/cm^2 at 0.3 mg/cm^2 for solid cinderblock. Predicted biases for the Warrington XRF ranged from -0.03 mg/cm^2 at 1.6 mg/cm^2 for plasterboard to 1.1 mg/cm^2 at 0.3 mg/cm^2 for concrete. Predicted biases for the PGT XRF ranged from 0.1 mg/cm^2 at 0.3 mg/cm^2 for 4" cinderblock to -0.9 mg/cm^2 at 1.6 mg/cm^2 for 1/8" aluminum.

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SECTION 1

INTRODUCTION

1.1   BACKGROUND

The adverse health effects resulting from exposure of young children to environmental lead have caused increased public concern in recent years. Studies have shown that chronic exposure even to low levels of lead can result in impairment of the central nervous system, mental retardation, and behavioral disorders.[1,2] Although young children are at the greatest risk, adults may suffer harmful effects as well.[3]

Numerous programs involving research on the toxicity and bioavailability of lead, the environmental monitoring of lead, lead abatement, and clearance testing of housing are currently active. Examples of past projects include the U.S. Department of Housing and Urban Development (HUD) National Survey,[4] the Urban Soil Lead Abatement Demonstration Project[5] and method evaluation studies sponsored by the U.S. Environmental Protection Agency (EPA), and abatement programs carried out by Maryland, Massachusetts, and many other groups.

The major sources of exposure to lead in housing units are paint, dust, and soil. Currently, lead-based paint is receiving emphasis by HUD[6] as the principal source for lead contamination and exposure. House dust contaminated with lead from deteriorating interior paint and from tracked-in exterior paint has been implicated as the most common route of exposure for young children.[7] It is particularly hazardous when painted walls, woodwork, and furniture are accessible to young children to touch and to chew.

Public housing authorities are required, by 1994, to randomly inspect all their housing projects for lead-based paint.[8] Currently, the most common approach to screening housing for the presence of lead in paint is the use of the portable X-ray fluorescence (XRF) detector, which is relatively inexpensive (0.1 - 0.2 hours/test for labor), gives rapid results, and can be used with minimal damage.[9,10] Inconclusive XRF measurements must be confirmed with field-collected samples back in the laboratory using a more accurate analytical method such as atomic absorption spectrometry (AAS) or inductively coupled plasma emission spectrometry (ICP).[6]

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1.2 OBJECTIVES/PURPOSE OF THE STUDY

The biases and precisions of portable XRF instruments for measurements of lead-in-paint concentrations near the HUD action level for abatement (1.0 mg/cm^2)[6] have not been well established. Therefore, at the request of the EPA, the Research Triangle Institute (RTI) has evaluated three of the portable XRFs currently being used for field measurements: the Scitec MAP-3, the Warrington Microlead I, and the Princeton Gamma-Tech (PGT), XK-3. The purpose of the evaluation was to compare these very different, commercially available portable XRFs, on as equal a basis as possible, for their biases and precisions when measuring lead in paint on particular substrates. Biases were calculated by comparing lead concentrations of the standards as measured by each XRF to the lead concentrations measured by digestion/ICP analysis.[11]

Another goal of the project was to determine a mechanism or protocol for comparison and evaluation of current and future portable XRFs on as equal a basis as possible.

1.3 STUDY DESIGN

RTI's evaluation of portable XRF technology was performed using a phased approach. When the experiments were begun in 1990, the Scitec MAP-3 was the portable XRF that was most widely used for field measurements of lead in paint at "scattered-site" housing. However, at that time, no paint film reference materials were available for testing the responses of the XRF to various concentrations of lead. Therefore, RTI developed a procedure for preparing standard latex and oil-based paint films containing known amounts of lead.[12] The lead concentrations of the paint films that were prepared ranged from nominally 0 to 7.16 mg/cm^2 as confirmed by digestion using a modification of NIOSH Method 7082[11] and analysis by ICP. This range represents that typically encountered in actual field measurements.[4] Different substrates of varying densities were chosen to represent the types of building materials likely to be encountered in housing units. A Scitec MAP-3 portable XRF rented from Scitec Corporation was used to make triplicate measurements for the various paint film/substrate combinations.

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In 1992, two additional instruments, the Warrington Microlead I and the Princeton Gamma-Tech XK-3, were available to RTI for testing. Using the information gained in the Scitec evaluation, a measurement plan was developed for these two XRFs to collect data that would allow comparison of the three instruments. Mr. William Boyce of Scitec Corporation had observed a hysteresis effect when the XRF was used to measure lead in paint on a low density substrate after it was used to measure lead in paint on a high density substrate. Hysteresis effects also may be observed when painted surfaces containing low levels of lead are measured immediately following the measurement of surfaces containing high levels of lead.[13] Therefore, the measurement sequence was not ordered by lead concentration or substrate density. Instead, a randomized test matrix, presented in Table 1, was developed to determine the order of the measurements so that the hysteresis effects, if present, would be randomized. No tests were performed to determine the presence or the magnitude of the hysteresis effects. The measurement plan called for triplicate measurements of each combination of paint film and substrate for the Warrington and PGT instruments. In order to perform a measurement, the test

**Table 1. Randomized Test Matrix - Order (1-56) for Testing
Each Combination of Sample and Substrate**

Substrate	20D1 (7.16)	20D2 (6.20)	Paint Sample ID (conc., mg/cm²) 20B2 (1.27)	20A2 (0.52)	17B (0.00)	120-2-B (0.07)	120-5-B (4.96)
1/2" Plasterboard	18	48	37	44	7	12	51
3/4" Plywood	24	5	35	32	30	52	15
Cinderblock, Std	17	54	40	10	16	39	1
1/8" Steel	41	20	26	9	47	36	38
1/8" Aluminum	18	43	2	22	55	45	11
5" Concrete	27	14	29	23	53	21	25
Brick	34	13	28	8	33	42	49
Cinderblock, Solid	3	4	50	6	56	46	31

paint film was placed against the substrate, and an attempt was made to position the XRF probe on the center of the film so that the measurement would be made on nominally the same area each time. The triplicate measurements were made consecutively with no repositioning of the instrument between readings.

A "measurement" for each particular instrument was performed as defined in Table 2. Scitec recommends a 60-second reading for a "test" and a 240-second reading for "confirmation".[14] For this study, an intermediate measurement time of 120 seconds was chosen because a previous study indicated that there were no significant differences in the biases and precisions for 60- and 120-second reading times.[15] The 4-minute reading would only be performed in the field to confirm levels within the action range. The manufacturer's instructions for Warrington XRF defines a measurement as the average value for the lead concentration that is displayed when the trigger is depressed for three read cycles (approximately 15 to 20 seconds for a new source). The manufacturer recommends that at least three measurements per test location should be made before any conclusions are drawn concerning the presence or absence of a lead hazard.[16] The PGT manufacturer recommends that a measurement be made by taking three readings (15 to 20 seconds each for a new source), recording the values, and manually averaging them.[17]

Table 2. Test Procedures

Instrument	Measurement Procedure	# of Measurements
Scitec	Take one 120 sec reading	3
Warrington	Take one 3-cycle reading (15-20 sec)*, temporarily halting after each cycle to record the value displayed; manually average	3
PGT	Take 3 readings (15-20 sec each)*, record values and manually average	3

* new ^{57}Co excitation source

SECTION 2

OVERVIEW OF THE PORTABLE XRF

2.1 INSTRUMENT BASICS

The portable XRF consists of an excitation source, a detector, and some means of specifically determining the lead X-rays emitting from the sample.[18] Characteristics of the three portable XRFs used in the study described in this report are summarized in Table 3, Section 3. The excitation source for portable units consists of a radioactive source. Examples of source materials include ^{241}Am, ^{109}Cd, ^{244}Cm, ^{57}Co, and ^{55}Fe. These emit X-rays or gamma rays of sufficient energy to cause excitation of the target atoms. Different isotopes are preferred for different ranges of elements because of the need to match the energy of the excitation source emission with the energy needed to cause excitation and X-ray emission (fluorescence) from the element of interest. ^{55}Fe, for example, is well suited for the light elements Al - V (K-shell X-rays) and Nb - Sb (L-shell X-rays). ^{109}Cd is well suited for excitation of lead L-shell X-rays, while ^{57}Co is well suited for both lead K- and L-shell X-rays. (The K and L designations describe X-rays produced from electron transitions between the K and L shells, respectively, and the higher level shells; the L X-ray is of lower energy while the K X-ray is of higher energy and therefore can penetrate deeper.)[19]

Several types of detectors are available.[19] The solid-state detector used in the Scitec XRF consists of the semiconductor material SiLi. When an X-ray passes through the material, the X-ray creates free electrons and "holes." When a voltage is applied across this detector, and an X-ray passes through the detector, a pulse of current flows across the detector. The number of free electrons and "holes" produced, and subsequently the magnitude of this current pulse, is a function of the energy of the X-ray, which, in turn, is specific to the emitting element. Specific detection of lead is accomplished by measurement of the magnitude of the current pulse and relating this pulse magnitude to a standard. This is done with a pulse height analyzer, that is, complex electronic circuity which differentiates current pulses by their magnitude, deals

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with overlapping pulses, and keeps track of the number of pulses of each magnitude. The number of pulses at a particular magnitude is directly related to the concentration of the fluorescing element.

