EVALUATION OF HOMES
REPORTED TO BE CONSTRUCTED
WITH DOMESTIC DRYWALL

Prepared For:

U.S. Consumer Product Safety Commission
4330 East West Highway
Bethesda, MD 20814

Prepared By:

Environmental Health & Engineering, Inc.
117 Fourth Avenue
Needham, MA 02494-2725

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LIST OF ABBREVIATIONS AND ACRONYMS

A/30d	angstroms per 30 days
ACGIH	American Conference of Governmental Industrial Hygienists
ACH	air changes per hour
Ag_2S	silver sulfide
AgCl	silver chloride
AHU	air handling unit
AIHA	American Industrial Hygiene Association
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.
ASTM	ASTM International (formerly American Society for Testing and Materials)
CO_2	carbon dioxide
CPSC	U.S. Consumer Product Safety Commission
Cu_2S	copper sulfide
CuO	copper oxide
EH&E	Environmental Health & Engineering, Inc.
EPA	U.S. Environmental Protection Agency
FTIR	Fourier transform infrared
GC/ECD	gas chromatography/electron capture detector
LBNL	Lawrence Berkeley National Laboratory
mg/kg	milligrams per kilograms
NIOSH	National Institute for Occupational Safety and Health
OSHA	U.S. Occupational Safety and Health Administration
ppb	parts per billion
ppm	parts per million
QA/QC	quality assurance quality control
QAPP	Quality Assurance Project Plan
S_8	elemental (orthorhombic) sulfur
VOC	volatile organic compound
XRF	x-ray fluorescence
°C	degrees Celsius
°F	degrees Fahrenheit
$\mu g/m^3$	micrograms per cubic meter
<	less than
>	greater than
′	feet
%	percent

1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

Under contract with the U.S. Consumer Product Safety Commission (CPSC), Environmental Health & Engineering, Inc. (EH&E) conducted an investigation of homes reported to be constructed of domestic drywall. This investigation was conducted in support of CPSC's continuing evaluation of residential problem drywall installations that have elicited occupant complaints. The issue with problem drywall was originally commonly referred to as the "Chinese drywall" issue because early reports of problem drywall appeared to be associated with material that was imported from the People's Republic of China. This specific project was designed to determine if source markers, hydrogen sulfide, and corrosion conditions previously identified to be associated with problem drywall installations are present in complaint homes reported to be constructed of domestic drywall. The specific goals of the project were as follows:

1) Characterize the indoor environment of homes selected by the CPSC due to occupant complaints, and reported by homeowners to be constructed with domestic drywall.

2) Compare the drywall composition, indoor air quality, and corrosion conditions in those homes to corresponding parameters observed in residences from the 51-Home Study and laboratory findings from the CPSC catalog samples of drywall.

The CPSC has developed a comprehensive assessment program of the characteristics of problem drywall. EH&E has been responsible for aspects of the in-home testing and evaluations, certain laboratory-based studies of the source materials, characterizing indoor environmental conditions, and the effects associated with wallboard typically described by the public, media, and others as "Chinese drywall." Summaries of this work have been presented to key stakeholders and are described in detail in publicly available reports (CPSC 2011; EH&E 2010a; EH&E 2010b). The previous investigations have highlighted the link between specific components of drywall in a home and several indoor environmental quality parameters, including increased levels of hydrogen sulfide in indoor air and increased rates of silver and copper corrosion. The CPSC and EH&E

also identified elemental sulfur (S_8) and strontium content in drywall as useful markers of problematic drywall.

In addition to those findings, these investigations also demonstrated that not all drywall imported from the People's Republic of China is problematic. Additionally, the CPSC reported that they have received complaints of odor and corrosion from homeowners who believe their residences are constructed with domestically manufactured drywall. These homeowner complaints were reported to be similar to the descriptions of odor and corrosion that are typical of homes demonstrated by the CPSC and EH&E to contain problem drywall. This study was designed to evaluate homes reportedly constructed with only domestically produced drywall and compare the in-home test results with objective criteria established by the earlier investigations for the identification of the presence of problem drywall. CPSC staff performed in-depth investigations during the home selection process to remove those homes from the study where Chinese markings were clearly present.

1.2 OVERVIEW OF STUDY DESIGN

1.2.1 Environmental Sampling

Methods developed in earlier CPSC studies for characterizing the composition of drywall, constituents of indoor air, and rates of corrosion were used to address the objectives of this project. To ensure that results from this investigation were directly comparable to previous indoor environmental characterizations conducted by the CPSC and EH&E, all sample collection and analytic methods were kept consistent with those used in the "51-Home Study" and the "Source Characterization Study" (EH&E 2010a; EH&E 2010b). Key elements of the indoor environmental characterization are described in the following sections.

The 51-Home Study was an extensive indoor environmental quality characterization commissioned by the CPSC. The field study was conducted on a set of 41 homes where CPSC had received complaints of sulfur-like odors and rapid corrosion of various metal surfaces in the homes. In addition, 10 homes were recruited by the CPSC as non-complaint, or control, homes (Note: the in-home investigation confirmed that 38 of the 41 "complaint" homes evaluated were adversely impacted by problem drywall). The

Source Characterization Study was an in-depth, laboratory-based examination of the elemental and mineral content of drywall samples obtained from known sources. These known samples were also subjected to a standardized chamber test procedure where their capacity to cause copper corrosion was quantified. In addition, many of these samples were analyzed by Lawrence Berkeley National Laboratory (LBNL) to determine the off-gassing of sulfur compounds (LBNL 2010). These studies provide a robust set of reference data for assessing results from this study.

For this current evaluation, field personnel conducted a full-day visit to each study home, to perform an environmental quality assessment. This work was carried out between September 20 and 29, 2010. During the visit, the field team performed the following activities: collected drywall samples, inspected ground wires and air handling unit(s) (AHU) for corrosion, conducted air exchange measurements, and deployed passive samplers for determining indoor air concentrations of specific gases and assessing corrosion rates. A summary of each method follows, with details provided in Section 3. Field sampling was conducted in accordance with the previously developed Quality Assurance Project Plan (QAPP) described in the 51-Home Study.

1.2.1.1 Source Characterization

The field team used an x-ray fluorescence (XRF) analyzer as a screening tool to scan multiple locations on each wall of every room in the home. This *in situ* assessment focused on quantifying strontium concentrations in the drywall, with the goal of obtaining spatially resolved data for estimating the amounts/types of drywall present.

In addition to *in situ* measurements, multiple drywall samples were collected from each room. The samples were taken, using a coring tool, from areas of drywall located behind wall outlet covers. Drywall samples taken from the home were analyzed for strontium and carbonate content, as well as S_8 concentration.

1.2.1.2 Air Sampling

Hydrogen sulfide and formaldehyde measurements were obtained in multiple rooms of each home using passive samplers. The passive samplers were deployed for a two-week integrated sampling period.

1.2.1.3 Measurement of Corrosion Effects

In-home corrosion was assessed using two methods. First, the field team inspected and rated corrosion on the ground wires of representative electrical outlets. Second, corrosion classification coupons, consisting of pre-cleaned copper and silver metal coupons, were deployed for two-week periods at two locations in the home, the main living area, and at one AHU air supply register.

1.2.1.4 Environmental Conditions

Temperature and relative humidity were monitored over the two-week period when passive samplers were deployed. Air exchange rate of the home was determined during the initial visit by releasing a known volume of carbon dioxide (CO_2) into the home and monitoring its decay. In addition, an electronic sensor was used to record the duty cycle of the AHU(s) during the two-week collection period.

1.2.1.5 Alternate Source Sampling—Water

Because the homes that were recruited into this study are thought to be constructed of domestic drywall, it was important to evaluate alternative sources of sulfides and sulfide corrosion in homes in addition to the penetration of outdoor air. Evidence of the influence of hydrogen sulfide emissions from water sources was found in one home from the 51-Home Study. Therefore, the home characterization in this study included sampling and analysis of tap water, and if present, irrigation water, for sulfides.

1.2.2 Evaluation for the Presence of Problem Drywall

Test results in this study were evaluated on a home-by-home basis. The evaluation consisted of two components: 1) comparison of the test results to the distribution of results obtained from homes with problem drywall, and those without, in the previously conducted 51-Home Study; and 2) evaluation of the test results for each home against the criteria from the *Identification Guidance for Homes with Corrosion from Problem Drywall,* which was developed by the Federal Interagency Task Force on Problem Drywall (the Interagency Task Force) and published by the CPSC and the U.S.

Department of Housing and Urban Development (HUD), regarding the identification of homes with corrosion from problem drywall (CPSC 2011).

1.2.2.1 Comparison with Results from the 51-Home Study

The 51-Home Study comprised a set of homes demonstrated to be adversely impacted by problem drywall, and homes that represent typical, non-impacted homes (i.e., control homes). The distributions of the results for each parameter tested are presented as box plots, and two box plots are presented for comparison (homes with problem drywall v. control homes). The box represents the 25th and 75th percentile values; the dotted line represents the mean; the solid line represents the median; the “whiskers” represent the 10th and 90th percentile values; and the individual points are values that fell outside of the 10th and 90th percentile values.

1.2.2.2 Overview of Guidance from the Interagency Task Force on Problem Drywall

The Interagency Task Force released a summary guidance document for identification of homes with problem drywall (i.e., drywall associated with corrosion) (CPSC 2011). The identification method, based on extensive testing of problem drywall in homes and in laboratory settings (EH&E 2010a; EH&E 2010b; LBNL 2010), involves two steps: 1) conducting threshold inspection of the home; and 2) verifying the presence of corroborating evidence. A summary of the steps and criteria are provided in Table 1.1. Briefly, a positive result for Step 1 includes the observation of the blackening of the copper materials found in the home and verifying that drywall was installed in the home during the relevant time period (2001 – 2009). Positive results for both criteria are a prerequisite to any further consideration. Once the Step 1 criteria are met, confirmation of the presence of several pieces of corroborating evidence is also necessary to properly identify the home as having problem drywall. Depending upon the date of drywall installation, the number of pieces of corroborating evidence will vary. For homes built/renovated between 2001 and 2004, at least four of the Step 2 criteria must be met. For homes built/renovated between 2005 and 2009, at least two of the Step 2 criteria must be met.

The rationale for including each parameter in the guidance is detailed in the Interagency Task Force's guidance document (CPSC 2011). The decision criteria used by EH&E to evaluate whether a parameter was similar to values of problem drywall-impacted homes from the 51-Home Study are presented in the last column of Table 1.1.

Table 1.1 Summary of Interagency Task Force's Guidance for Identification of Homes with Corrosion from Problem Drywall, March 18, 2011

Steps	Interagency Criteria	Decision Criteria
Step 1 – Threshold Inspection	a) Blackening of copper electrical wiring and/or air conditioning evaporator coils.	Mean ground wire corrosion rating >2.
	-- AND --	
	b) The installation of drywall (for new construction or renovations) between 2001 and 2009.	Reported installation date fits range.
Step 2 – Corroborating Evidence[a]	a) Elemental sulfur levels in samples of drywall core found in the home exceeding 10 mg/kg.	Elemental sulfur present at concentrations >10 mg/kg.
	b) Corrosive conditions in the home, demonstrated by the formation of copper sulfide on copper coupons (test strips of metal) placed in the home for a period of two weeks to 30 days or confirmation of the presence of sulfur in the blackening of the grounding wires and/or air conditioning coils.	Cu_2S formation rate >100 A/30d (room-level) or >300 A/30d (air handling unit air supply register).
	c) Confirmed markings of Chinese origin for drywall in the home.	Visual observation of markings.
	d) Hydrogen sulfide, carbonyl sulfide, and/or carbon disulfide emitted from samples of drywall from the home when placed in test chambers.	Elevated levels of listed gases using standardized headspace testing.
	e) Corrosion of copper metal to form copper sulfide when copper is placed in test chambers with drywall samples taken from the home.	Elevated rates of copper sulfide formation in chamber testing.

>	greater than
mg/kg	milligrams per kilograms
Cu_2S	copper sulfide
A/30d	angstroms per 30 days

[a] For homes built/renovated between 2001 and 2004, at least four of the Step 2 criteria must be met. For homes built/renovated between 2005 and 2009 at least two of the Step 2 criteria must be met.

In addition, EH&E evaluated several other relevant factors that, when combined with other test results, are useful for aiding in the determination of the presence or absence of problem drywall in a home. These include: elevated rates of silver sulfide formation on silver coupons (>300 angstroms per 30 days [A/30d] [room-level] or >1,000 A/30d [AHU air supply register]); the presence of the strontium/carbonate marker (>1,200 milligrams per kilograms [mg/kg] and 5 absorbance units, respectively); and hydrogen sulfide detected in indoor air.

1.3 SUMMARY OF FINDINGS

Using the 51-Home Study results as the comparison data, five of the 11 homes (Homes A – E) in this study had test results consistent with homes that contained problem drywall. Using the Interagency Task Force's identification criteria, nine of the 11 homes met the Step 1 criteria (visible observation of corrosion on existing copper wiring and relevant date of construction/renovation) (Homes A – E and H – K). Of those nine homes, five had a sufficient number of pieces of corroborating evidence outlined in Step 2 to be classified as having problem drywall (Homes A – E). These correspond to the same five homes identified using the 51-Home Study comparison data, which included additional parameters as points of comparison. Detailed results and analysis for each home are presented in the body of this report. All results, for each home, are presented in Appendix A (Table A.1).

1.4 CONCLUSIONS

Based on: 1) the characterization of the drywall and indoor environments of these homes; 2) comparison of results in this study to existing data from homes known to be impacted by problem drywall; 3) evaluation of test results in relation to the CPSC guidance on identification of homes with corrosion from problem drywall; and 4) EH&E's extensive experience in conducting in-home investigations of homes with problem drywall, EH&E concludes that five of the homes in this study have drywall that is consistent with problem drywall.

The focus of this report was to evaluate homes reported to be constructed with domestically produced drywall. Homeowners self-reported their homes as being constructed of domestically produced drywall, and CPSC staff performed in-depth investigations to remove those homes from the study where Chinese markings were clearly present. EH&E was not able to independently confirm that all of the drywall in the impacted homes was domestically produced, as this would have required extensive removal of the interior drywall. This extremely invasive activity was excluded from the scope of work for this study. Therefore, conclusions regarding the presence of domestic drywall throughout the houses identified as being problematic cannot be confirmed at this time without further invasive investigation or detailed documentation of the origin of the drywall in the impacted homes.

2.0 BACKGROUND

2.1 PURPOSE AND SCOPE

EH&E was retained by CPSC to provide support to them in their continuing evaluation of residential drywall installations that have elicited occupant complaints. The issue with problem drywall was originally commonly referred to as the “Chinese drywall” issue because early reports of problem drywall appeared to be associated with material that was imported from the People’s Republic of China. This specific project was designed to determine if source markers, hydrogen sulfide, and corrosion conditions previously identified to be associated with problem drywall are present in complaint homes reported to be constructed of domestic drywall. The specific goals of the project were as follows:

1) Characterize the indoor environment of homes selected by the CPSC due to occupant complaints, and reported by homeowners to be constructed with domestic drywall.