The Warrington XRF uses a scintillation counter composed of a cesium thallium iodide doped crystal to convert the X-ray photon into a light photon. When radiation interacts with the crystal, the transmitted energy excites the iodine atom and raises it to a higher energy state. When the iodine atom returns to its ground electronic state, the energy is re-emitted as a light pulse in the ultraviolet region which is then absorbed by the thallium atom and re-emitted as fluorescent light. The light is detected by a 1/2" photomultiplier tube.

The detector for the PGT XRF is a proportional counter. This is a xenon-filled tube across which a high voltage potential is applied. When an X-ray enters the tube, the xenon gas is ionized, producing ion pairs. The charged particles migrate toward the appropriate electrodes under the voltage gradient. Each electron acquires sufficient energy to produce another ion pair upon collision with another xenon atom. This process is repeated many times so that each original X-ray entering the counter results in a large number of electrons traveling toward the anode. An electronic pulse is produced that is proportional to the number of electrons reaching the anode and, accordingly, the energy of the X-ray.

The simpler XRF units are preset to count only pulses equivalent to lead X-ray energies; these are called "direct reading" instruments. The more complex instruments, called "spectrum analyzers," take and store the entire range of X-ray emissions in a small on-board computer that performs the task of relating current pulse amplitude and numbers of pulses to information stored from standards. This computer will automatically identify the elements and determine their concentrations.

A major limitation of XRF is that the efficiency of production of the fluorescing X-rays is very dependent upon the paint matrix and the substrate. The numbers of X-rays produced will depend upon (1) the ability of the exciting or source X-rays to penetrate the matrix and reach the atoms of interest; (2) secondary X-rays (created from the interaction of the primary excitation X-rays with other elements in the sample) reaching and causing fluorescence of the element of interest; (3) primary excitation X-

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rays being scattered by matrix and substrate components so as to hit the atoms of element of interest from all angles; and (4) the ability of the X-rays emitted from the atoms of interest to escape from the matrix and reach the detector without being electromagnetically reabsorbed or scattered by the matrix. In the laboratory, great care is taken to match the matrix of the standards and unknowns. This is very difficult in the field, and impossible with instruments used to perform direct readings off walls, floors, etc.

Two principal approaches are being taken to deal with this substrate problem when analyzing lead-containing paint. In the first, which provides for a partial correction, a reading of the surface is taken. Then the paint is scraped off the surface and a second reading is taken to obtain a background reading, which is subtracted from the first. This substrate correction approach was applied for the Warrington Microlead I and Princeton Gamma-Tech XK-3 instruments. In the second approach, information is taken from the total X-ray emission spectrum, and, using proprietary software, a substrate correction is calculated. The software includes mathematical variables determined from measurement of standard paint films placed on different substrates, e.g., wood, plasterboard, metal, etc. The Scitec MAP-3 instrument evaluated in this study uses this second approach.

2.2   AVAILABLE INSTRUMENTS

At the time of these evaluations in 1992, three manufacturers were widely recognized as having commercially available XRFs designed for in-situ paint testing. The instruments that were tested by RTI and addresses of these manufacturers are as follows:

Princeton Gamma-Tech XK-3

Princeton Gamma-Tech Inc.
1200 State Road
Princeton, NJ 08540
(609) 724-7310

Warrington Microlead I

Warrington Corporation
2205 West Braker Lane
Austin, TX 78758
(800) 233-9491

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Scitec Corporation
1029 Kellogg Street
Kennewick, WA 99336
(509) 783-9850

SECTION 3
LABORATORY TESTS OF THE
PORTABLE XRF UNITS

3.1 INTRODUCTION

The Scitec, Warrington, and PGT portable X-ray fluorescence units (XRF) were employed to measure lead in paint using standard paint films and selected substrate materials. These instruments were pre-calibrated by the manufacturer and were not recalibrated by RTI. The paint films, containing known concentrations of lead, were prepared by RTI from new latex and oil-based paints and pure lead salts. The concentration of lead in each paint film was confirmed by digestions using a modification of NIOSH Method 7082[11] and ICP spectrometry. The characteristics of the three XRFs are discussed in the following sections and summarized in Table 3.

3.2 SCITEC MAP-3

3.2.1 Description

The Scitec X-ray fluorescence unit consists of the Ambient Scanner and the MAP-3 Console with battery power and cable. The MAP-3 Console is basically a portable computer that contains the calibration data and has memory for more than 1000 entries, including measurement values, identification numbers, analysis times and methods chosen. The data can be retrieved by connecting the console to an IBM PC-XT. The Ambient Scanner houses the radioactive ^{57}Co source. The system should be returned to Scitec once a year for source replacement and recalibration.

After connection of the Ambient Scanner to the console, the appropriate values for calibration program, identification number, and analysis time may be chosen. The surface to be analyzed is positioned against the rubber boot and shutter of the scanner. The shutter then is opened to expose the sample to the source, and the analysis is controlled from the console.

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Table 3. Portable XRF Characteristics

	Scitec MAP-3	Warrington Microlead 1	PGT XK-3
Type	Spectrum Analyzer	Direct Reader	Direct Reader
Source (Halflife: Days)	^{57}Co (276)	^{57}Co (276)	^{57}Co (276)
Decay Compensation	---	Source date in software	Ta foil internal ref
Detector	SiLi	Scintillation Counter	Xe gas, prop. counter
Shell detected (KeV)	K (74.96) L (10.55)	K (74.96)	K (74.96)
Substrate Correction	Proprietary Algorithm	Scrape	Scrape
Potential Interferences	K=Au, Bi, Hg, Tl L=As, Cd, Cu, Mo, Zn	K, same	K, same
Range of Calibration	0 - 6.19 mg/cm^2	0.6 - 2.00 mg/cm^2	0.6 - 2.99 mg/cm^2
Substrates Used for Calibration	>30	up to 15	none
Calibration Materials	Old HUD/NIST & RTI prepared	Old HUD/NIST	Old HUD/NIST
Strength of Source Used for Study (Original Strength)	37.8 mCi (40 mCi)	3.4 mCi (10.4 mCi)	9.1 mCi (10.4 mCi)
Recommended Source Replacement	Once/year	Once/14 months	Once/year

3.2.2 Experimental Procedure

The Scitec MAP-3 unit used by RTI in this evaluation contained a new ^{57}Co source and had been calibrated by the manufacturer over the range of 0 to 6.19 mg/cm^2 of lead using films prepared by RTI and the old HUD/NIST films. The XRF was used in the "universal" substrate correction mode to make three 120-second measurements each of selected paint films placed one at a time on selected substrates. The Scitec measurements were made prior to the development of the randomized test matrix (Table 1) and, therefore, were not made in the order specified in the matrix. In addition, several paint film/substrate combinations specified in the matrix (Table 1) had not been made when the Scitec system was being evaluated. Measurement data are reported in Appendix A.

3.3 WARRINGTON MICROLEAD I

3.3.1 Description

The Warrington Microlead I is a portable, microcomputer-based XRF with a ^{57}Co source. The instrument has built-in "Zero Standard" and "Lead Standard" functions so the user can establish a zero reference using a "standard" substrate and check that the analyzer reads the lead concentration correctly with a "standard" paint film provided by Warrington. The background density is displayed with each reading to alert the inspector to changes in substrate that might affect the accuracy of the lead reading. Up to 1000 pieces of information (lead readings, project numbers, apartment numbers, times and dates, for example) can be stored and subsequently printed on a portable printer. Warrington recommends that the source be changed every 14 months.

The probe is placed against the test surface and the trigger is pulled until the analyzer beeps and displays the lead reading. Successive readings are averaged automatically. Warrington recommends that the trigger be depressed through three successive cycles to obtain a lead measurement.

3.3.2 Experimental Procedure

The Warrington XRF used in this evaluation was borrowed from Dr. Mary McKnight of the National Institute of Standards and Technology. It contained a used

source with a strength of ~3.4 mCi. Some measurements were performed in the "auto" mode (by depressing the trigger through three read cycles to obtain an automatically-calculated average) prior to the development of the randomized test matrix. In a memorandum dated 3/26/92 to the RTI XRF team, the EPA Work Assignment Manager recommended that the randomized tests be performed in the "manual" mode (i.e., the trigger would be released after each read cycle so that the lead concentration read during that cycle could be recorded and an average of the three readings be calculated manually to represent one measurement). The reason for this modified procedure was that Warrington's definition of a single reading was interpreted to be three count cycles while PGT's single reading is one count cycle. This "halted" reading procedure would allow comparison of the XRFs on a more equal basis.

When the analyst began to work through the randomized test matrix, he made the decision to omit film/substrate combinations that had already been measured in the automatic mode. However, since these measurements were made at a different time and in a different mode than the randomized measurements, they were not included in this evaluation and do not appear in the Warrington data presented in Appendix A.

A discussion with a representative of Warrington corporation revealed that the precision obtained using the automatic mode will be better than the precision obtained using the manual mode.[20] When the trigger is depressed through three read cycles, a "running average" is generated continuously. When the trigger is released after each cycle, the data from the previous cycle is not included in the following cycle. In addition to the paint film/substrate measurements, measurements were made of each substrate alone so that the randomized data could be corrected for substrate effects. The "zero standardize" procedure described in the user's manual was performed at the beginning, middle, and end of each analysis day.

3.4 PRINCETON GAMMA-TECH XK-3

3.4.1 Description

The Princeton Gamma-Tech XK-3 utilizes a ^{57}Co scintillation source with a tantalum foil internal reference device to automatically correct for source decay. The instrument's internal programming determines exposure time by referring to the count

for the ^{73}Ta foil. When the ^{73}Ta counter discriminator/channel is full, the instrument triggers a shutter release. One charge of the battery pack will provide 8 hours of operation. The manufacturer recommends that the source be changed once a year at the PGT factory.

The user presses the face-plate of the instrument against the surface to be analyzed, pushing down firmly on the handle. Depression of the spring-loaded handle opens the shutter. After 15 to 20 seconds, a reading appears on the digital display. PGT recommends taking three successive readings and manually averaging the results to obtain a lead measurement.

3.4.2 Experimental Procedure

The PGT XRF used in this evaluation was borrowed from Mr. Jim Hayes of the North Carolina State Government Health Services Section. The ^{57}Co source had been replaced by Warrington Corporation and was new (first half-life). Mr. Hayes reported that replacements had been made by Warrington previously and that the XRF performed properly each time such a replacement was made.[21] Three readings were taken manually and averaged to obtain one lead measurement. In addition to the paint film/substrate measurements, measurements were made of each substrate alone so that the randomized data could be corrected for substrate effects. Measurement data are reported in Appendix A.

SECTION 4

RESULTS AND DISCUSSION

4.1 EXPERIMENTAL PRECISION AND BIAS

Data from the triplicate measurements of each paint film/substrate combination using each of the three XRFs are presented in Appendix A. The effects of lead concentration and substrate on the precision and bias of XRF measurements can be determined by examination of the data presented in Tables 4 through 6. The tables are ordered by decreasing lead concentration in the paint films and by increasing substrate density as determined by the Warrington XRF. The relative standard deviation (RSD) of each set of triplicate measurements, an indicator of precision, is calculated as

$$RSD = (SD/\bar{X}) \times 100$$

where $\bar{X}$ is the average value of the three measurements and

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

The percent difference (% Diff) of the XRF measured value from the ICP measured value, an indicator of bias, is calculated as

$$\% \text{ Diff} = \left(\frac{\text{ICP value} - \bar{x}}{\text{ICP value}} \right) \times 100$$

The data show that, in general, precision and bias improve as the lead concentration in the paint film increases. No trend with respect to substrate was apparent from visual inspection of the data; no statistical tests for substrate effects were performed.

4.2 LINEAR REGRESSION ANALYSES

Linear regression analyses were performed on the experimental XRF data presented in Appendix A using a standard linear calibration computer program.[22]

Table 4. Relative standard deviations and percent differences for triplicate measurements of lead in paint films using portable XRF: Scitec

ICP Anal. mg/cm$_2$	1/2" Plasterboard		3/4" Plywood		1/8" Aluminum		1/8" Steel		4" Cinderblock		Solid Cinderblock		Brick		5" Concrete	
	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff
7.16	8.7	-3.2	9.2	-5.0	8.0	6.1	3.7	0.6	5.6	-5.5	1.4	15.0	5.6	-10.6	18.0	-29.7
6.20	15.1	11.3	4.9	-4.3	9.1	20.4	11.6	18.3	3.7	8.6	4.0	28.5	12.9	3.8	16.3	-13.4
4.96	NA	NA	5.0	-38.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1.27	10.0	-21.3	24.1	-50.1	14.3	-16.0	20.8	15.5	142	-79.0	8.5	275	173	-92.1	96.6	-63.3
0.52	35.3	-16.7	33.3	-42.3	20.0	-3.8	17.3	28.2	40.0	-3.8	56.8	451	173	-93.6	---	-100
0.0	---	---	---	---	---	---	173	--	63.0	---	5.1	---	---	---	---	---

Table 5. Relative standard deviations and percent differences for triplicate measurements of lead in paint films using portable XRF: Warrington

ICP Anal. mg/cm$_2$	1/2" Plasterboard		3/4" Plywood		1/8" Aluminum		1/8" Steel		4" Cinderblock		Solid Cinderblock		Brick		5" Concrete	
	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff
7.16	0.8	-9.2	0.6	-10.8	1.7	-3.6	2.5	1.7	1.0	-1.7	2.5	-5.4	2.0	-5.5	6.1	-6.1
6.20	2.3	-4.1	1.0	-4.6	1.9	2.6	0.3	4.0	1.3	2.7	3.8	0.8	2.6	6.1	0.0	11.9
1.27	1.4	0.0	8.2	11.5	9.3	11.0	6.0	55.1	22.7	27.8	12.1	5.8	6.4	40.9	7.7	74.8
0.52	18.6	24.4	16.5	23.1	42.4	75.0	10.1	176	---	---	45.5	42.9	8.2	101	5.7	235
0.07	NA	NA	NA	NA	NA	NA	22.3	1267	13.7	424	149	105	31.5	467	12.2	1362
0.0	1530	---	28.9	---	31.4	---	32.9	--	30.3	---	13.9	---	28.2	---	12.2	---

Table 6. Relative standard deviations and percent differences for triplicate measurements of lead in paint films using portable XRF: PGT

ICP Anal. mg/cm²	1/2" Plasterboard		3/4" Plywood		1/8" Aluminum		1/8" Steel		4" Cinderblock		Solid Cinderblock		Brick		5" Concrete	
	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff	RSD	% Diff
7.16	5.8	-15.1	1.0	-20.8	1.7	-27.1	1.3	-18.8	NA	NA	2.4	-21.3	6.6	-26.2	0.6	-34.6
6.20	6.3	-10.6	4.9	-16.5	5.3	-26.2	2.0	-6.8	2.6	-21.6	7.7	-26.9	7.9	-28.5	3.9	-28.9
4.96	5.5	11.3	3.4	-39.2	6.8	-17.9	6.7	8.3	3.2	23.6	3.9	9.2	10.9	-26.9	10.2	-6.3
1.27	16.5	-3.9	25.8	-48.3	67.9	-65.1	14.6	-68.8	37.8	-23.4	41.4	-38.8	28.2	-16.8	29.3	-24.7
0.52	5.9	-1.9	54.1	3.2	NA	NA	243	-103	71.6	10.3	32.8	-46.8	39.3	-42.3	6.0	-44.2
0.07	32.9	424	24.7	-300	20.1	-976	8.2	1110	82.0	224	208	-243	121	-371	4015	114
0.0	---	---	68.7	---	163	---	2.3	---	86.7	---	456	---	24.2	---	17.2	---

Regression parameters were calculated for each substrate for each portable XRF using the model $y = a + bx$, where a is the intercept and b is the slope. The data were entered as x,y pairs where x is the lead concentration of the paint film measured in the laboratory using acid digestion/ICP and y is the concentration measured by XRF. A least squares analysis assumes that the independent variable, x, is measured without error. The laboratory analysis of the paint films showed some variability. However, least squares analysis can be used if the error of x is less than one-tenth of the average scatter of the x's from their mean.[23] Examination of the paint film laboratory analysis results revealed that this condition was met. Results of the linear regression analyses are presented in Tables 7 through 14.