2) Compare the drywall composition, indoor air quality, and corrosion conditions in those homes to corresponding parameters observed in residences from the 51-Home Study and laboratory findings from the CPSC catalog samples of drywall.

2.2 BACKGROUND

The Interagency Task Force has developed a comprehensive assessment program for investigation of the characteristics of problem drywall. EH&E has conducted the field investigations and certain laboratory-based studies of the source materials, characterizing indoor environmental conditions and the effects associated with wallboard typically described by the public, media, and others as “Chinese drywall.” Summaries of this work have been presented to key stakeholders and are described in detail in publicly available reports (CPSC 2011; EH&E 2010a; EH&E 2010b). The ongoing investigation has highlighted the link between specific components of drywall in a home and several indoor environmental quality parameters, including increased levels of hydrogen sulfide in indoor air and increased rates of silver and copper corrosion. The CPSC and EH&E also identified S_8 and strontium content in drywall as useful markers of problematic drywall.

The earlier 51-Home Study was an extensive indoor environmental quality characterization commissioned by the CPSC. The field study was conducted on a set of 41 homes where the CPSC had received complaints of sulfur-like odors and rapid corrosion of various metal surfaces in the homes. In addition, 10 homes were recruited by the CSPC as non-complaint or control homes. (Note: the in-home investigation confirmed that 38 of the 41 "complaint" homes evaluated were adversely impacted by problem drywall.) The Source Characterization Study was an in-depth, laboratory-based examination of the elemental and mineral content of drywall samples obtained from known sources. These known samples were also subjected to a standardized chamber test procedure where their capacity to cause copper corrosion was quantified. In addition, many of these samples were analyzed by LBNL for off-gassing of sulfur compounds (LBNL 2010). These studies provide a robust set of reference data for assessing results from this study.

In addition, these investigations also demonstrated that not all drywall imported from the People's Republic of China is problematic. Additionally, the CPSC reported that they have received complaints of odor and corrosion from homeowners that believe their residences are constructed with domestically manufactured drywall. These homeowner complaints were reported to be similar to the descriptions of odor and corrosion that are typical of homes demonstrated by the CPSC and EH&E to contain problem drywall. This study was designed to evaluate those claims against criteria established by the earlier investigations for the identification of the presence of problem drywall.

3.0 SAMPLING AND ANALYTICAL METHODS

3.1 OVERVIEW

Methods developed in earlier CPSC studies for characterizing the composition of drywall, constituents of indoor air, and rates of corrosion were used to address the objectives of this project. To ensure that results from this investigation were directly comparable to previous indoor environment characterizations conducted by the CPSC and EH&E, all sample collection and analytic methods were kept consistent with those used in the “51-Home Study” and the “Source Characterization Study” (EH&E 2010a; EH&E 2010b). Field sampling was conducted in accordance with the previously developed QAPP described in the 51-Home Study.

For this evaluation, field personnel conducted a full-day visit to each study home to conduct an environmental quality assessment. This work was carried out between September 20 and 29, 2010. During the visit, the field team conducted the following activities: collected drywall samples; inspected drywall for markings of Chinese origin (where accessible); inspected ground wires and AHU(s) for corrosion; conducted air exchange measurements; and deployed passive samplers for determining indoor air concentrations of specific gases and assessing corrosion rates.

The following sections describe the sampling and analytical procedures used to collect data in each home, the procedures used to process and analyze the data, and the quality assurance and quality control (QA/QC) procedures implemented by EH&E.

3.2 SOURCE DRYWALL MEASUREMENTS

Material characteristics of representative sections of drywall from each of the 11 homes were determined using gas chromatography/electron capture detector (GC/ECD), XRF, and Fourier transform infrared (FTIR) spectrometry. These methods have been assessed previously and validated for analysis of markers in problem drywall (EH&E 2010b). As described below, the elemental composition analysis was conducted using XRF in the field at each home. More detailed analyses, using a combination of GC/ECD, XRF, and FTIR were obtained subsequently in the laboratory from the bulk samples of drywall collected and archived from each home. The number of representative drywall bulk samples collected from each of the homes and analyzed at EH&E’s main facility by these methods ranged from 55 to 111 (average 84), depending on the size of the home.

3.2.1 Elemental Sulfur (S_8) Analysis by GC/ECD

In each home, a total of eight drywall samples were analyzed for content of S_8. The samples selected for analysis were chosen in a manner that maximized the likelihood of detecting S_8 and also ensured representative samples were analyzed. This was done by first selecting the drywall samples with the highest strontium concentrations because strontium and S_8 have been found to be positively correlated in problem drywall (EH&E 2010b). Once samples with the highest strontium were selected, additional samples were selected by choosing drywall boards across the full distribution of strontium concentrations as determined by XRF.

Drywall samples were sent to an independent laboratory (Columbia Analytical Services, Inc., Simi Valley, California) for analysis of S_8 using GC/ECD. A detailed description of this method can be found in a previous report (CPSC 2011).

3.2.2 X-Ray Fluorescence Analysis

An XRF Spectrometer (Innov-X OMEGA™ Handheld XRF, Innov-X Systems, Inc., Woburn, Massachusetts) provided on-site and laboratory metals analysis in this study. This device is a handheld, portable XRF analyzer and was used to identify and quantify the elements in representative wall surfaces in each home, as well as in the bulk samples collected from each home.

Every wall, including the ceilings in each home, was gridded into approximately 4′ x 4′ areas, and at least one XRF measurement was obtained from each grid in all of the homes included in the study. The elemental scanning profile for each location was stored on the internal flash memory card of the XRF. The location of each measurement was marked on a floor plan and recorded in the master field log binder. Data files were downloaded daily and saved on a central file server. In addition, drywall bulk samples collected from each of the homes were scanned, analyzed, and downloaded with the XRF software package in EH&E’s main facility. Samples of drywall with known strontium concentrations were tested repeatedly (at the beginning and at the end of each day of testing) as a means of assessing instrument drift and repeatability.

3.2.3 Fourier Transform Infrared Analysis

Bulk samples of drywall collected from the study homes were tested using FTIR at EH&E's main facility. FTIR measurements were obtained using the A2 Technologies Exoscan instrument, a full-scanning Fourier transform mid-infrared spectrometer, equipped with a Michelson interferometer and non-hydroscopic optics. The diffuse reflectance Exoscan was configured for porous and rough-surfaced materials. It has an optical design that focuses an infrared light beam perpendicular to the sample surface, resulting in diffusely scattered infrared light. This scattered infrared light interacts with the sample and is subsequently reflected back to the detector in the Exoscan. This diffuse reflectance configuration provides spectra for drywall analysis. Each sample was scanned, analyzed, and the results downloaded with the A2 Technologies Microlab PC software package. Samples of drywall were tested repeatedly (at the beginning and at the end of each day of laboratory testing) during laboratory analysis.

3.3 AIR SAMPLING

Passive monitors were placed in multiple locations in each home to collect two-week integrated samples for hydrogen sulfide and aldehydes using Radiello Diffusive Sampling Systems (Buzica et al. 2008; Cocheo et al. 1996; Sigma-Aldrich 2006; Swaans et al. 2007).

Two indoor locations and one outdoor sampling location were selected in each home. At one indoor station per house, a duplicate sampling device for each analyte was used to assess repeatability of these methods. In addition, one field and one shipping blank were collected from each home for analysis of H_2S, and shipping and field blanks were collected from every other home for formaldehyde analysis. To begin sampling, the adsorbent cartridge was transferred from the sealed storage tube into the diffusive body and was screwed onto the supporting plate. Field personnel recorded the start time and date on the field log sheet, and the assembled device was attached to the sampling tripod at a sampling height of approximately four feet. To achieve the desired limit of detection, the sampling devices were deployed for 13 – 15 days in each of the test homes. Upon completion of the sampling period, a field investigator retrieved the sampling device, sealed the chemiadsorbing cartridge into the storage tube, and shipped the sample to the analytical laboratory. All samples were temperature-controlled before and after the sampling period, and QA/QC samples were sent to the analytical laboratory in a blinded manner. Statistical analysis of blank and duplicate samples is discussed in Appendix B.

3.4 RELATIVE HUMIDITY/TEMPERATURE

Real-time temperature and relative humidity measurements were collected in each home using HOBO® U10 Temperature Relative Humidity Data Loggers (U10-003) manufactured by Onset Computer Corporation (Bourne, Massachusetts). The temperature sensor is a thermistor, and relative humidity is measured by a thin-film capacitive sensor. The data loggers were programmed to record 5-minute average measurements with a sampling rate of 5 seconds. A minimum of two temperature and humidity monitoring locations were selected in each of the homes: one typically in the central room of the house and the second typically in the master bedroom. Monitors were also located at the supply vent and outdoors at each home. If the home had two stories, one monitor was placed on each floor. Temperature and relative humidity measurements were collected for approximately 13 – 15 days in each home.

3.5 AIR EXCHANGE RATE

The air exchange rates in each test home were assessed using the method detailed in American Society for Testing and Materials (ASTM) Standard E741-00, *Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution*. Air exchange rate determinations utilized CO_2 as a tracer, given that this gas is readily available in the field and can be measured accurately using calibrated real-time instruments. The tests were conducted by introducing approximately five pounds of CO_2 throughout the home, allowing the gas to mix, and recording the decaying part of the tracer curve over time.

CO_2 concentrations were measured continuously at multiple locations inside the home using a Q-Trak Model 8551 Indoor Air Quality Monitor, manufactured by TSI, Inc. (St. Paul, Minnesota). The CO_2 sensor utilized by this monitor is non-dispersive infrared (NDIR) and is accurate within 3% (or 50 parts per million [ppm] at 25 degrees Celsius [°C] (78 degrees Fahrenheit [°F]) of the reading. Prior to each air exchange rate test, the sensors were calibrated at zero using hydrocarbon free air and spanned to 2,000 ppm (nominal) of CO_2 using certified gas standards. Air exchange rates were calculated from the CO_2 decay results using the regression method.

3.6 CORROSION ASSESSMENT

In order to evaluate corrosion of metal building components, EH&E conducted a detailed inspection of each home to qualitatively determine the extent of corrosion found on specific surfaces, as well as to deploy devices to quantitatively measure the corrosion rate in each home over a fixed time period.

3.6.1 Visual Inspection

Detailed visual inspections were performed on the electrical grounding wires, air handling units, plumbing components, and appliances. Notes were also made regarding other home contents that could show visible evidence of corrosion.

Grounding wires were evaluated on a three-point scale. A score of one indicated no visible corrosion, two indicated moderate visible corrosion, and three indicated significant visible corrosion. Field team members performed cross reference evaluations during training to ensure consistency between teams in the field. Visual corrosion ratings were recorded in the master field log binder. Examples of grounding wires and the associated evaluation are provided in Figure 3.1.

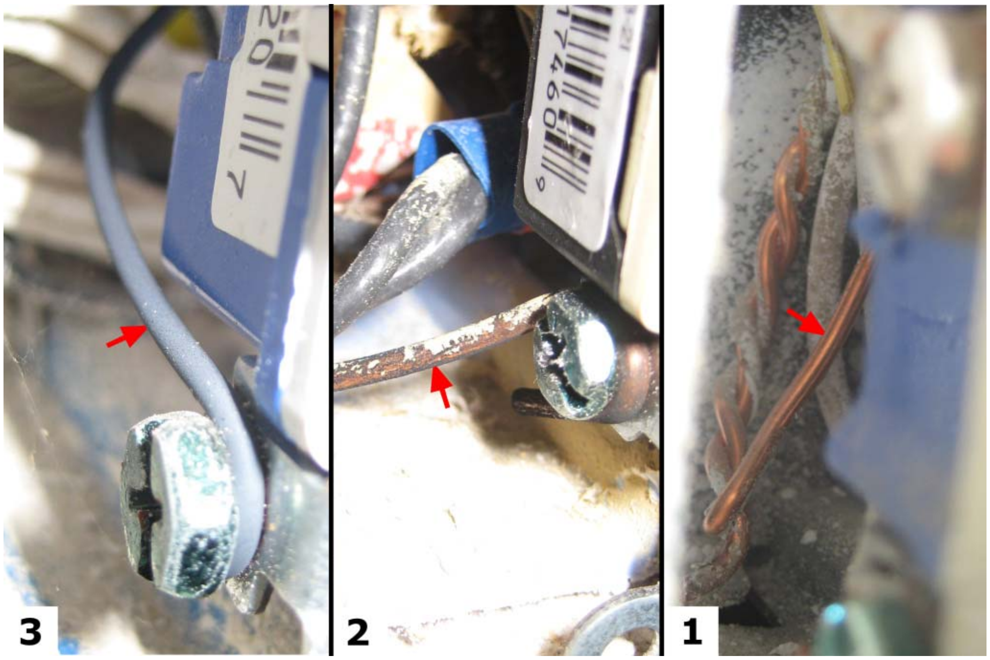

Figure 3.1 Example of Visual Corrosion Ratings, Electrical Ground Wire
(3—Significant Visible Corrosion, 2—Moderate Visible Corrosion, 1—No Visible Corrosion)

Air handling unit inspection focused on the cooling coils and associated copper refrigerant lines. Surfaces were photographed and all locations were logged into the master field log binder. Appliances and fixtures, including accessible refrigerator components, hot water heaters, faucets, plumbing lines, and other items indicating patterns of corrosion were logged and photographed.

3.6.2 Corrosion Classification Coupons

Corrosion classification coupons were used to determine the integrated corrosion rate present in the study homes. The corrosion coupons used in this study contained copper and silver metal and were supplied by Purafil, Inc., Research and Development Laboratory in Doraville, Georgia. Copper and silver corrosion coupons were placed at three indoor locations (one in the master bedroom, one in the living room, and one at the AHU air supply register) and one outdoor location for approximately a two-week period (range of 13 to 15 days). At one indoor station per house, a duplicate coupon sampling device was collected. In addition, field blank coupons were collected from every other home. At the end of the sampling period, the corrosion coupons were collected, placed in sealed containers and returned to Purafil for analysis. The laboratory measured the thickness of several copper and silver compounds, including silver sulfide (Ag_2S), silver chloride (AgCl), silver (Ag) unknown, copper sulfide (Cu_2S), copper oxide (CuO), and copper (Cu) unknown present in the sample corrosion coupons. The laboratory normalized the data using the actual period of exposure and reported the result in units of “angstroms per 30 days of exposure.”

3.7 DRINKING WATER SAMPLING METHODS

Samples of drinking water were collected from the kitchens and outdoor spigot (if any) in each of the homes and analyzed for sulfide to assess the potential for corrosive sulfur compounds volatilizing from drinking water sources. Four duplicate and four field blanks (using distilled water provided by the laboratory) were collected for QA/QC purposes.

The samples were collected using specially cleaned bottles containing preservatives specified by the reference method and provided by the analytical laboratory. Prior to sample collection, faucets were flushed for approximately 1 – 2 minutes. Samples were placed on ice, in a cooler, for transport via overnight shipping to the analytical laboratory. Sulfide analysis was performed by Columbia Analytical Services (Kelso, Washington) using the SM 4500-S2-D method.

3.8 REPORTING LIMITS

Table 3.1 lists the reporting limits from the measurements collected during the study.

Table 3.1 Analytical Reporting Limits

Analyte	Units	Reporting Limit (range)
Hydrogen Sulfide (air)	$\mu g/m^3$	0.52 – 0.67
Formaldehyde	$\mu g/m^3$	0.47 – 5.4
Corrosion (Cu_2S)	A/30d	32
Corrosion (Ag_2S)	A/30d	32
Sulfides (water)	mg/L	0.05
Strontium	mg/kg	9.0 – 160
Carbonate	absorbance	1.7*

$\mu g/m^3$	micrograms per cubic meter
Cu_2S	copper sulfide
A/30d	angstroms per 30 days
Ag_2S	silver sulfide
mg/L	milligrams per liter
mg/kg	milligrams per kilogram

* Calculated based on 3 times the standard deviation from the repeat readings.

3.9 QUALITY ASSURANCE AND QUALITY CONTROL PROCEDURES

The overall project QA/QC measures used to design, implement, and report the results of the study and analysis described in this Report are presented in Appendix B. Every effort was made in each phase of the project to ensure completeness and accuracy of data collection, application of analytical methods, data entry, calculation procedures, and reporting of results.

All sampling and analytical procedures for the project utilized appropriate and valid monitoring procedures approved and recommended in relevant published sources, either from regulatory agencies, such as the U.S. Environmental Protection Agency (EPA), the U.S. Occupational Safety and Health Administration (OSHA), other cognizant governmental organizations, such as the National Institute for Occupational Safety and Health (NIOSH), consensus standard organizations, such as ASTM, or the peer-reviewed scientific literature.

4.0 DECISION CRITERIA FOR THE EVALUATION OF THE PRESENCE OF PROBLEM DRYWALL

Test results in this study were evaluated on a home-by-home basis. The evaluation consisted of two components: 1) comparison of the test results to the distribution of results obtained from homes with problem drywall, and those without, in the previously conducted 51-Home Study, and 2) evaluation of the test results for each home against the guidance criteria provided by the Interagency Task Force regarding the identification of homes with corrosion from problem drywall (CPSC 2011).

4.1 COMPARISON WITH RESULTS FROM THE 51-HOME STUDY

The 51-Home Study comprised a set of homes demonstrated to be adversely impacted by problem drywall, and homes that represent typical, non-impacted homes (i.e., control homes). The distributions of the results for each parameter tested are presented as box plots, and two box plots are presented for comparison (homes with problem drywall v. control homes). The box represents the 25th and 75th percentile values; the dotted line represents the mean; the solid line represents the median; the “whiskers” represent the 10th and 90th percentile values; and the individual points are values that fell outside of the 10th and 90th percentile values. In presenting the results for each home in this study, the value for each home is shown as a star, which can be compared to the distribution of results from the 51-Home Study (Figures 5.2 – 5.12).

In addition to the specific guidance provided in the Interagency Task Force document, we evaluated several other relevant factors that, when combined with other test results, are useful for aiding in the determination of the presence or absence of problem drywall in a home. These include: elevated rates of silver sulfide formation on silver coupons; the presence of the strontium/carbonate marker in drywall samples (>1,200 mg/kg and 5 absorbance units, respectively); and hydrogen sulfide detected in the air.

Decision criteria and supporting information are presented in Section 4.3.

4.2 OVERVIEW OF GUIDANCE FROM THE INTERAGENCY TASK FORCE

The Interagency Task Force released a summary guidance document for identification of homes with problem drywall (i.e., drywall associated with corrosion) (CPSC 2011). The identification method, based on extensive testing of problem drywall in homes and in laboratory settings (EH&E 2010a; EH&E 2010b; LBNL 2010), involves two steps: 1) conducting threshold inspection of the home, and 2) verifying the presence of corroborating evidence. A summary of the steps and criteria are provided in Table 4.1. Briefly, a positive result for Step 1 includes the observation of the blackening of the copper materials found in the home and verifying that drywall was installed in the home during the relevant time period (2001 – 2009). Positive results for both criteria are a prerequisite to any further consideration. Once the Step 1 criteria are met, confirmation of the presence of several pieces of corroborating evidence is also necessary to properly identify the home as having problem drywall. Depending on the date of drywall installation, the number of pieces of corroborating evidence will vary. For homes built/renovated between 2001 and 2004, at least four of the Step 2 criteria must be met. For homes built/renovated between 2005 and 2009, at least two of the Step 2 criteria must be met.

The rationale for including each parameter in the guidance is detailed in the Interagency Task Force's guidance document (CPSC 2011), and is described in Table 4.1. The decision criteria used by EH&E to evaluate whether a parameter was similar to values of problem drywall-impacted homes from the 51-Home Study are presented in the last column of Table 4.1.

Table 4.1 Summary of the Interagency Task Force Guidance for Identification of Homes with Corrosion from Problem Drywall, March 18, 2011

Steps	Interagency Task Force Criteria	Decision Criteria
Step 1 – Threshold Inspection	a) Blackening of copper electrical wiring and/or air conditioning evaporator coils.	Mean ground wire corrosion rating >2.
	-- AND --	
	b) The installation of drywall (for new construction or renovations) between 2001 and 2009.	Reported installation date fits range.
Step 2 – Corroborating Evidence[a]	a) Elemental sulfur levels in samples of drywall core found in the home exceeding 10 mg/kg.	Elemental sulfur present at concentrations >10 mg/kg.
	b) Corrosive conditions in the home, demonstrated by the formation of copper sulfide on copper coupons (test strips of metal) placed in the home for a period of two weeks to 30 days or confirmation of the presence of sulfur in the blackening of the grounding wires and/or air conditioning coils.	Cu_2S formation rate >100 A/30d (room-level) or >300 A/30d (air handling unit air supply register).
	c) Confirmed markings of Chinese origin for drywall in the home.	Visual observation of markings.
	d) Elevated levels of hydrogen sulfide, carbonyl sulfide, and/or carbon disulfide emitted from samples of drywall from the home when placed in test chambers.	Elevated levels of listed gases using standardized headspace testing.
	e) Corrosion of copper metal to form copper sulfide when copper is placed in test chambers with drywall samples taken from the home.	Elevated rates of copper sulfide formation in chamber testing.

>	greater than
mg/kg	milligrams per kilograms
Cu_2S	copper sulfide
A/30d	angstroms per 30 days

[a] For homes built/renovated between 2001 and 2004, at least four of the Step 2 criteria must be met. For homes built/renovated between 2005 and 2009, at least two of the Step 2 criteria must be met.

4.3 DECISION CRITERIA FOR EVALUATING TEST RESULTS

The following section describes the decision criteria used by CPSC and/or EH&E to evaluate the test results from homes in this study.

Blackening of copper electrical wiring and/or air conditioning evaporator coils

Results from the 51-Home Study found that every home in that study that was impacted by problem drywall had at least one ground wire rated with the highest level of corrosion. In most cases, the majority of ground wires were significantly corroded (i.e., heavily blackened) (Figure 4.1), and there was evidence of significant corrosion on copper cooling coils.

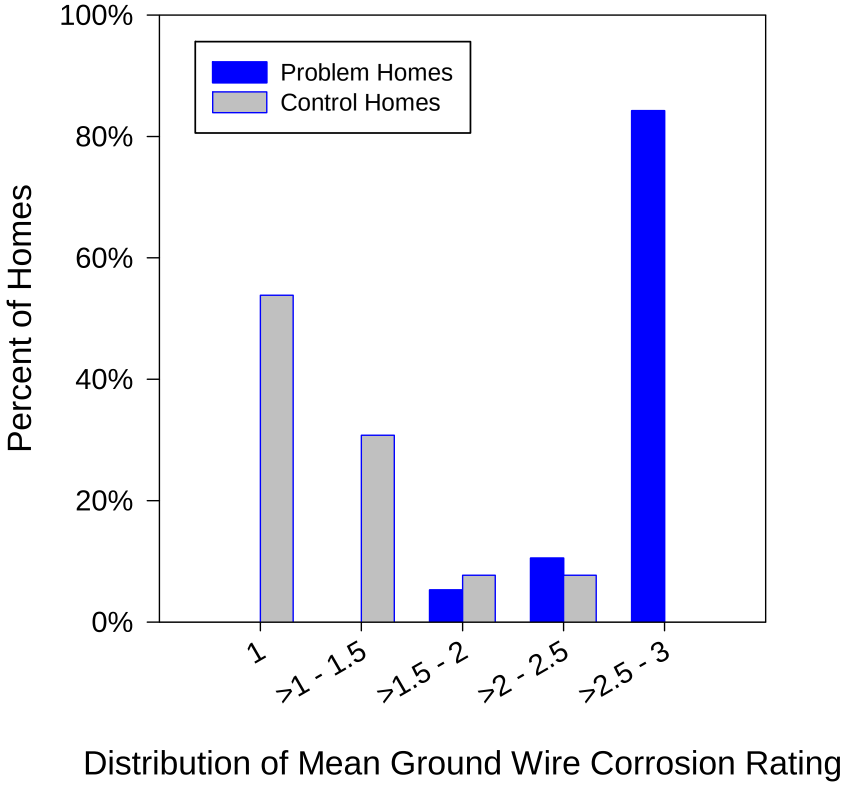

Figure 4.1 Distribution of Mean Ground Wire Corrosion Rating in 51-Home Study Homes with Problem Drywall (n=38) and Control Homes (n=13)

The installation of new drywall (for new construction or renovations) between 2001 and 2009

This date range corresponds to the time period when drywall was installed for the majority of drywall-related complaints received by the CPSC.

Elemental sulfur levels in samples of drywall core found in the home exceeding 10 ppm

Elemental sulfur levels >10 mg/kg (10 ppm) in drywall samples have been found to be a sensitive and specific marker of problem drywall (EH&E 2010b) (Figure 4.2). Elemental sulfur concentrations in drywall were associated with chamber-based measurements of hydrogen sulfide gas levels and coupon corrosion. Consistent findings were observed when this relationship was evaluated using archived samples of drywall and measurements of hydrogen sulfide gas levels and metal corrosion in the 51-Home Study.

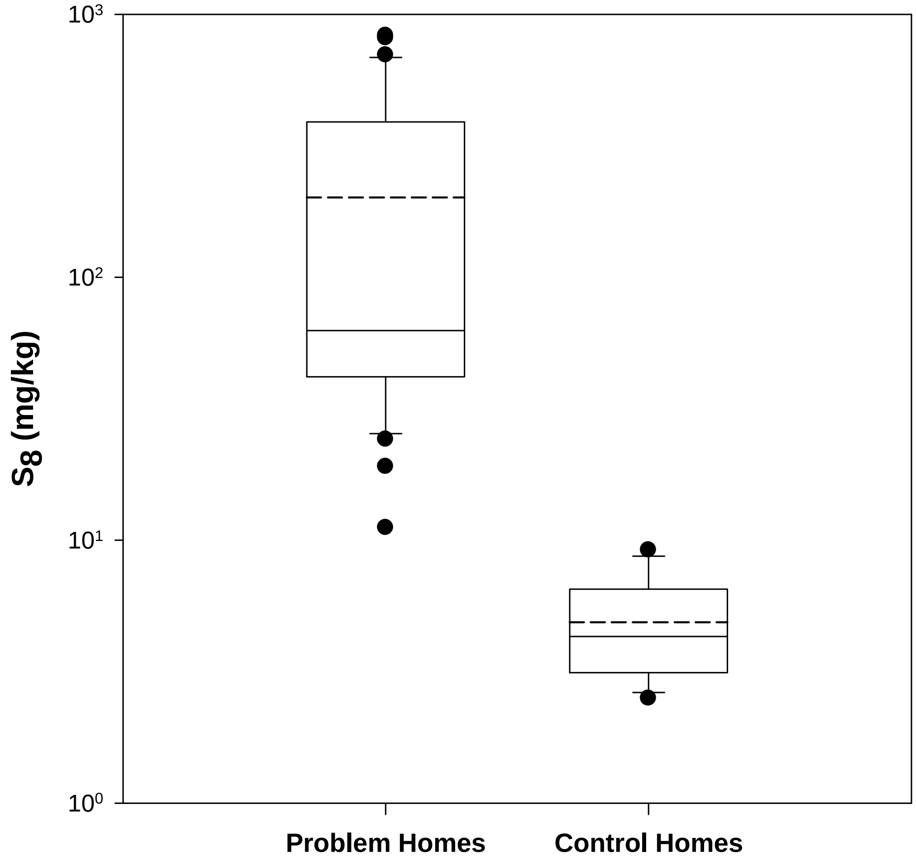

Figure 4.2 Distribution of Mean S_8 Concentrations in Homes Impacted by Problem Drywall and Control Homes from 51-Home Study

Corrosive conditions in the home, demonstrated by the formation of copper sulfide on copper coupons

Previous testing of homes with and without problem drywall identified significantly different rates of copper sulfide formation on classification coupons between the two groups (EH&E, 2010a). For coupons placed at an AHU air supply register, elevated rates of copper sulfide formation are defined as those greater than 300 A/30d (Figure 4.3). For coupons placed in rooms within the home, elevated rates of copper sulfide formation are defined as those greater than 100 A/30d.

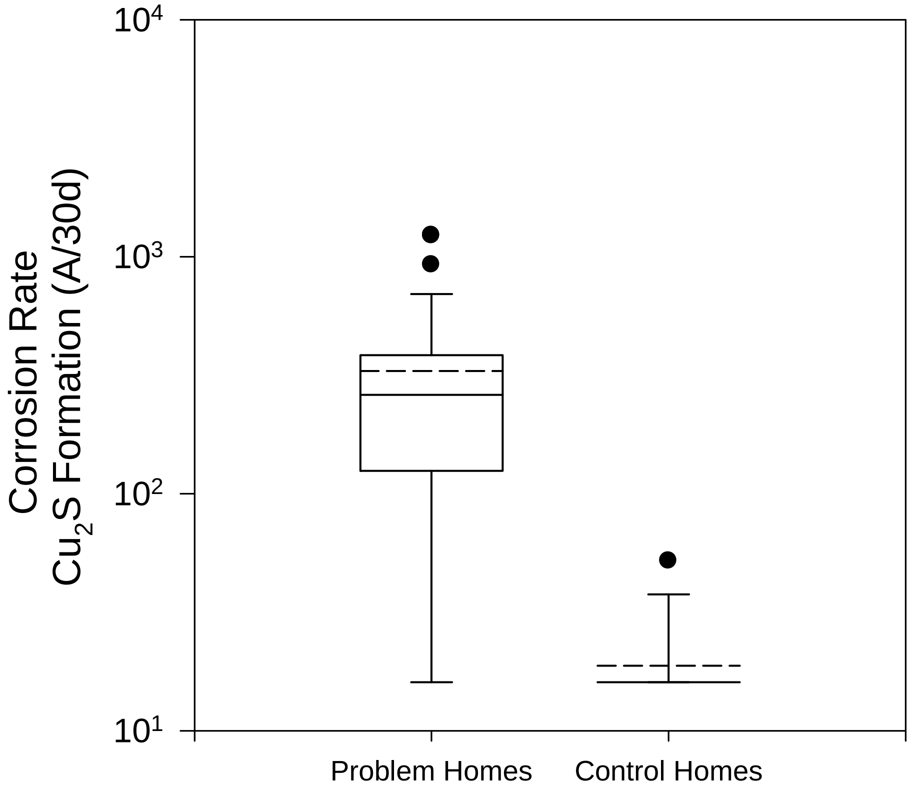

Figure 4.3 Distribution of Room Average Copper Corrosion Rates in Homes Impacted by Problem Drywall and Control Homes from 51-Home Study

Confirmed markings of Chinese origin for drywall in the home

The problem drywall issue was originally associated with drywall imported from the People's Republic of China. Because this study was focused on homes reported to be built/renovated with domestic drywall, the absence of finding markings may not be relevant, while the presence of such markings would provide important evidence in establishing that not all of the drywall in these homes was domestically produced. Importantly, the CPSC notes that it is not absolutely necessary for the markings to be found because in some cases even problem drywall of Chinese origin does not have markings indicating the nation of origin.