4.2.1 Hypothesis Testing

After the regression values were computed, tests were performed to determine slopes that are statistically equal to one at the 95 percent confidence level according to the following:

$$b = 1 \text{ if } \left| \frac{b-1}{(se)_b} \right| \leq t_{1 - \alpha/2, \, n-2}$$

where b = slope, $(se)_b$ = standard error of the slope and
$t_{1-\alpha/2, \, n-2}$ = critical value with (n-2) degrees of freedom.

Similarly, tests were performed to determine intercepts that are statistically equal to zero at the 95 percent confidence level according to the following:

$$a = 0 \text{ if } \left| \frac{a}{(se)_a} \right| \leq t_{1 - \alpha/2, n - 2}$$

where a = intercept, $(se)_a$ = standard error of the intercept and
$t_{1-\alpha/2, \, n-2}$ = critical value with (n-2) degrees of freedom.

Slopes that are statistically equal to one and intercepts that are statistically equal to zero are indicated by asterisks in Tables 7 through 14.

Table 7. ½" Plasterboard

		Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs		15	15	15	21	21
Slope		1.043*	0.915	0.915	0.812	0.812
SD_{slope}		0.051	0.014	0.014	0.032	0.032
Intercept		-0.108**	0.413	0.103**	0.386	0.096**
$SD_{intercept}$		0.216	0.060	0.060	0.129	0.129
Corr. Coef.		0.9851	0.9985	0.9985	0.9859	0.9859
Residual Variance, %		2.96	0.30	0.30	2.80	2.80
Standard Error of Estimate of X from Y		0.539	0.172	0.172	0.494	0.494
Estimated bias[†] and 95% confidence interval at:[††]	0.3 mg/cm^2	-0.09 ± 1.35	+0.39 ± 0.37	+0.08 ± 0.37	+0.33 ± 0.91	+0.04 ± 0.91
	0.8 mg/cm^2	-0.07 ± 1.34	+0.34 ± 0.37	+0.04 ± 0.37	+0.24 ± 0.91	-0.05 ± 0.91
	1.0 mg/cm^2	-0.06 ± 1.34	+0.33 ± 0.37	+0.03 ± 0.37	+0.20 ± 0.90	-0.09 ± 0.90
	1.3 mg/cm^2	-0.05 ± 1.33	+0.30 ± 0.37	-0.01 ± 0.37	+0.14 ± 0.90	-0.15 ± 0.90
	1.6 mg/cm^2	-0.04 ± 1.33	+0.28 ± 0.37	-0.03 ± 0.37	+0.09 ± 0.90	-0.20 ± 0.90

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b-1}{(se)_b} \right| \le t_{1-\alpha/2,\, n-2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \le t_{1-\alpha/2,\, n-2} \right)$

[†] Bias is calculated as XRF predicted value minus the known concentration of the paint film.

[††] Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

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Table 8. 3/4" Plywood

		Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs		18	15	15	21	21
Slope		0.934*	0.873	0.873	0.799	0.799
SD_{slope}		0.056	0.014	0.014	0.031	0.031
Intercept		-0.341**	0.651	0.301	0.231**	-0.199**
$SD_{intercept}$		0.248	0.060	0.060	0.125	0.125
Corr. Coef.		0.9721	0.9983	0.9983	0.9863	0.9863
Residual Variance, %		5.5	0.34	0.34	2.72	2.72
Standard Error of Estimate of X from Y		0.689	0.182	0.182	0.487	0.487
Estimated bias[†] and 95% confidence interval at:[††]	0.3 mg/cm^2	-0.36 ± 1.53	+0.61 ± 0.38	+0.26 ± 0.38	+0.17 ± 0.88	-0.26 ± 0.88
	0.8 mg/cm^2	-0.39 ± 1.52	+0.55 ± 0.38	+0.20 ± 0.38	+0.07 ± 0.88	-0.36 ± 0.88
	1.0 mg/cm^2	-0.41 ± 1.51	+0.52 ± 0.37	+0.17 ± 0.37	+0.03 ± 0.87	-0.40 ± 0.87
	1.3 mg/cm^2	-0.43 ± 1.50	+0.49 ± 0.37	+0.14 ± 0.37	-0.03 ± 0.87	-0.46 ± 0.87
	1.6 mg/cm^2	-0.45 ± 1.50	+0.45 ± 0.37	+0.10 ± 0.37	-0.09 ± 0.87	-0.52 ± 0.87

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b - 1}{(se)_b} \right| \le t_{1 - \alpha/2, \, n - 2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \le t_{1 - \alpha/2, \, n - 2} \right)$

[†] Bias is calculated as XRF predicted value minus the known concentration of the paint film.

[††] Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 9. 1/8" Aluminum

		Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs		15	15	15	18	18
Slope		1.137	0.931	0.931	0.773	0.773
SD_{slope}		0.044	0.020	0.020	0.031	0.031
Intercept		-0.117**	0.267	1.387	0.188**	-0.492
$SD_{intercept}$		0.186	0.086	0.086	0.136	0.136
Corr. Coef.		0.9906	0.9970	0.9970	0.9875	0.9875
Residual Variance, %		1.87	0.60	0.60	2.48	2.48
Standard Error of Estimate of X from Y		0.428	0.243	0.243	0.476	0.476
Estimated bias[†] and 95% confidence interval at:[††]	0.3 mg/cm²	-0.08 ± 1.17	+0.25 ± 0.54	+0.37 ± 0.54	+0.12 ± 0.86	-0.56 ± 0.86
	0.8 mg/cm²	-0.01 ± 1.16	+0.21 ± 0.53	+0.33 ± 0.53	+0.01 ± 0.85	-0.67 ± 0.85
	1.0 mg/cm²	+0.02 ± 1.15	+0.20 ± 0.53	+0.32 ± 0.53	-0.04 ± 0.85	-0.72 ± 0.85
	1.3 mg/cm²	+0.06 ± 1.15	+0.18 ± 0.53	+0.30 ± 0.53	-0.11 ± 0.85	-0.79 ± 0.85
	1.6 mg/cm²	+0.10 ± 1.14	+0.16 ± 0.53	+0.28 ± 0.53	-0.18 ± 0.84	-0.86 ± 0.84

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b-1}{(se)_b} \right| \le t_{1-\alpha/2,\, n-2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \le t_{1-\alpha/2,\, n-2} \right)$

[†] Bias is calculated as XRF predicted value minus the known concentration of the paint film.

[††] Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 10. 1/8" Steel

	Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs	15	18	18	21	21
Slope	1.064*	0.893	0.893	0.917*	0.917*
SD_{slope}	0.046	0.013	0.013	0.043	0.043
Intercept	0.115**	-0.575	0.895	0.484	-0.756
$SD_{intercept}$	0.199	0.051	0.051	0.175	0.175
Corr. Coef.	0.9879	0.9983	0.9983	0.9797	0.9797
Residual Variance, %	2.41	0.34	0.34	4.02	4.02
Standard Error of Estimate of X from Y	0.486	0.177	0.177	0.591	0.591
Estimated bias† and 95% confidence interval at:††	0.3 mg/cm²	+0.13 ± 1.24	-0.61 ± 0.36	+0.86 ± 0.36	+0.46 ± 1.24	-0.78 ± 1.24
	0.8 mg/cm²	+0.17 ± 1.23	-0.66 ± 0.36	+0.81 ± 0.36	+0.42 ± 1.23	-0.82 ± 1.23
	1.0 mg/cm²	+0.18 ± 1.23	-0.68 ± 0.36	+0.79 ± 0.36	+0.40 ± 1.23	-0.84 ± 1.23
	1.3 mg/cm²	+0.20 ± 1.22	-0.71 ± 0.36	+0.76 ± 0.36	+0.38 ± 1.22	-0.86 ± 1.22
	1.6 mg/cm²	+0.22 ± 1.22	-0.75 ± 0.36	+0.72 ± 0.36	+0.35 ± 1.22	-0.89 ± 1.22

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \frac{b - 1}{(se)_b} \right| \leq t_{1 - \alpha/2,\, n - 2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \frac{a}{(se)_a} \right| \leq t_{1 - \alpha/2,\, n - 2} \right)$

† Bias is calculated as XRF predicted value minus the known concentration of the paint film.

†† Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 11. 4" Cinderblock

	Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs	15	15	15	18	18
Slope	1.017*	0.929	0.929	0.717	0.717
SD_{slope}	0.055	0.019	0.019	0.028	0.028
Intercept	-0.155**	1.796	0.486	0.405	0.155**
$SD_{intercept}$	0.236	0.082	0.082	0.091	0.091
Corr. Coef.	0.9814	0.9972	0.9972	0.9883	0.9883
Residual Variance, %	3.69	0.56	0.56	2.33	2.33
Standard Error of Estimate of X from Y	0.601	0.239	0.239	0.388	0.388
Estimated bias† and 95% confidence interval at:†† 0.3 mg/cm²	-0.15 ± 1.48	+1.77 ± 0.53	+0.46 ± 0.53	+0.32 ± 0.64	+0.07 ± 0.64
0.8 mg/cm²	-0.14 ± 1.47	+1.74 ± 0.52	+0.43 ± 0.52	+0.18 ± 0.64	-0.07 ± 0.64
1.0 mg/cm²	-0.14 ± 1.46	+1.72 ± 0.52	+0.41 ± 0.52	+0.12 ± 0.64	-0.13 ± 0.64
1.3 mg/cm²	-0.13 ± 1.46	+1.70 ± 0.52	+0.39 ± 0.52	+0.04 ± 0.63	-0.21 ± 0.63
1.6 mg/cm²	-0.13 ± 1.45	+1.68 ± 0.52	+0.37 ± 0.52	-0.05 ± 0.63	-0.30 ± 0.63

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b-1}{(se)_b} \right| \le t_{1-\alpha/2,\, n-2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \le t_{1-\alpha/2,\, n-2} \right)$

† Bias is calculated as XRF predicted value minus the known concentration of the paint film.

†† Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 12. Solid Cinderblock

		Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs		15	18	18	21	21
Slope		0.697	0.934	0.934	0.749	0.749
SD_{slope}		0.075	0.020	0.020	0.032	0.032
Intercept		3.434	1.851	0.251	0.401	-0.189
$SD_{intercept}$		0.321	0.078	0.078	0.130	0.130
Corr. Coef.		0.9323	0.9964	0.9964	0.9832	0.9832
Residual Variance, %		13.08	0.72	0.72	3.33	3.33
Standard Error of Estimate of X from Y		1.132	0.260	0.260	0.539	0.539
Estimated bias† and 95% confidence interval at:††	0.3 mg/cm^2	+3.34 ± 2.01	+1.83 ± 0.56	+0.23 ± 0.56	+0.33 ± 0.92	-0.26 ± 0.92
	0.8 mg/cm^2	+3.19 ± 1.99	+1.80 ± 0.55	+0.20 ± 0.55	+0.20 ± 0.91	-0.39 ± 0.91
	1.0 mg/cm^2	+3.13 ± 1.99	+1.79 ± 0.55	+0.19 ± 0.55	+0.15 ± 0.91	-0.44 ± 0.91
	1.3 mg/cm^2	+3.04 ± 1.98	+1.77 ± 0.55	+0.17 ± 0.55	+0.07 ± 0.91	-0.51 ± 0.91
	1.6 mg/cm^2	+2.95 ± 1.97	+1.75 ± 0.55	+0.15 ± 0.55	0.00 ± 0.91	-0.59 ± 0.91

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \frac{b-1}{(se)_b} \right| \leq t_{1-\alpha/2,\, n-2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \frac{a}{(se)_a} \right| \leq t_{1-\alpha/2,\, n-2} \right)$

† Bias is calculated as XRF predicted value minus the known concentration of the paint film.

†† Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 13. Brick

	Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs	15	18	18	21	21
Slope	1.019*	0.918	0.918	0.721	0.721
SD_{slope}	0.056	0.021	0.021	0.036	0.036
Intercept	-0.495**	2.118	0.528	0.373	-0.227**
$SD_{intercept}$	0.238	0.081	0.081	0.146	0.146
Corr. Coef.	0.9812	0.9959	0.9959	0.9772	0.9772
Residual Variance, %	3.72	0.82	0.82	4.51	4.51
Standard Error of Estimate of X from Y	0.604	0.276	0.276	0.627	0.627
Estimated bias† and 95% confidence interval at:††	0.3 mg/cm²	-0.49 ± 1.49	+2.09 ± 0.58	+0.50 ± 0.58	+0.29 ± 1.03	-0.31 ± 1.03
	0.8 mg/cm²	-0.48 ± 1.48	+2.05 ± 0.58	+0.46 ± 0.58	+0.15 ± 1.03	-0.45 ± 1.03
	1.0 mg/cm²	-0.48 ± 1.47	+2.04 ± 0.57	+0.45 ± 0.57	+0.09 ± 1.03	-0.51 ± 1.03
	1.3 mg/cm²	-0.47 ± 1.47	+2.01 ± 0.57	+0.42 ± 0.57	+0.01 ± 1.02	-0.59 ± 1.02
	1.6 mg/cm²	-0.46 ± 1.46	+1.99 ± 0.57	+0.40 ± 0.57	-0.07 ± 1.02	-0.67 ± 1.02

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b - 1}{(se)_b} \right| \leq t_{1 - \alpha/2, \, n - 2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \leq t_{1 - \alpha/2, \, n - 2} \right)$

† Bias is calculated as XRF predicted value minus the known concentration of the paint film.

†† Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

Table 14. 5" Concrete

		Scitec	Warrington (uncorrected)	Warrington (corrected)	PGT (uncorrected)	PGT (corrected)
No. of Data Pairs		15	18	18	21	21
Slope		0.809	0.854	0.854	0.669	0.669
SD_{slope}		0.058	0.030	0.030	0.030	0.030
Intercept		-0.279**	2.288	1.098	0.370	-0.150**
$SD_{intercept}$		0.248	0.119	0.119	0.120	0.120
Corr. Coef.		0.9682	0.9901	0.9901	0.9820	0.9820
Residual Variance, %		6.26	1.97	1.97	3.57	3.57
Standard Error of Estimate of X from Y		0.783	0.430	0.430	0.557	0.557
Estimated bias[†] and 95% confidence interval at:[††]	0.3 mg/cm^2	-0.34 ± 1.55	+2.24 ± 0.85	+1.05 ± 0.85	+0.27 ± 0.85	-0.25 ± 0.85
	0.8 mg/cm^2	-0.43 ± 1.54	+2.17 ± 0.84	+0.98 ± 0.84	+0.11 ± 0.84	-0.41 ± 0.84
	1.0 mg/cm^2	-0.47 ± 1.54	+2.14 ± 0.84	+0.95 ± 0.84	+0.04 ± 0.84	-0.48 ± 0.84
	1.3 mg/cm^2	-0.53 ± 1.53	+2.10 ± 0.84	+0.91 ± 0.84	-0.06 ± 0.84	-0.58 ± 0.84
	1.6 mg/cm^2	-0.58 ± 1.53	+2.05 ± 0.84	+0.86 ± 0.84	-0.16 ± 0.84	-0.68 ± 0.84

* Slope (b) = 1 at the 95% level of confidence $\left(\left| \dfrac{b-1}{(se)_b} \right| \leq t_{1-\alpha/2,\, n-2} \right)$

** Intercept (a) = 0 at the 95% level of confidence $\left(\left| \dfrac{a}{(se)_a} \right| \leq t_{1-\alpha/2,\, n-2} \right)$

[†] Bias is calculated as XRF predicted value minus the known concentration of the paint film.

[††] Lead concentrations chosen by reference to HUD Guidelines (see Table 15).

4.2.2 Confidence Intervals

The slopes of the calibration curves with their 95 percent confidence intervals are plotted in Figure 1 for each portable XRF and each substrate. The graph shows that the slopes are not significantly different from one for the Scitec XRF on plywood, plasterboard, 4" cinderblock, brick and steel and for the PGT XRF on steel. However, the standard deviations for PGT and Scitec XRFs generally are greater than the standard deviations for the Warrington XRF. Also, the PGT and Scitec XRFs show more scatter in the slopes for the various substrates than does the Warrington.

If the confidence interval of a given slope overlaps the center estimate of another slope, there is probably no difference between the two slopes. However, overlapping of intervals where neither interval overlaps the center estimate of the other is not a strong indication that the slopes are equivalent.[24]

4.3 PREDICTED BIAS AT SELECTED LEAD CONCENTRATIONS

The linear regression equations were used to calculate predicted values for y (the lead concentration measured by XRF) at various observed values of x (the "true" lead concentration of a paint film as measured by ICP). The values of x were chosen by reference to the HUD Guidelines[6] as summarized in Table 15.