Elevated levels of hydrogen sulfide, carbonyl sulfide, and/or carbon disulfide emitted from samples of drywall from the home when placed in test chambers

Testing conducted by LBNL found that problem drywall had higher emission rates for several sulfur gases, on average, compared to control samples.

This study, like the earlier 51-Home Study (EH&E, 2010a) was intentionally designed to identify source characteristics of drywall and characterize the indoor environment in the home where the complaint was reported. The CPSC did not task EH&E with conducting laboratory-based testing during this phase of the investigation; therefore, chamber emissions testing and chamber-based corrosion testing were not performed as part of the suite of tests.

Corrosion of copper metal to form copper sulfide when copper is placed in test chambers with drywall samples taken from the home

EH&E previously conducted a chamber-based study of representative samples of drywall of known origin. In this controlled study, problem drywall was associated with elevated rates of copper sulfide formation in the chamber (EH&E, 2010b).

This study, like the earlier 51-Home Study (EH&E, 2010a) was intentionally designed to identify source characteristics of drywall and characterize the indoor environment in the home where the complaint was reported. The CPSC did not task EH&E with conducting laboratory-based testing during this phase of the investigation; therefore, chamber emissions testing and chamber-based corrosion testing were not performed as part of the suite of tests.

Corrosive conditions in the home, demonstrated by the formation of silver sulfide on silver coupons

Formation of silver sulfide on the silver coupons has previously been found to be a useful indicator of corrosive conditions in the homes associated with problem drywall (EH&E 2010a). For silver coupons deployed at an AHU air supply register, elevated silver sulfide formation rates are defined as those greater than 1,000 A/30d (Figure 4.4). For silver coupons deployed in rooms in the home, elevated silver sulfide formation rates are defined as those greater than 300 A/30d.

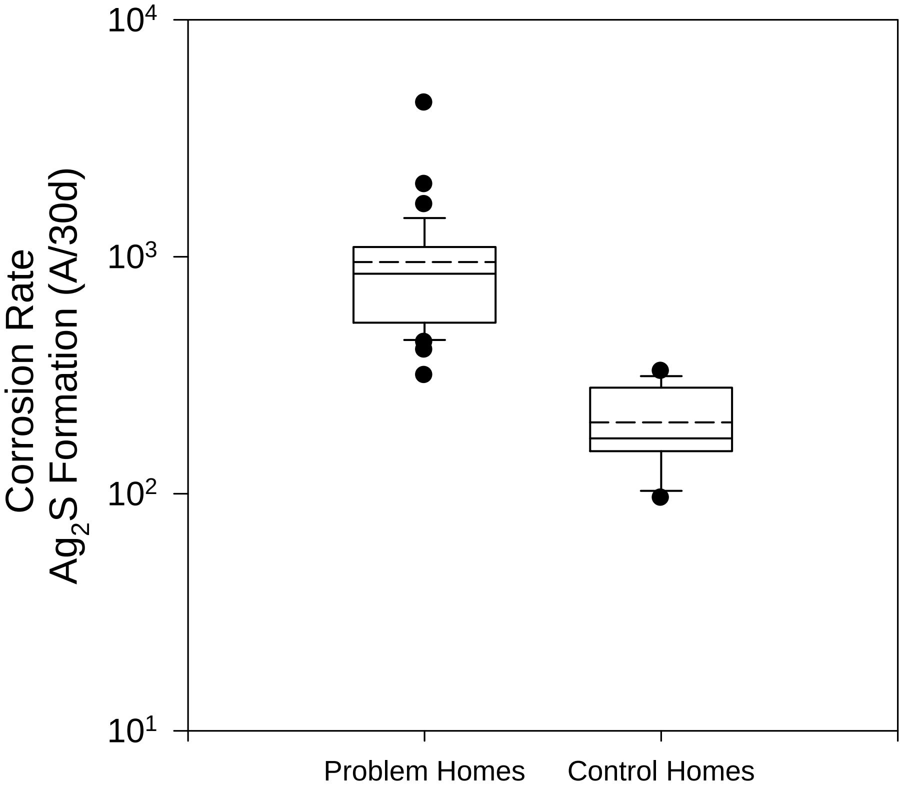

Figure 4.4 Distribution of Room Average Silver Corrosion Rates in Homes Impacted by Problem Drywall and Control Homes from 51-Home Study

Presence of Strontium/Carbonate Marker in Drywall Samples

Elevated levels of strontium and carbonate, defined as >1,200 mg/kg and 5 absorbance units, respectively, have been demonstrated to be a useful screening tool to aid in the identification of homes with problem drywall when they are found jointly in a sample (EH&E 2010a). In addition, strontium concentrations can be used as a means of identifying samples that may have elevated elemental sulfur content because previous studies have shown that strontium and elemental sulfur are positively correlated in problem drywall (EH&E 2010b). Because strontium can be measured more rapidly, directly, and inexpensively than elemental sulfur, a greater number of samples throughout the home can be screened for strontium. Using the strontium measurements to select samples for elemental sulfur analysis, therefore, reduces the likelihood of not finding a problem drywall board in the home if one is present due to insufficient sample size (Type II error).

Presence of Hydrogen Sulfide in Indoor Air

In-home and laboratory-based studies have both demonstrated that hydrogen sulfide is associated with problem drywall (EH&E 2010a; EH&E 2010b; LBNL 2010). Test results from the 51-Home Study demonstrated that there were significant differences in the concentrations of hydrogen sulfide between homes with problem drywall and control homes, on average (Table 4.2) (EH&E 2010a).

Table 4.2 House Average Hydrogen Sulfide Concentrations in Air (μg/m^3)

Analyte	Home Status	n	% Det	Mean	Min	P50	Max
Hydrogen sulfide	Problem Homes	38	68.7	0.98	<LOD	0.85	3.11
	Control Homes	13	35.3	0.56	<LOD	<LOD	3.11

μg/m^3	micrograms per cubic meter
n	number of samples
% Det	percent detected
Min	minimum
P	percentile
Max	maximum
<LOD	less than the limit of detection

5.0 RESULTS

Results of the building system performance (e.g., air exchange rate, temperature) and additional parameters monitored (e.g., formaldehyde) were consistent for this group of homes. As a result, a general description and discussion of results for these parameters is presented, in aggregate, in Section 5.1.

Results for testing parameters related to problem drywall (e.g., corrosion) are presented on a home-by-home basis in Sections 5.2 – 5.12. The results for each home are plotted alongside the distribution of results from the two sets of homes in the 51-Home Study (homes known to be impacted with problem drywall [“Problem Homes”] and those not impacted by problem drywall [“Control Homes”]). Corrosion data presented in the boxplots are from the room-level corrosion monitoring. Data for corrosion rates measured at the AHU air supply register can be found in Table A.1, Appendix A.

A summary of all of the results by home in relation to the Interagency Task Force’s guidance is presented in Section 6.1. Detailed results for all of the homes, grouped by analyte, can be found in Table A.1, Appendix A,.

5.1 AIR EXCHANGE RATE, THERMAL COMFORT, FORMALDEHYDE, SULFIDES IN WATER

All of the homes in this study had ventilation rates, measured in air changes per hour (ACH) (range: 0.16 – 0.63 ACH; median = 0.23 ACH), that are typical for residential buildings in North America. Typical air exchange rates in North American homes range from a seasonal average of about 0.2 ACH for tightly constructed homes, to upwards of 2 ACH for loosely constructed housing (ASHRAE 2005). Additional studies have shown that an ACH of approximately 0.4 to 0.5 is a reasonable estimate of average seasonal air exchange rate for residences (ASHRAE 2005; Ek et al. 1990; Grimsrud et al. 1982; Palmiter and Brown 1989; Parker et al. 1990).

Formaldehyde concentrations in the indoor air of these study homes were consistent with those found in recently constructed homes, and results from the 51-Home Study (Figure 5.1). For example, Hodgson et al. (2000) evaluated air exchange rates and formaldehyde concentrations in newly manufactured houses and site-built houses. The average indoor concentrations for those 14 residences was 49 micrograms per cubic meter (μg/m^3) (40 parts per billion [ppb]) with a median of 47 μg/m^3 (38 ppb) with a range from 9 – 66 μg/m^3 (7 – 54 ppb).

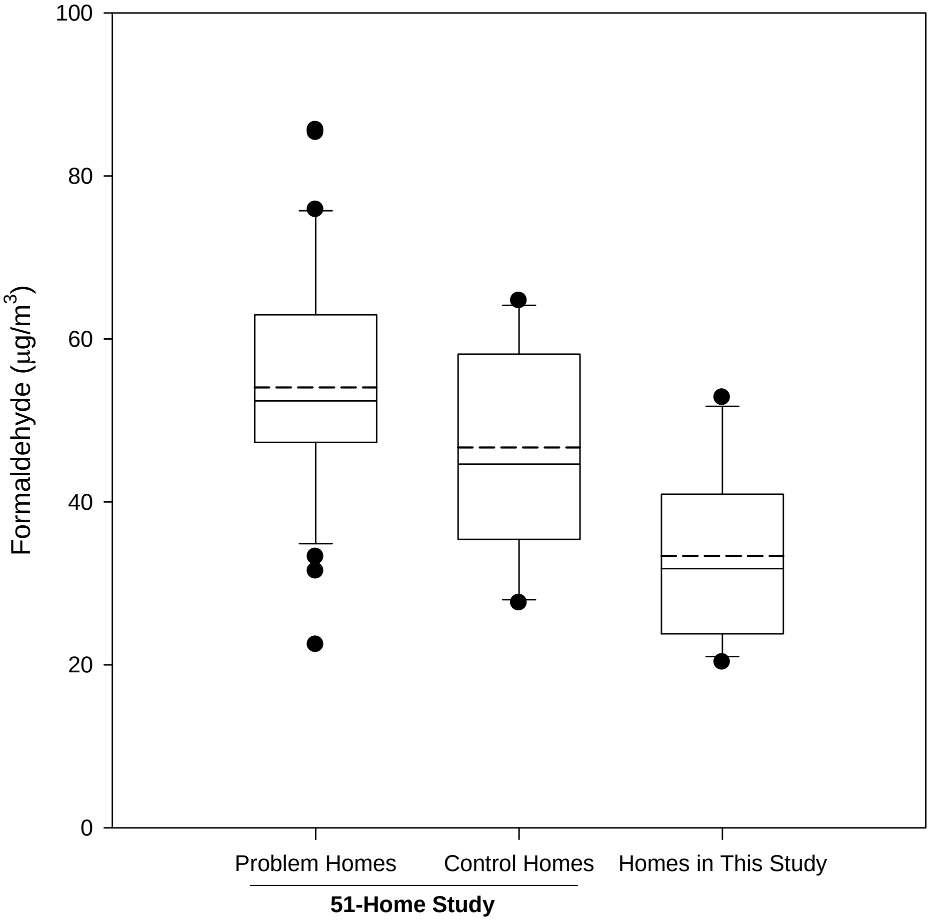

Figure 5.1 Comparison of Distribution of House Average Formaldehyde Concentrations Measured in the 51-Home Study (both homes impacted by problem drywall and control homes) and Homes in this Study

Sulfides were not detected in any water samples from any of the 11 homes and, therefore, are not likely a potential contributing factor to measured indoor corrosion rates.

Average temperature and humidity conditions within the homes were typically within the ranges recommended by ASHRAE for summer months (ASHRAE 55-2004). Average indoor temperature and humidity conditions varied within the homes, and as expected, were generally higher in homes situated in southern Florida, when compared to homes located in Pennsylvania and North Carolina (Table 5.1).

Table 5.1 Results of Continuous Temperature, Relative Humidity, and Dew Point Monitoring, September 2010

		Temperature (°F)		Humidity			
				Relative Humidity (%)		Dew Point (°F)	
Home	Location	Range	Ave	Range	Ave	Range	Ave
A	Florida	74 – 78	76	42 – 57	48	51 – 58	55
B	Florida	75 – 82	80	47 – 63	51	58 – 64	61
C	Florida	79 – 83	81	45 – 58	50	57 – 66	61
D	Florida	73 – 87	79	39 – 61	49	48 – 70	59
E	Florida	78 – 79	79	41 – 51	45	53 – 59	56
F	North Carolina	70 – 75	73	40 – 62	52	48 – 59	54
G	Pennsylvania	66 – 73	70	44 – 61	51	47 – 55	51
H	Florida	78 – 86	82	51 – 71	62	60 – 74	68
I	Florida	72 – 78	74	39 – 51	42	47 – 55	50
J	Florida	76 – 78	77	39 – 48	42	51 – 56	52
K	Florida	74 – 79	76	44 – 58	49	52 – 63	55

°F degrees Fahrenheit
Ave average

Although the ASHRAE recommended ranges for thermal comfort are considered good guidelines (72 degrees Fahrenheit [°F] to 80 °F for summer months, and 68 °F to 76 °F for winter months), optimal thermal comfort also depends on a variety of factors, including individual occupant preferences, an individual's metabolic rate, transfer of body heat to the surrounding environment, and body temperature.

5.2 HOME A (CONSTRUCTED 2006)

Test results for Home A in comparison to results from the 51-Home Study are depicted by the star in Figure 5.2. Drywall samples from Home A had elevated concentrations of S_8 in multiple drywall samples analyzed (mean concentration = 500 mg/kg) and nearly 40% of the drywall samples tested in the home had the strontium/carbonate marker (the living room and master bedroom had the strontium/carbonate marker present in 75% and 100% of samples, respectively). Hydrogen sulfide was detected in the air of the home. There was strong evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Cu_2S and Ag_2S formation on the copper and silver coupons deployed in rooms in the home. Additionally, elevated rates of corrosion were also observed in copper and silver coupons at the AHU air supply register (Appendix A, Table A.1). Indoor corrosion rates in the rooms were up to six times higher than outdoor corrosion rates.