The predicted values were used to estimate the biases, and their 95 percent confidence intervals, of the lead concentrations as measured by XRF compared to the laboratory analyzed concentrations. A negative bias indicates that the concentration measured by XRF is predicted to be lower than the "true" lead concentration in the paint film; conversely, a positive bias indicates that the concentration measured by the XRF is predicted to be higher than the "true" lead concentration.

The estimated biases and their 95 percent confidence intervals for each XRF/substrate combination at 1 mg Pb/cm^2 are plotted in Figure 2. This lead concentration level was chosen because it is the HUD level of hazard. The biases include zero for all combinations except the Warrington XRF on steel and concrete and the Scitec XRF on solid cinderblock. The 95 percent confidence intervals for both the Scitec and PGT XRFs are generally larger than those for the Warrington XRF.
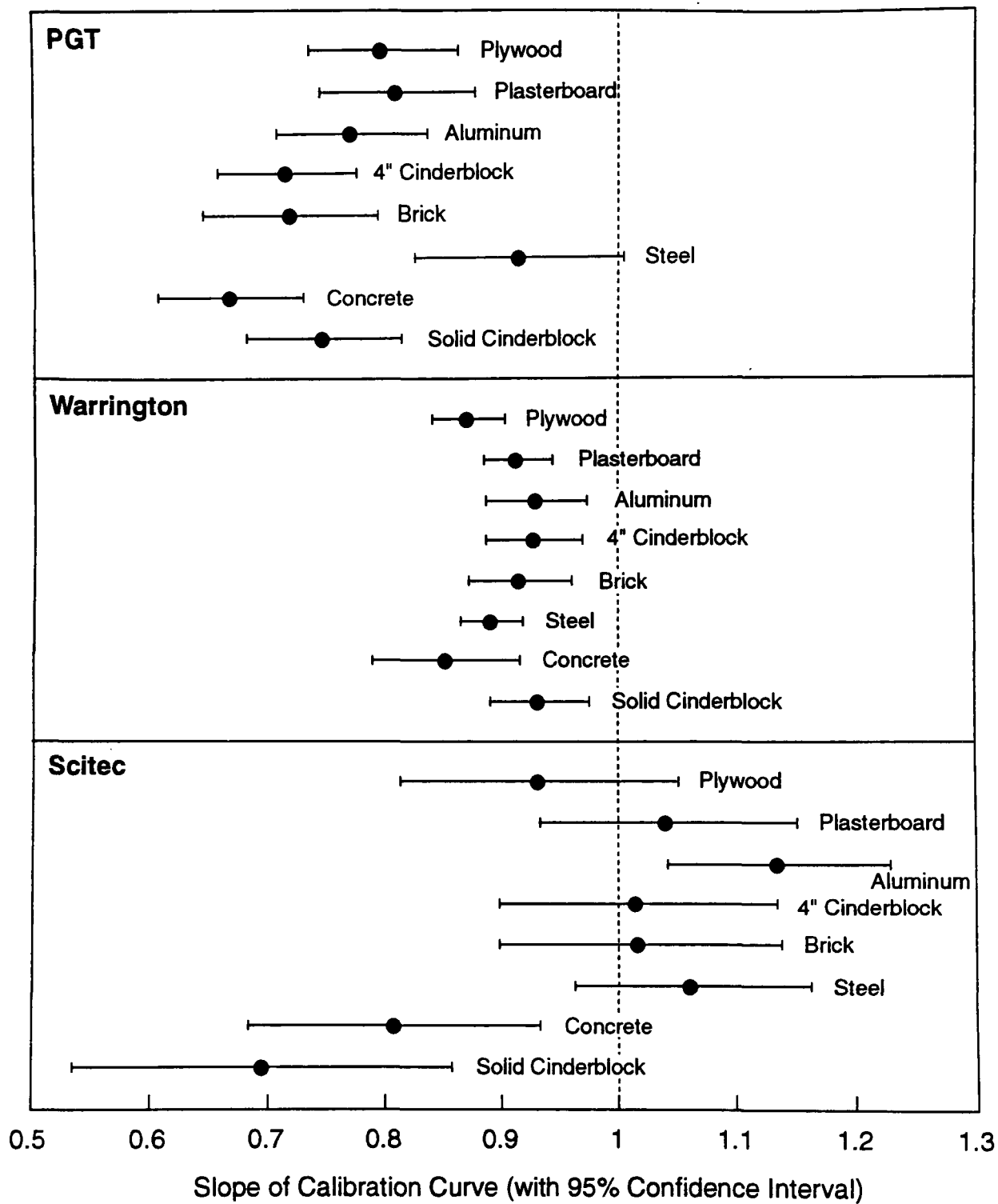
Figure 1.   Comparison of experimentally generated slopes for portable XRF/substrate combinations across the lead concentration range of 0 to 7.16 mg/cm².

Table 15. HUD Guidelines for Pb Testing Using Portable XRF Instrumentation

Type of Dwelling	XRF Type	XRF Measured Pb Level Considered Negative (mg/cm^2)	XRF Measured Pb Level Requiring Abatement (mg/cm^2)
Multi-family	Direct Reading*	< 0.5	≥ 1.6
Multi-family	Spectrum Analyzer	< 0.8	≥ 1.3
Scattered Site	Direct Reading*	**	≥ 1.6
Scattered Site	Spectrum Analyzer	≤ 0.3	≥ 1.3

* Concentrations are substrate corrected.

** Pb levels of 1.5 mg/cm^2 or less require confirmatory testing.

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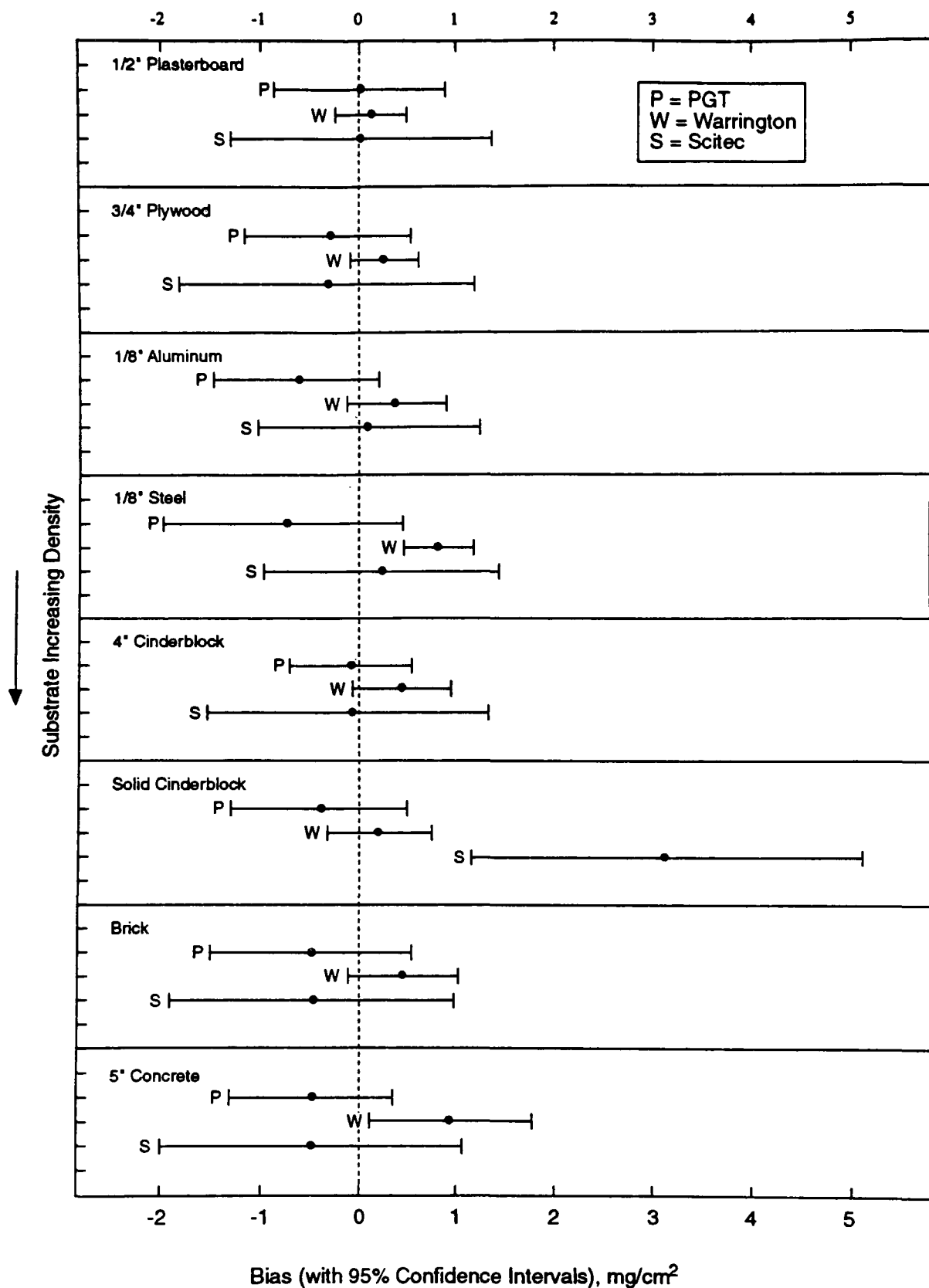
Figure 2. Comparison of predicted biases at 1 mg Pb/cm^2 for portable XRF/substrate combinations.

Again, if the interval of a given bias overlaps the center estimate of another bias, there is probably no difference between the two biases. However, overlapping of intervals where neither interval overlaps the center estimate of the other is not a strong indication that the biases are equivalent.

4.4   SCITEC MAP-3

The Scitec instrument was evaluated using the "universal" calibration installed by the manufacturer to cover the range from 0 to 6.19 mg/cm^2. In an earlier study, to determine whether the Scitec results could be improved by applying a substrate correction, the Scitec was used to measure the bare substrate alone for wood, plasterboard, 4" cinderblock, brick, aluminum siding and 1/8" steel.[15] All substrates gave readings very close to 0 mg/cm^2 (0.00 to 0.03 mg/cm^2). Therefore, no substrate correction was applied for this evaluation. The standard paint films yielded correlation coefficients ranging from 0.93 for solid cinderblock to 0.995 for 1/8" steel. The standard error of the estimate of x from y ranged from 0.30 mg/cm^2 for 1/8" steel to 1.13 mg/cm^2 for solid cinderblock. The bias of the predicted values ranged from -0.6 mg/cm^2 at 1.6 mg/cm^2 for 5" concrete to 3.3 mg/cm^2 at 0.3 mg/cm^2 for solid cinderblock. The bias of the predicted values for solid cinderblock is nearly an order of magnitude greater than the bias for any other of the substrates tested. With the exception of 4" cinderblock, all substrates showed a change in predicted bias with a change in concentration of lead; the predicted bias for 4" cinderblock was nearly constant at -0.15 to -0.13 mg/cm^2 over the range 0.3 to 1.6 mg/cm^2. The data in Table 4 show that, in general, the Scitec precision improves as the lead concentration in the paint film increases; no trend with respect to substrate was observed.

4.5   WARRINGTON MICROLEAD I

The Warrington instrument was evaluated by first measuring the lead concentration in the paint films placed on the various substrates and then measuring the "apparent lead concentration" of the substrates alone so that a substrate correction could be applied. The correlation coefficients were consistent, ranging from 0.990 for concrete to 0.998 for plasterboard, plywood and steel. The standard error of the estimate of x

from y was nearly constant, ranging from 0.2 mg/cm^2 for plasterboard, plywood and steel to 0.4 mg/cm^2 for concrete. The data that had not been corrected for substrate effects showed a positive predicted bias for all substrates except 1/8" steel. Application of a substrate correction decreased the magnitude of the predicted bias for all substrates except 1/8" aluminum and 1/8" steel. For 1/8" steel, the substrate correction changed the sign of the predicted bias from negative to positive (from -0.68 mg/cm^2 to +0.79 mg/cm^2 at 1.0 mg/cm^2). The largest predicted biases observed were for the more dense substrates cinderblock (4" and solid), brick and concrete. The predicted biases ranged from -0.03 mg/cm^2 at 1.6 mg/cm^2 for plasterboard to 1.1 mg/cm^2 at 0.3 mg/cm^2 for concrete and were found to change with a change in concentration for all substrates. The data in Table 5 show that, in general, the Warrington precision improves as the lead concentration in the paint film increases; no trend with respect to substrate was observed.

4.6   PRINCETON GAMMA-TECH XK-3

The PGT instrument was evaluated using the same substrate correction procedure as described in Section 4.5 for the Warrington XRF. The correlation coefficients were consistent, ranging from 0.977 for brick to 0.988 for 1/8" aluminum and 4" cinderblock. The standard error of the estimate of x from y ranged from 0.39 mg/cm^2 for 4" cinderblock to 0.63 mg/cm^2 for brick. Application of a substrate correction generally changed the sign of the predicted bias from positive to negative and increased the magnitude of the bias. The predicted bias after correction ranged from 0.1 mg/cm^2 at 0.3 mg/cm^2 for 4" cinderblock to -0.9 mg/cm^2 at 1.6 mg/cm^2 for 1/8" aluminum. The predicted bias was found to change with a change in concentration for all substrates; the largest changes were observed for concrete and 4" cinderblock. The data in Table 6 show that, in general, the PGT precision improves as the lead concentration in the paint film increases; no trend with respect to substrate was observed.

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SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based upon the data collected during this limited evaluation of the Scitec, Warrington, and Princeton Gamma-Tech portable XRFs, using the experimental conditions and test design described in Section 1.3, it appears that all instruments measure lead in paint films more accurately (as determined by inspection of bias) on 1/2" plasterboard than on the other substrates tested. The Warrington XRF gave a lower standard error of the estimate of x from y and a lower residual variance than the Scitec and PGT instruments for each of the eight substrates. Also, the standard deviations of the slope and intercept for the Warrington XRF were lower than those for the Scitec and PGT XRFs for all substrates, with one exception; the Warrington and PGT XRFs had the same standard deviation of the slope for 5" concrete.

The predicted biases for the three instruments on each of the eight substrates are not significantly different except for two cases: (1) the bias of the Scitec XRF is predicted to be significantly higher than the biases of the PGT and Warrington XRFs on solid cinderblock and (2) the bias of the Warrington XRF is predicted to be higher than that of the PGT XRF on 1/8" steel and 5" concrete.

The data show that, in general, precision and bias improve as the lead concentration in the paint film increases. No trend with respect to substrate was apparent from visual inspection of the data.

5.2 RECOMMENDATIONS

The data presented in this report should be considered preliminary. Several improvements have been made to the portable XRFs and their calibration procedures. It is recommended that the evaluation be repeated with care being taken to ensure that the instruments are compared on as equivalent a basis as possible with a minimum number of tests. This would include the following:

1) Careful selection of instruments so that source age is similar for XRFs from each of the three manufacturers.

2)   Testing of multiple XRFs (at least 3) from each manufacturer to obtain more representative data.

3)   Careful definition of "measurement" so that each XRF is being used as intended by the manufacturer to obtain data that are directly comparable.

4)   Following a randomized matrix, in the order specified, for each XRF.

5)   Using the new NIST-certified standard paint films (SRM-2759) and any other characterized research materials that have become available since this limited evaluation was performed.

6)   Refining the test matrix to minimize the number of substrates tested.

SECTION 6

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APPENDIX A

XRF DATA:

Scitec
Warrington Uncorrected
Warrington Substrate Corrected
PGT Uncorrected
PGT Substrate Corrected

Scitec
mg/cm²

Sample ID	ICP Analyzed Conc	1/2" Plasterboard	3/4" Plywood	1/8" Aluminum	1/8" Steel	4" Cinderblock	Solid Cinderblock	Brick	5" Concrete
20D1	7.16	7.0 6.3 7.5	6.1 7.0 7.3	8.3 7.2 7.3	7.5 7.1 7.0	7.2 6.6 6.5	8.3 8.3 8.1	6.8 6.3 6.1	4.9 4.2 6.0
20D2	6.20	5.7 7.5 7.5	6.1 6.1 5.6	6.7 8.0 7.7	6.5 7.3 8.2	7.0 6.5 6.7	8.1 7.6 8.2	6.7 7.1 5.5	6.1 4.4 5.6
120-5-B	4.96	N/A	2.9 3.2 3.1	N/A	N/A	N/A	N/A	N/A	N/A
20B2	1.27	0.9 1.1 1.0	0.5 0.6 0.8	1.1 1.2 0.9	1.2 1.4 1.8	0.1 0 0.7	4.7 5.2 4.4	0.3 0 0	0.9 0.5 0
20A2	0.52	0.3 0.4 0.6	0.2 0.4 0.3	0.5 0.4 0.6	0.6 0.6 0.8	0.3 0.5 0.7	4.0 3.6 1.0	0 0 0.1	0 0 0
120-2-B	0.07	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
17B	0.00	0 0 0	0 0 0	0 0 0	0.1 0 0	0.5 0.5 0.1	3.7 4.1 3.9	0 0 0	0 0 0