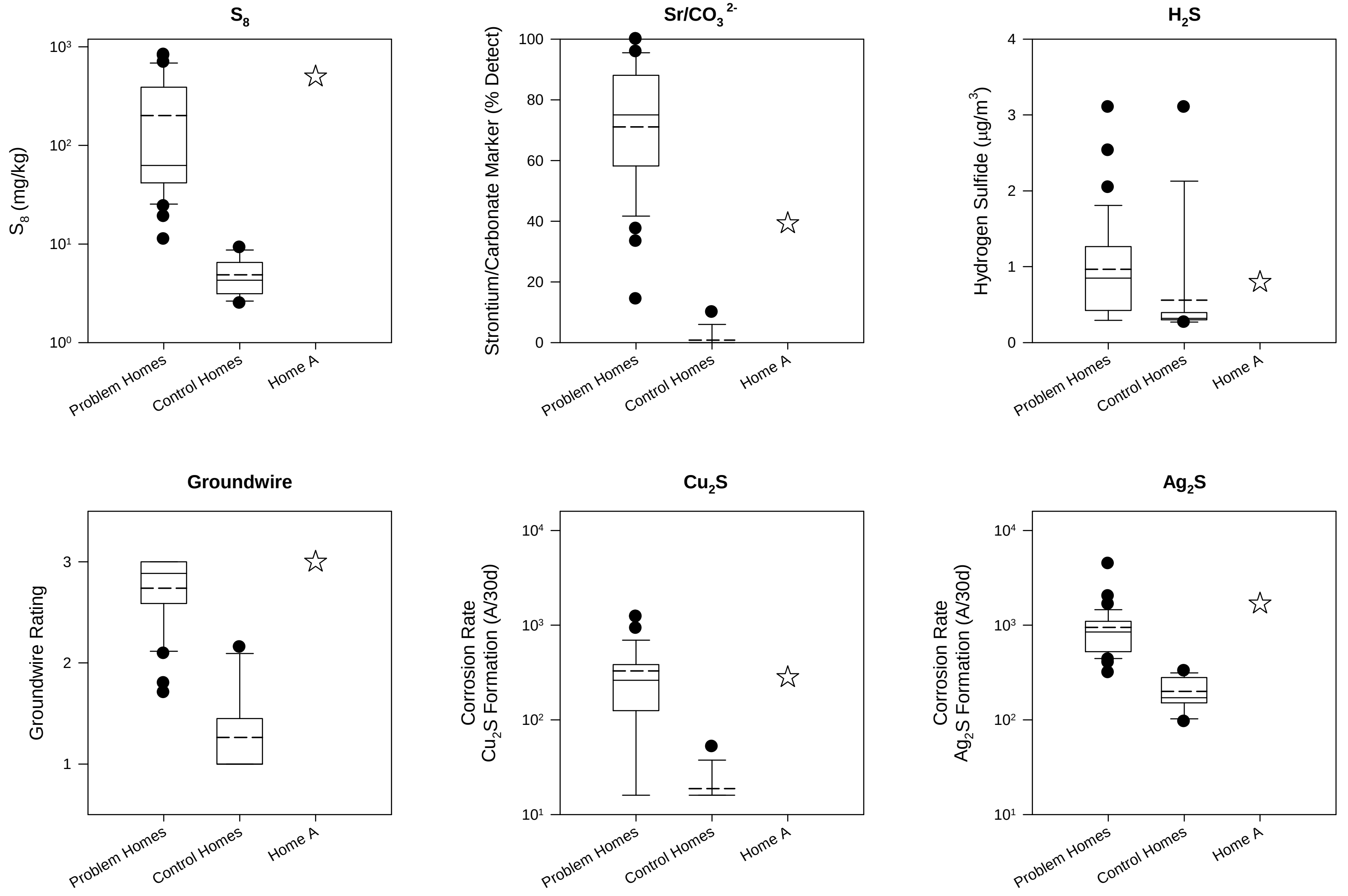

Figure 5.2 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home A

5.3 HOME B (CONSTRUCTED 2006)

Test results for Home B in comparison to results from the 51-Home Study are depicted by the star in Figure 5.3. Drywall samples from Home B had elevated concentrations of S_8 in multiple drywall samples (mean concentration = 500 mg/kg). The strontium/carbonate marker was present in 17% of the samples from the entire home. Source markers varied by room in the home; neither S_8 nor the strontium/carbonate marker were found in the living room, but both were found in the master bedroom. Hydrogen sulfide was detected in the air of the home. There was evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Ag_2S and Cu_2S formation in coupons deployed in all of the rooms (Appendix A, Table A.1). The ground wire corrosion rating was significantly higher in the master bedroom (2.6) compared to the living room (1.7) where markers of problem drywall were not detected. Cu_2S and Ag_2S formation rates were not elevated at the AHU air supply register. Indoor corrosion rates in the rooms were up to 2.5 times higher than outdoor corrosion rates.

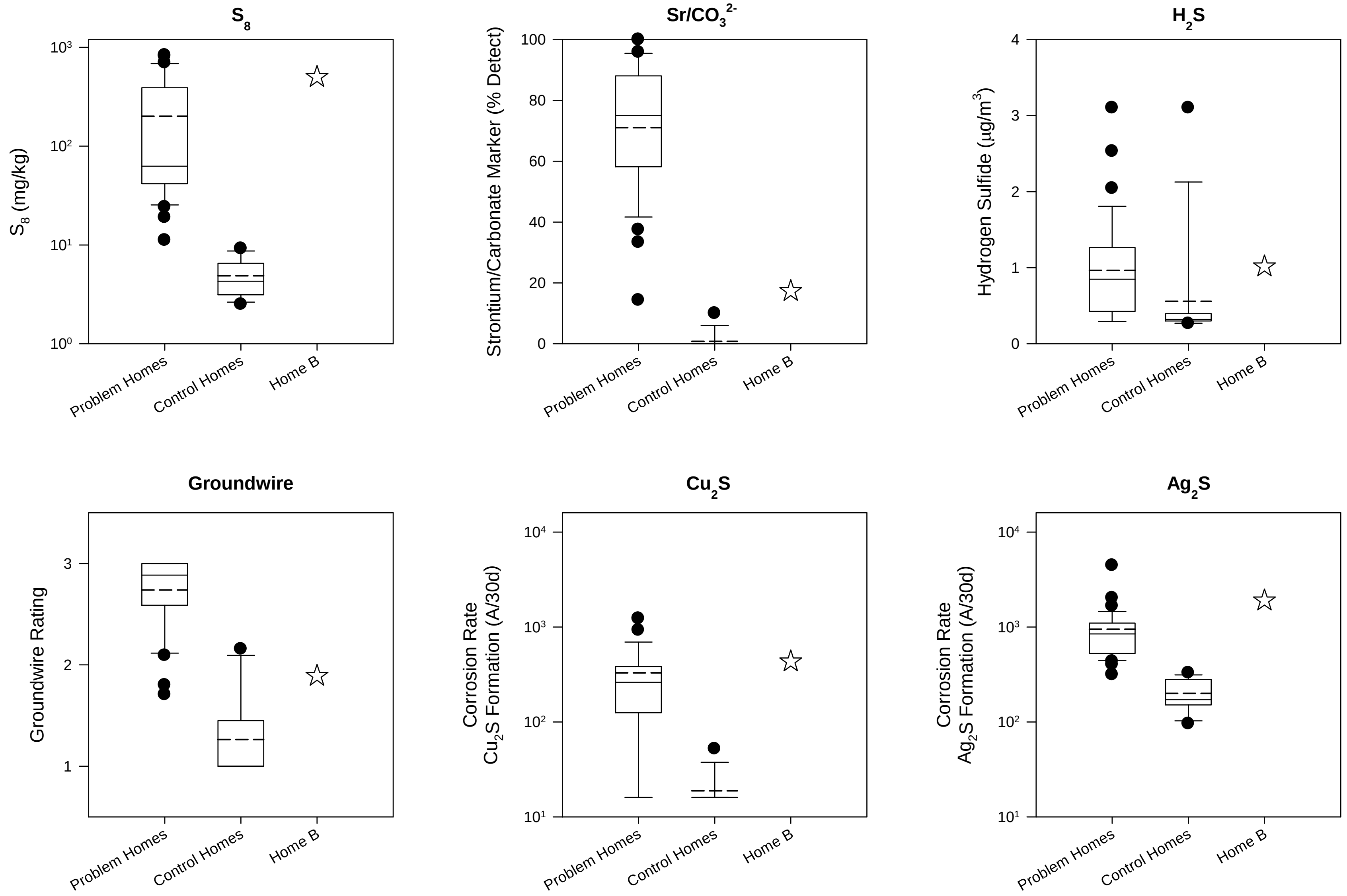

Figure 5.3 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home B

5.4 HOME C (CONSTRUCTED 2005-2006)

Results for Home C in relation to results from the 51-Home Study are depicted by the star in Figure 5.4. Drywall samples from Home C had elevated concentrations of S_8 in multiple drywall samples (mean concentration = 810 mg/kg). The strontium/carbonate marker was present in 25% of the samples from the entire home. Both the S_8 and strontium/carbonate source markers were detected in the living room but not in the master bedroom. Hydrogen sulfide was not detected in the air of the home. There was evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Cu_2S and Ag_2S formation in coupons deployed in rooms in the home. Cu_2S formation rates were higher in the living room compared to the bedroom (230 v. <32 A/30d); Ag_2S formation rates were similar across rooms (1,500 v. 1,900 A/30d). Additionally, elevated rates of corrosion were also observed in copper and silver coupons at the AHU air supply register (Appendix A, Table A.1). Indoor corrosion rates in the rooms were up to four times higher than outdoor corrosion rates.

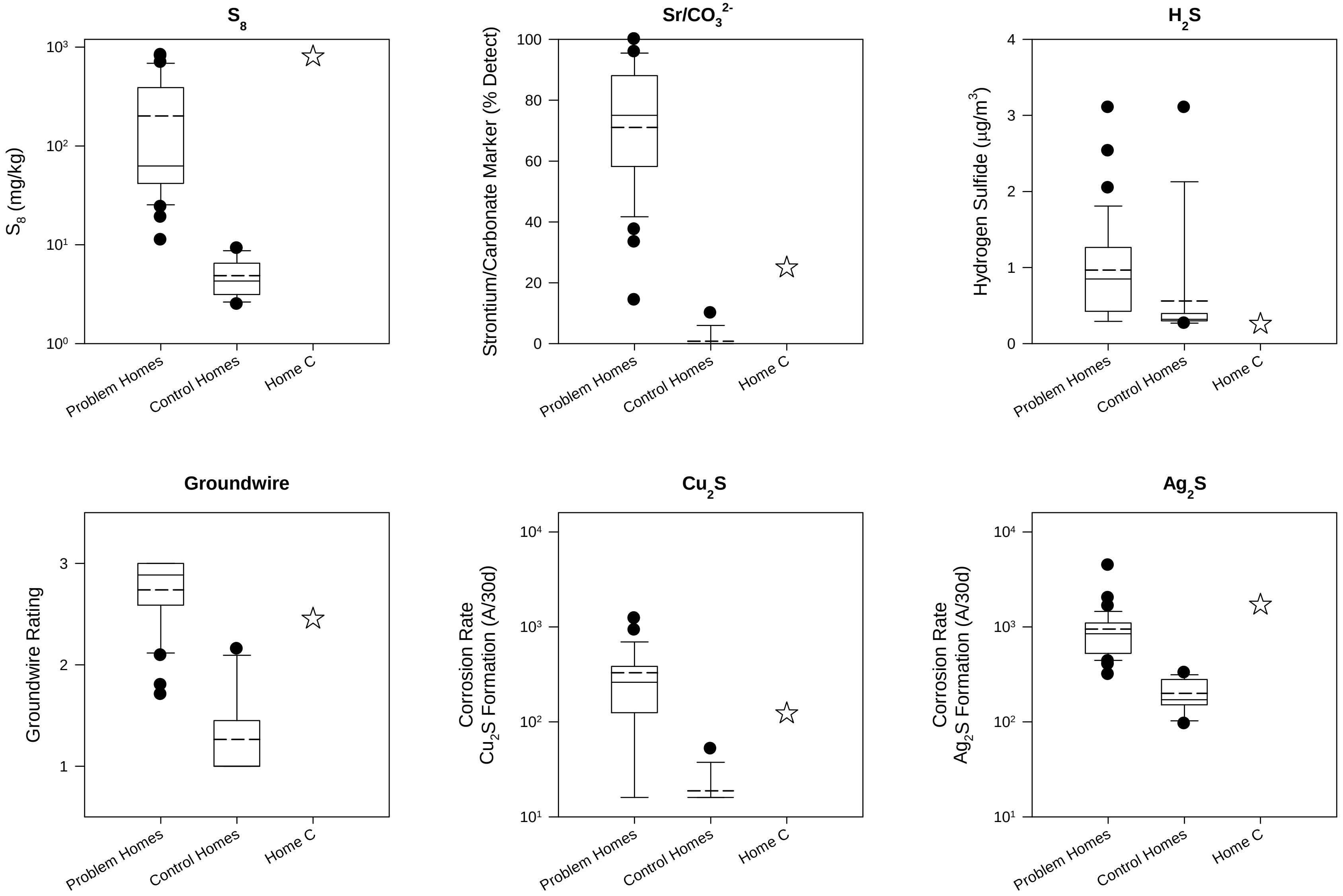

Figure 5.4 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home C

5.5 HOME D (CONSTRUCTED 2005-2007)

Results for Home D in relation to results from the 51-Home Study are depicted by the star in Figure 5.5. Drywall samples from Home D had elevated concentrations of S_8 in 100% of drywall samples tested (mean concentration = 180 mg/kg) and a majority of samples (82%) had the strontium/carbonate marker. Hydrogen sulfide was detected in the air of the home. There was strong evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Ag_2S formation on coupons deployed in all locations. Elevated Cu_2S formation rates were observed at the AHU air supply register and in one room in the home (Appendix A, Table A.1). Indoor corrosion rates in the rooms were up to nine times higher than outdoor corrosion rates.

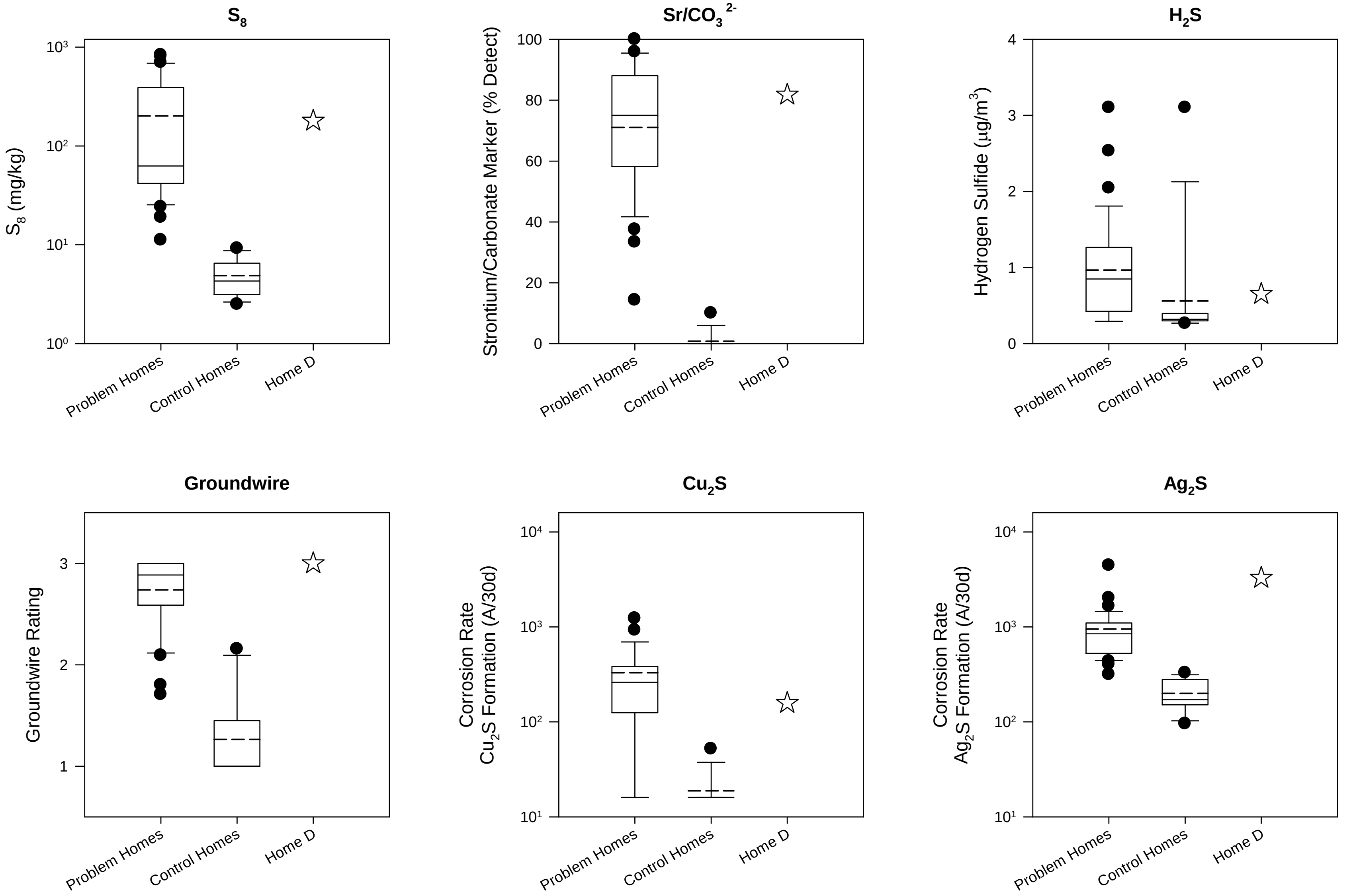

Figure 5.5 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home D

5.6 HOME E (CONSTRUCTED 2006)

Results for Home E in relation to results from the 51-Home Study are depicted by the star in Figure 5.6. Drywall samples from Home E had elevated concentrations of S_8 in multiple drywall samples (mean concentration = 1,100 mg/kg) and approximately 50% had the strontium/carbonate marker. Hydrogen sulfide was not detected in the air of the home. There was evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Ag_2S formation on coupons deployed in all locations. Cu_2S formation rates were elevated in one room in the home but not in the sample deployed at the AHU air supply register (Appendix A, Table A.1). Indoor corrosion rates in the rooms were up to two times higher than outdoor corrosion rates.

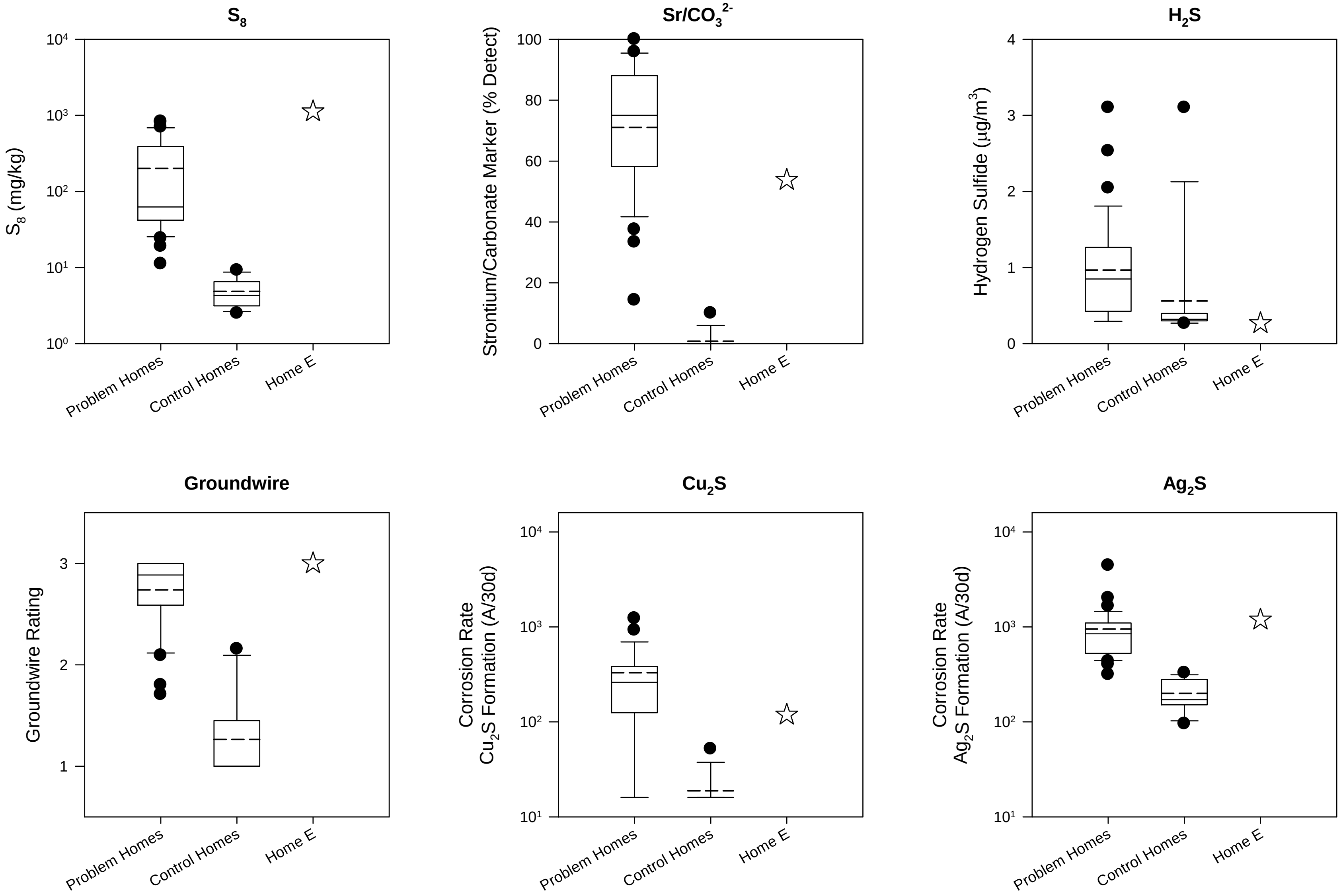

Figure 5.6 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home E

5.7 HOME F (CONSTRUCTED 2005-2006)

Results for Home F in relation to results from the 51-Home Study are depicted by the star in Figure 5.7. Drywall samples from Home F did not have elevated concentrations of S_8 in any drywall samples, nor did they have the strontium/carbonate marker. Hydrogen sulfide was not detected in the air of the home. There was no evidence of elevated rates of corrosion based on the ground wire corrosion rating or rates of Cu_2S and Ag_2S formation on deployed coupons in any locations within the home. Indoor corrosion rates were similar to outdoor rates.

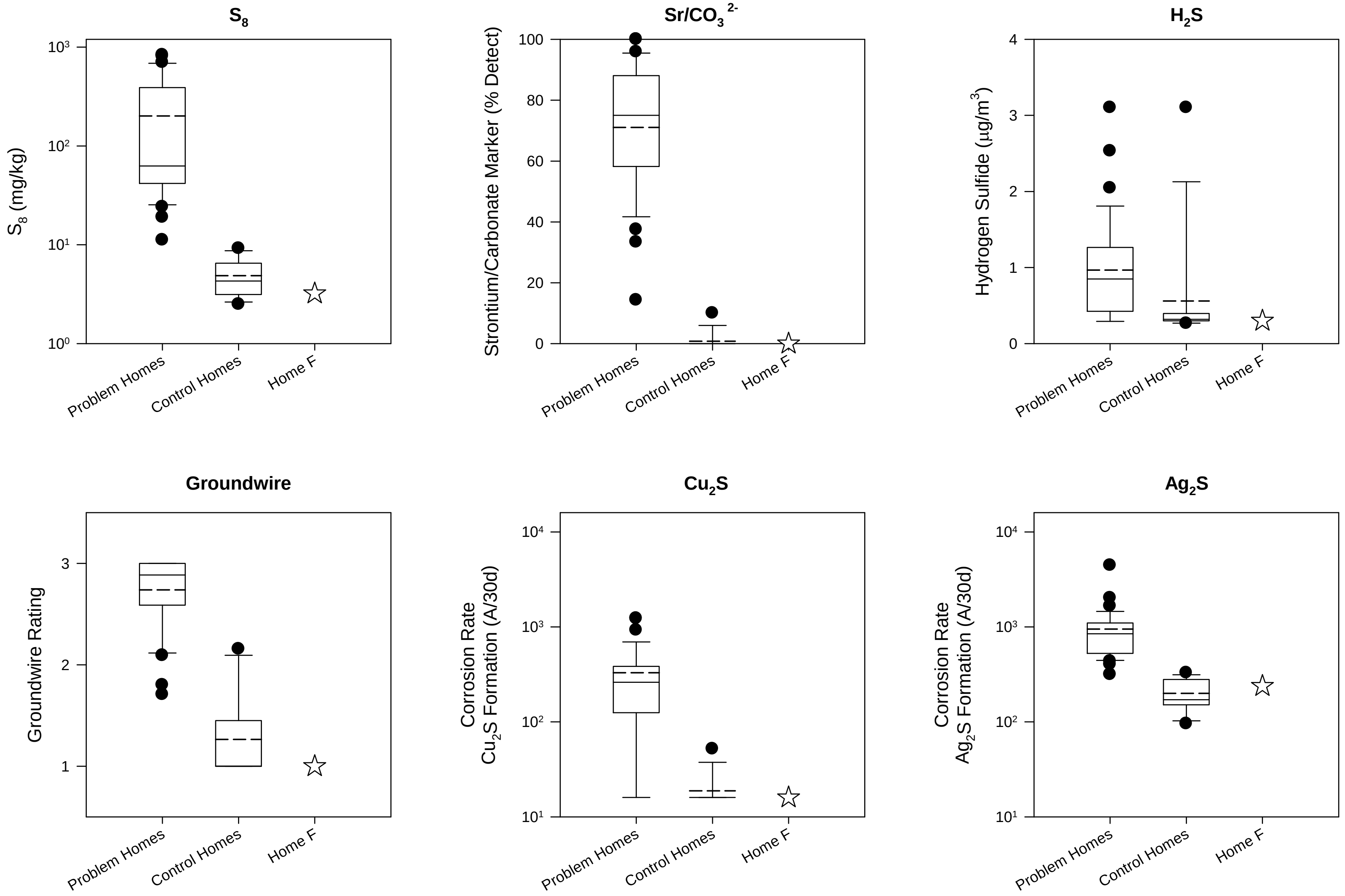

Figure 5.7 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home F

5.8 HOME G (CONSTRUCTED 2002)

Results for Home G in relation to results from the 51-Home Study are depicted by the star in Figure 5.8. Drywall samples from Home G did not have elevated concentrations of S_8 in drywall samples, nor did they have the strontium/carbonate marker. Hydrogen sulfide was not detected in the air of the home. There was no evidence of elevated rates of corrosion based on the ground wire corrosion rating and the rates of Cu_2S formationon deployed coupons in any locations within the home. Ag_2S formation rates were above the threshold level in the rooms within the home, but not at the AHU air supply register (Appendix A, Table A.1). Indoor Ag_2S formation rates were similar to, but slightly higher than, outdoor rates.

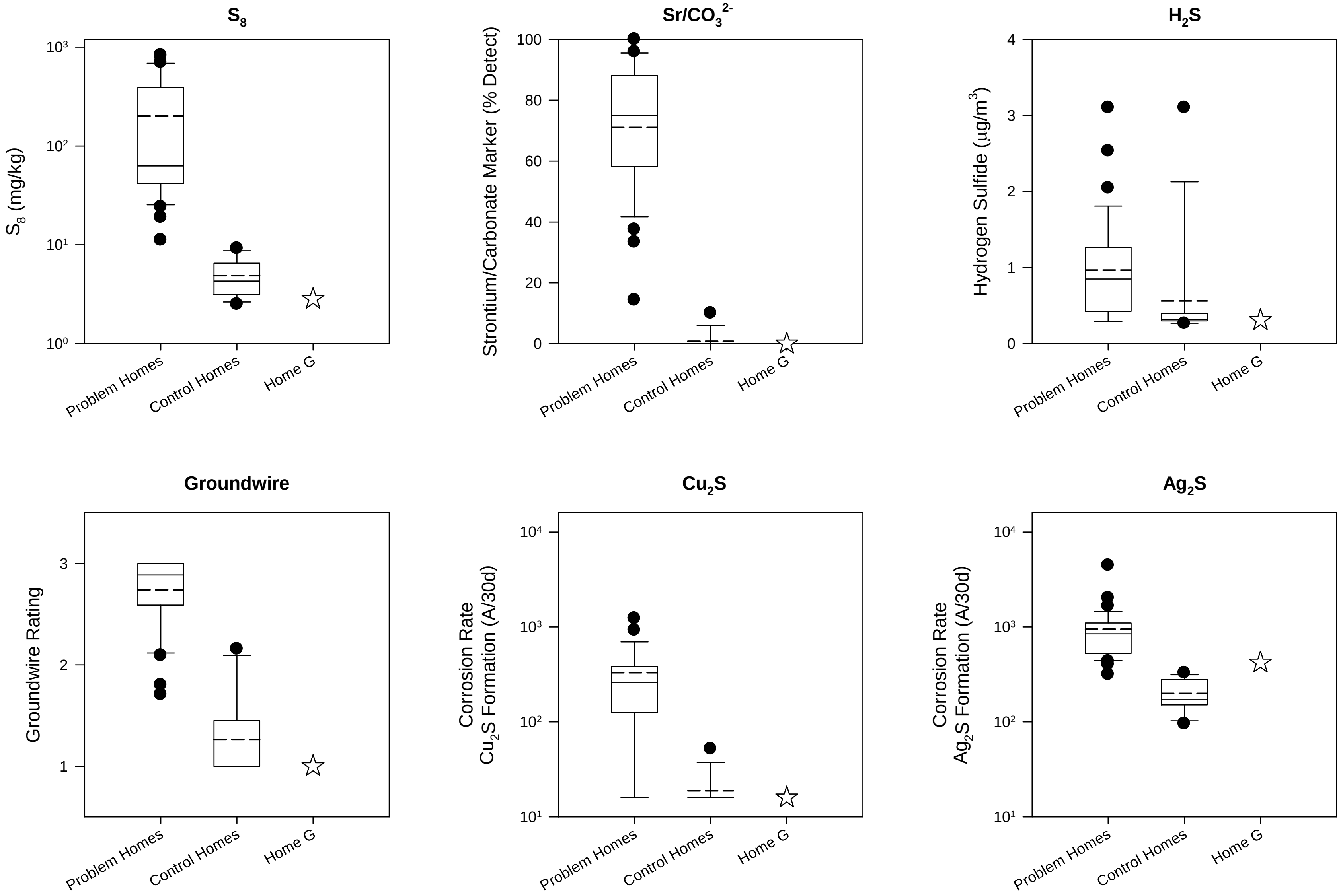

Figure 5.8 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home G

5.9 HOME H (CONSTRUCTED 2004)

Results for Home H in relation to results from the 51-Home Study are depicted by the star in Figure 5.9. Drywall samples from Home H did not have elevated concentrations of S_8 in drywall samples, nor did they have the strontium/carbonate marker. Hydrogen sulfide was not detected in the air of the home. There was evidence of elevated rates of corrosion based on the ground wire corrosion rating and the Cu_2S formationon coupons deployed at the AHU air supply register. Cu_2S formation rates in the rooms were not elevated, and Ag_2S formation rates were not elevated in any sample locations and were lower than outdoor rates (Appendix A, Table A.1).