N/A - Not Analyzed

Warrington Randomized Test - Uncorrected Data
mg/cm²

Sample ID	ICP Analyzed Conc	1/2" Plasterboard	3/4" Plywood	1/8" Aluminum	1/8" Steel	4" Cinderblock	Solid Cinderblock	Brick	5" Concrete
20D1	7.16	6.87 6.80 6.77	6.70 6.73 6.77	6.90 6.77 6.67	5.93 5.90 5.60	8.27 8.40 8.37	8.53 8.40 8.20	8.23 8.50 8.33	8.37 7.57 7.80
20D2	6.20	6.23 6.13 6.40	6.33 6.23 6.23	6.13 6.23 6.37	5.00 4.97 4.97	7.77 7.60 7.67	7.87 7.60 8.07	8.37 8.07 8.07	8.13 8.13 8.13
20B2	1.27	1.60 1.57 1.57	1.93 1.67 1.70	1.43 1.27 1.17	0.40 0.47 0.63	3.33 2.60 2.87	2.83 2.87 3.13	3.37 3.50 3.27	3.23 3.43 3.57
20A2	0.52	0.97 0.83 1.07	0.87 1.03 1.07	0.87 1.13 0.37	0.03 -0.20 0.07	N/A	2.20 2.73 2.10	2.60 2.73 2.57	2.83 3.03 2.93
120-2-B	0.07	N/A	N/A	N/A	-0.27 -0.60 -0.67	1.67 1.73 1.63	1.50 1.83 1.90	1.93 1.90 2.13	2.27 2.07 2.30
17B	0.00	0.10 0.50 0.37	0.80 0.77 0.60	0.40 0.43 0.17	-0.30 -0.63 -0.87	1.93 1.83 2.23	2.00 2.07 2.13	2.20 1.97 2.27	2.20 2.00 2.20

A - Not Analyzed

Warrington Randomized Test - Substrate Corrected Data
mg/cm^2

Sample ID	ICP Analyzed Conc	1/2" Plasterboard	3/4" Plywood	1/8" Aluminum	1/8" Steel	4" Cinderblock	Solid Cinderblock	Brick	5" Concrete
Substrate only	—	0.31	0.35	-0.12	-1.47	1.31	1.60	1.59	1.19
20D1	7.16	6.56	6.35	7.02	7.40	6.96	6.93	6.64	7.18
		6.49	6.38	6.89	7.37	7.09	6.80	6.91	6.38
		6.46	6.42	6.79	7.07	7.06	6.60	6.74	6.61
20D2	6.20	5.92	5.98	6.25	6.47	6.46	6.27	6.78	6.94
		5.82	5.88	6.35	6.44	6.29	6.00	6.48	6.94
		6.09	5.88	6.49	6.44	6.36	6.47	6.48	6.94
20B2	1.27	1.29	1.58	1.55	1.87	2.02	1.23	1.78	2.04
		1.26	1.32	1.39	1.94	1.29	1.27	1.91	2.24
		1.26	1.35	1.29	2.10	1.56	1.53	1.68	2.38
20A2	0.52	0.66	0.52	0.99	1.50		0.60	1.01	1.64
		0.52	0.68	1.25	1.27	N/A	1.13	1.14	1.84
		0.76	0.72	0.49	1.54		0.50	0.98	1.74
120-2-B	0.07				1.20	0.36	-0.10	0.34	1.08
		N/A	N/A	N/A	0.87	0.42	0.23	0.31	0.88
					0.80	0.32	0.30	0.54	1.11
17B	0.00	-0.21	0.45	0.52	1.17	0.62	0.40	0.61	1.01
		0.19	0.42	0.55	0.84	0.52	0.47	0.38	0.81
		0.06	0.25	0.29	0.60	0.92	0.53	0.68	1.01

N/A - Not Analyzed

PGT Randomized Test - Uncorrected Data
mg/cm²

Sample ID	ICP Analyzed Conc	1/2" Plasterboard	3/4" Plywood	1/8" Aluminum	1/8" Steel	4" Cinderblock	Solid Cinderblock	Brick	5" Concrete
20D1	7.16	6.77 6.20 6.13	6.07 6.17 6.07	5.93 5.80 5.97	7.10 6.97 7.10	N/A	6.37 6.10 6.20	5.90 5.53 6.23	5.17 5.20 5.23
20D2	6.20	6.03 5.43 6.03	5.50 5.43 5.90	5.07 5.53 5.17	7.03 6.90 7.13	5.17 5.20 4.97	4.77 5.13 5.47	5.00 4.70 5.40	5.13 4.83 4.83
120-5-B	4.96	3.77 3.73 3.43	3.33 3.47 3.53	3.47 3.60 3.23	3.73 4.07 4.00	3.53 3.73 3.70	3.30 3.47 3.27	2.93 3.40 2.93	3.33 2.83 2.97
20B2	1.27	1.53 1.70 1.30	0.90 1.13 1.23	1.47 0.93 0.97	1.67 1.67 1.57	1.40 0.80 1.47	1.03 1.67 1.40	1.50 1.47 2.00	1.33 1.30 1.80
20A2	0.52	0.77 0.80 0.83	0.83 0.77 1.30	N/A	1.20 1.20 1.27	1.17 0.93 0.37	0.80 0.97 0.83	0.77 0.93 1.00	0.80 0.83 0.80
120-2-B	0.07	0.77 0.67 0.53	0.33 0.27 0.27	-0.07 0.17 0.10	0.50 0.60 0.50	0.27 0.53 0.63	0.73 0.37 0.37	0.33 0.23 0.67	0.97 0.33 0.23
17B	0.00	0.07 0.30 0.50	0.10 0.23 0.37	0.43 0.40 0.80	0.50 0.50 0.47	0.40 0.70 0.33	0.10 0.63 0.80	0.20 0.07 0.27	0.07 0.20 0.10

N/A - Not Analyzed

PGT Randomized Test - Corrected Substrate Data
mg/cm^2

Sample ID	ICP Analyzed Conc	1/2" Plasterboard	3/4" Plywood	1/8" Aluminum	1/8" Steel	4" Cinderblock	Solid Cinderblock	Brick	5" Concrete
Substrate only	---	0.29	0.43	0.68	1.24	0.25	0.59	0.60	0.52
20D1	7.16	6.48 5.91 5.84	5.64 5.74 5.64	5.25 5.12 5.29	5.86 5.73 5.86	N/A	5.78 5.51 5.61	5.30 4.93 5.63	4.65 4.68 4.71
20D2	6.20	5.74 5.14 5.74	5.07 5.00 5.47	4.39 4.85 4.49	5.79 5.66 5.89	4.92 4.95 4.72	4.18 4.54 4.88	4.40 4.10 4.80	4.61 4.31 4.31
120-5-B	4.96	3.48 3.44 3.14	2.90 3.04 3.10	2.79 2.92 2.55	2.49 2.83 2.76	3.28 3.48 3.45	2.71 2.88 2.68	2.33 2.80 2.33	2.81 2.31 2.45
20B2	1.27	1.24 1.41 1.01	0.47 0.70 0.80	0.79 0.25 0.29	0.43 0.43 0.33	1.15 0.55 1.22	0.44 1.08 0.81	0.90 0.87 1.40	0.81 0.78 1.28
20A2	0.52	0.48 0.51 0.54	0.40 0.34 0.87	N/A	-0.04 -0.04 0.03	0.92 0.68 0.12	0.21 0.38 0.24	0.17 0.33 0.40	0.28 0.31 0.28
120-2-B	0.07	0.48 0.38 0.24	-0.10 -0.16 -0.16	-0.75 -0.51 -0.58	-0.74 -0.64 -0.74	0.02 0.28 0.38	0.14 -0.22 -0.22	-0.27 -0.37 0.07	0.45 -0.19 -0.29
17B	0.00	-0.22 0.01 0.21	-0.33 -0.20 -0.06	-0.25 -0.28 0.12	-0.74 -0.74 -0.77	0.15 0.45 0.08	-0.49 0.04 0.21	-0.40 -0.53 -0.33	-0.45 -0.32 -0.42

N/A - Not Analyzed