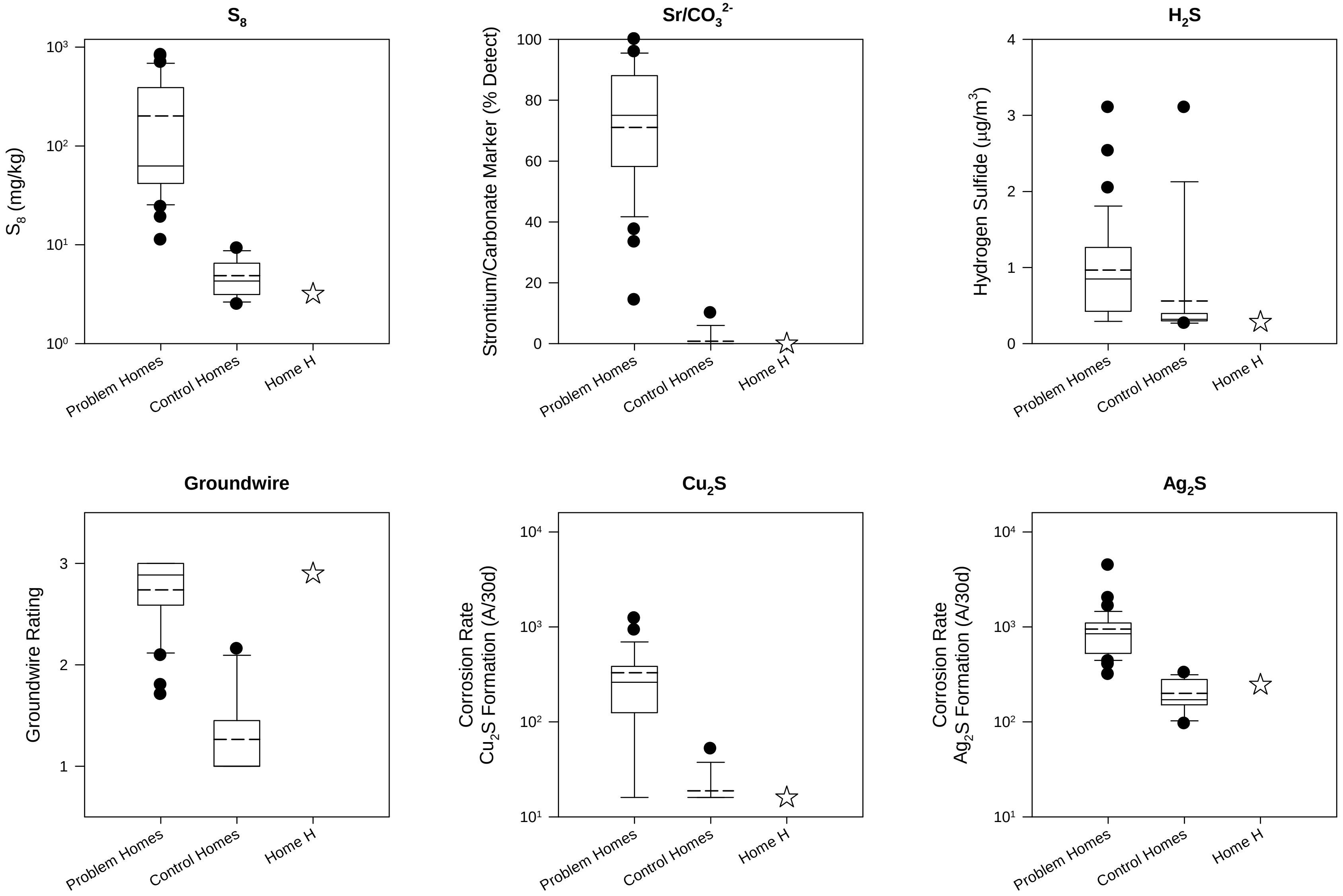

Figure 5.9 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home H

5.10 HOME I (CONSTRUCTED 2004)

Results for Home I in relation to results from the 51-Home Study are depicted by the star in Figure 5.10. Drywall samples from Home I did not have elevated concentrations of S_8 in drywall samples, nor did the samples have the strontium/carbonate marker. Hydrogen sulfide was not detected in the air of the home. There was evidence of elevated rates of corrosion based on the ground wire corrosion rating and rates of Ag_2S formation on coupons deployed in all sample locations (Appendix A, Table A.1). Cu_2S formation rates were not elevated. Outdoor rates of copper corrosion were similar to indoor rates and lower than, but similar to, indoor rates of silver corrosion.

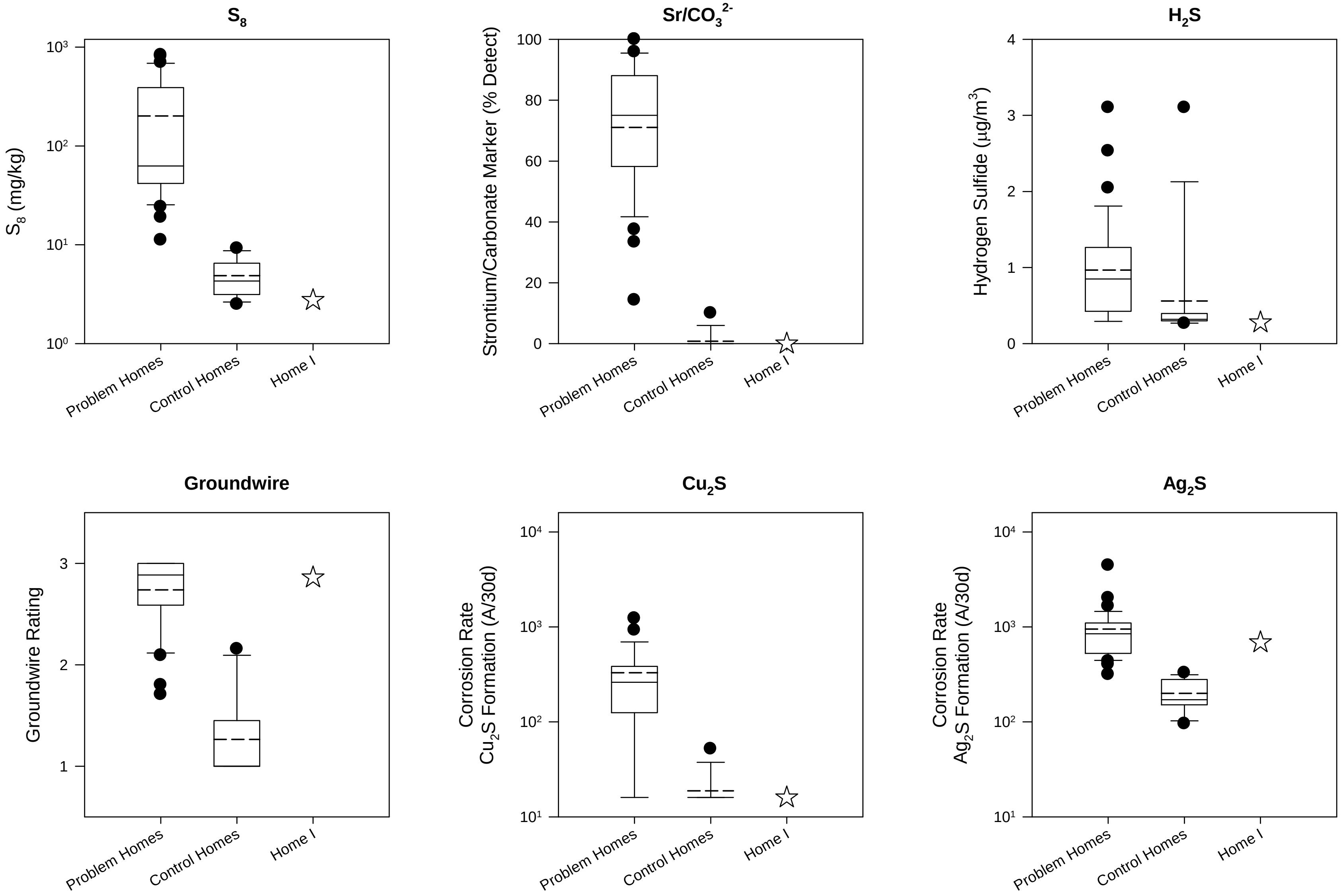

Figure 5.10 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home I

5.11 HOME J (CONSTRUCTED 2005-2006)

Results for Home J in relation to results from the 51-Home Study are depicted by the star in Figure 5.11. Drywall samples from Home J did not have elevated concentrations of S_8 in drywall samples, nor did they have the strontium/carbonate marker. Hydrogen sulfide was detected in the air of the home. Corrosion rates for both copper and silver coupons were elevated in rooms in the home, but not at the AHU air supply register (Appendix A, Table A.1). The silver corrosion rates observed in the home were similar to, but higher than, rates observed outdoors. Copper corrosion rates were higher indoors than outdoors.

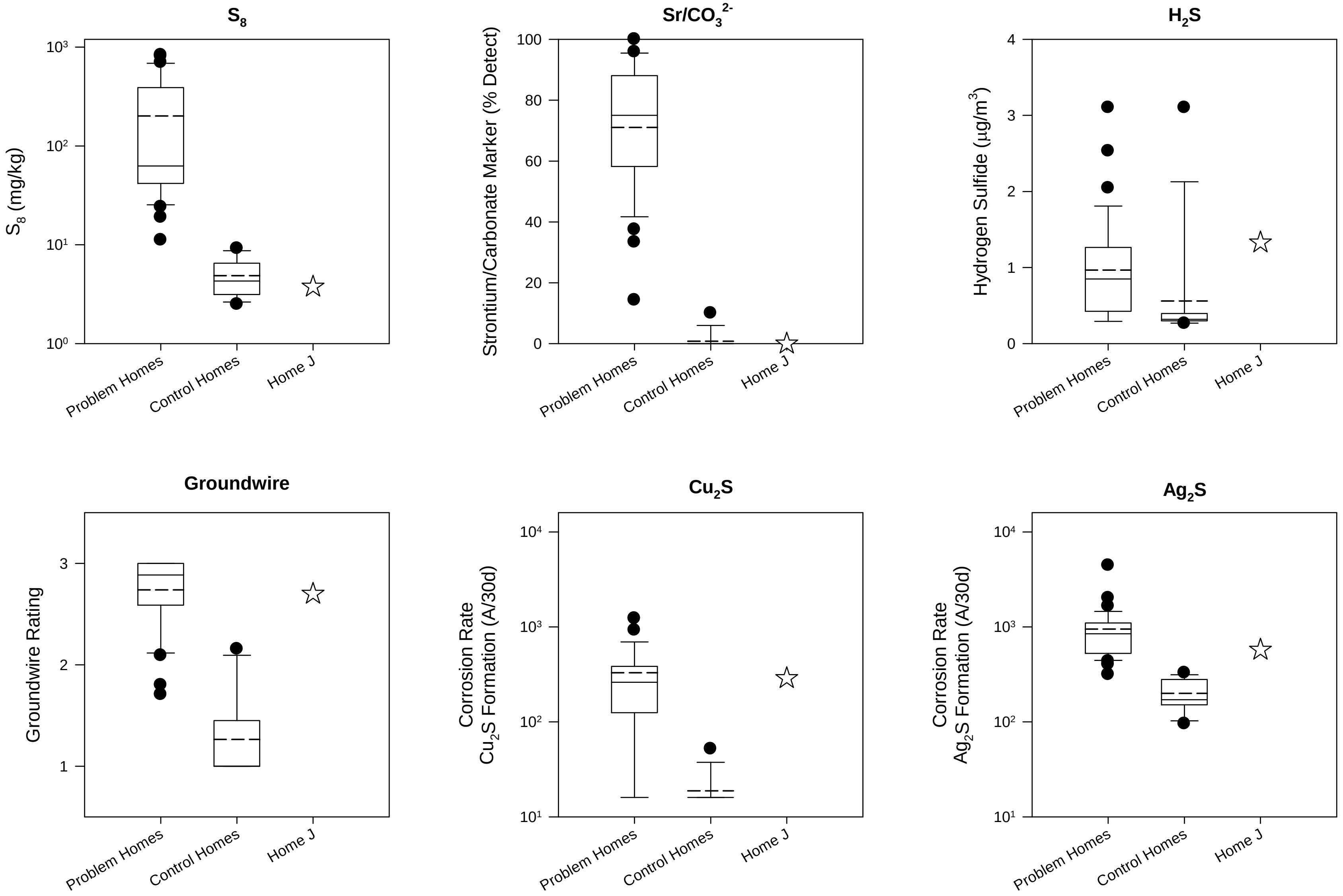

Figure 5.11 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home J

5.12 HOME K (CONSTRUCTED 2006)

Results for Home K in relation to results from the 51-Home Study are depicted by the star in Figure 5.12. Drywall samples from Home K did not have elevated concentrations of S_8 in drywall samples, nor did they have the strontium/carbonate marker. Hydrogen sulfide was detected in the air of the home; however, the indoor concentrations were similar to outdoor concentrations at the time of sampling. There was an elevated rate of corrosion based on the ground wire corrosion rating and elevated corrosion rates measured for silver coupons deployed in the rooms, but not at the AHU air supply register. Cu_2S formation rates were not elevated. Outdoor rates of copper and silver corrosion were similar to indoor rates.

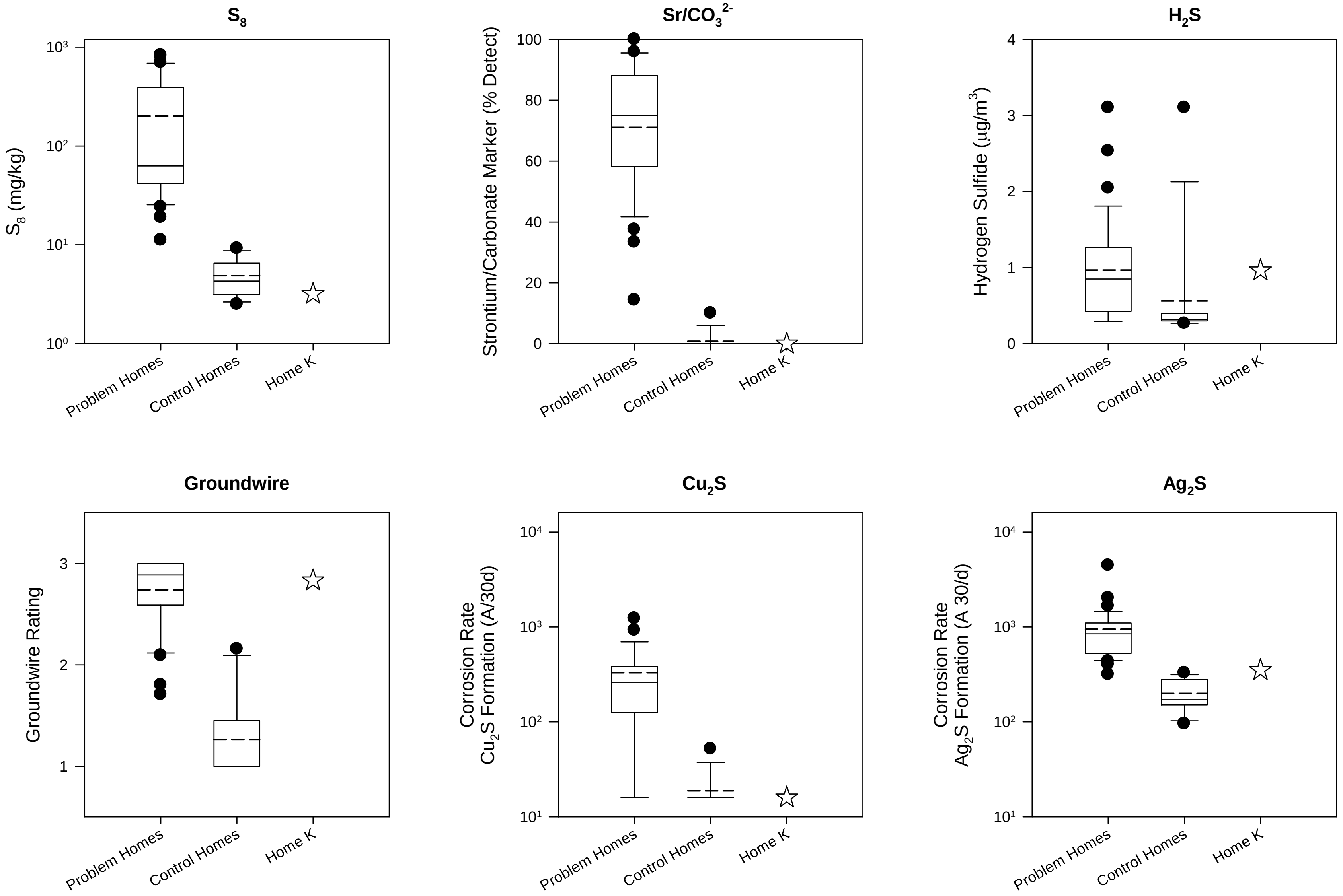

Figure 5.12 Comparison of Results from Homes Impacted by Problem Drywall (51-Home Study), Control Homes (51-Home Study) and Home K

6.0 DISCUSSION

6.1 SUMMARY

The CPSC has received complaints from homeowners regarding odors and rapid corrosion in their homes that were believed to be built using only domestically sourced drywall. The complaints are similar in nature to those associated with what is being termed problem drywall. The objective of this study was to conduct a detailed, in-home evaluation of homes that registered complaints and were reported to be constructed with domestic drywall, and then compare the results to in-home testing performed on homes known to be impacted by problem drywall in the 51-Home Study.

This study focused on a select group of parameters that were previously found to be associated with problem drywall. These included elevated levels of elemental sulfur and strontium in drywall, hydrogen sulfide in air, and elevated rates of copper and silver corrosion. Importantly, the methods of data collection and analysis used in this study were identical to those used in the 51-Home Study. This ensures comparability of results across the sets of homes.

With regard to the source markers, S_8 and strontium were strongly correlated in problem drywall samples in this study (Spearman R = 0.89; $p<0.01$; Figure 6.1), and the strontium/carbonate marker was perfectly correlated with the presence or absence of S_8 (Table 6.1), consistent with previous reports that found a strong, positive correlation between S_8 and strontium (EH&E, 2010a; EH&E, 2010b). This finding underscores the utility of strontium as a screening tool for identifying problem drywall because strontium can be measured in homes, real-time, in a nondestructive manner.

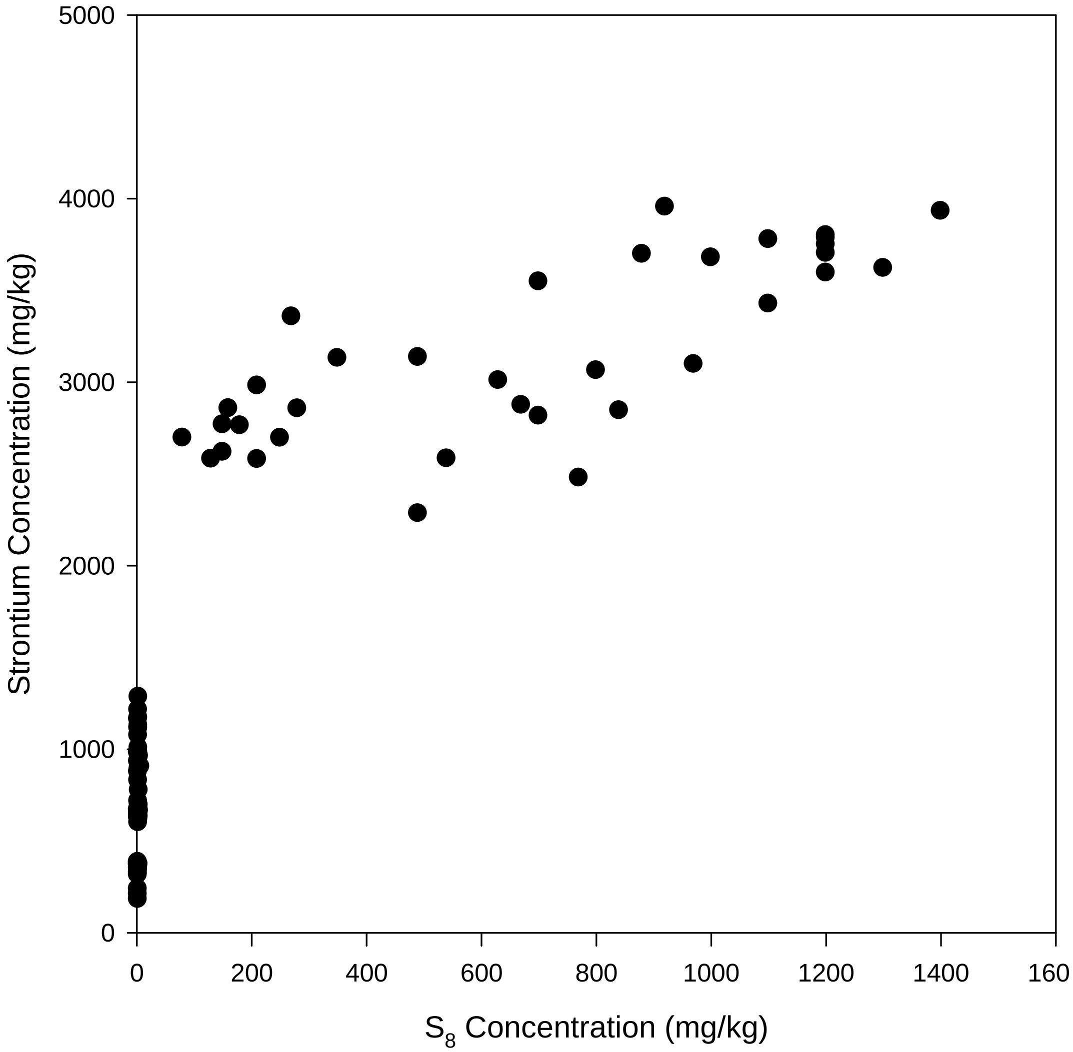

Figure 6.1 Scatterplot of S_8 and Strontium Concentrations (mg/kg) Measured in Drywall from Study Homes

Table 6.1 Comparison of Elemental Sulfur (S_8) and Strontium/Carbonate Markers

		Strontium/Carbonate Marker	
		Detected	**Not Detected**
S_8	**Detected**	35	0
	Not Detected	0	52

In addition to the results from the 51-Home Study, test results in this study were compared to the Interagency Task Force guidance on the identification of homes with corrosion from drywall. This guidance is based on the results of the 51-Home Study, as well as tests performed by other government agencies on behalf of the CPSC.

Using the 51-Home Study results as the comparison data, five of the 11 homes in this study had test results consistent with homes that contain problem drywall. Using the Interagency Task Force identification criteria, nine of the 11 homes met the Step 1 criteria (visible observation of corrosion on existing copper wiring and relevant date of construction/renovation). As shown in Table 6.2, of those nine homes, five had a sufficient number of pieces of corroborating evidence, outlined in Step 2, to be classified as having problem drywall. These correspond to the same five homes identified using the 51-Home Study comparison data, which included additional parameters.

Table 6.2 Environmental Test Results for Each Home, by Location

Step	Criteria		Home A	Home B	Home C	Home D	Home E	Home F	Home G	Home H	Home I	Home J	Home K
1	(a)	Blackening of copper?	🟥	🟥	🟥	🟥	🟥			🟥	🟥	🟥	🟥
	-- AND --												
	(b)	Drywall installed 2001 – 2009?	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
2	(a)	S_8 Marker?	🟥	🟥	🟥	🟥	🟥						
	(b)	Copper Sulfide on coupons?	🟥	🟥	🟥	🟥	🟥			▨		▨	
	(c)	Markings of Chinese origin?	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
	(d)	H_2S, COS, CS_2 in chamber test?	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	(e)	Copper Sulfide in chamber test?	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Factors	(a)	Silver Sulfide on Coupons?	🟥	🟥	🟥	🟥	🟥		▨		▨	▨	▨
	(b)	Strontium/Carbonate Marker?	🟥	🟥	🟥	🟥	🟥						
	(c)	H_2S in Indoor Air?	▨	▨		▨						🟥	▨

S_8	elemental sulfur
NF	not found in the limited areas accessible for visual inspection
H_2S	hydrogen sulfide
COS	carbonyl sulfide
CS_2	carbon disulfide
NA	not applicable

🟥	meets or exceeds the decision criteria
▨	meets or exceeds the decision criteria; potentially impacted by outdoor sources

Upon visual inspection, nine of the 11 homes had evidence of blackening of copper wires or cooling coils in the home. In all nine of those homes, test results from the copper and/or silver coupons indicated the continued presence of a corrosive environment in at least one location. Based on these observations, it is apparent that a corrosive environment exists in these nine homes. It is not surprising, then, to understand homeowners' complaints regarding their homes, and their assumption, based upon widespread reporting of drywall issues, that they have problem drywall. However, the homes impacted by problem drywall have been characterized thoroughly and meet a common set of environmental parameters, not all of which were observed in each of the nine homes with corrosive environments evaluated in this study.

An elevated rate of corrosion in a home is insufficient, by itself, to conclude that the corrosion is associated with problem drywall in the home. It is necessary to link the source (i.e., drywall) to the effect (i.e., corrosion). Elemental sulfur has been demonstrated to be a useful marker for this purpose. Five of the nine homes with a corrosive environment had elevated levels of elemental sulfur found in drywall samples. Importantly, homes with and without the elemental sulfur marker differed in the magnitude, extent, and sometimes characteristics of their corrosive environment. For example, in the five homes with the elemental sulfur marker (Homes A – E), the average silver sulfide formation rate at the AHU air supply register was approximately 3,700 A/30d. In contrast, the average rate in Homes H – K was only 870 A/30d. Additionally, in the five homes with the elemental sulfur marker (Homes A – E), the corrosion rates measured in the rooms exceeded outdoor corrosion rates by up to a factor of 9. This is consistent with results from the 51-Home Study; homes impacted with problem drywall had indoor corrosion rates that were typically much greater than outdoor corrosion rates (Figures 6.2 and 6.3). For Homes H – K, the outdoor corrosion rates were similar to indoor corrosion rates measured in the rooms. Therefore, based upon the fact that the outdoor corrosion rates seem to be driving the indoor rates, it is likely that there is some external source(s) that is impacting these homes.

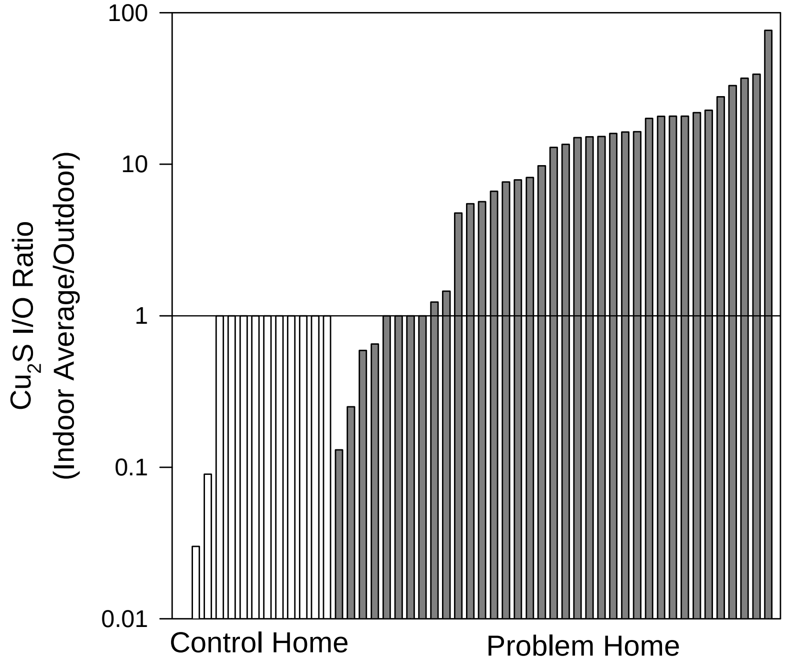

Figure 6.2 Indoor/Outdoor Ratio for Cu_2S Formation in Homes from 51-Home Study

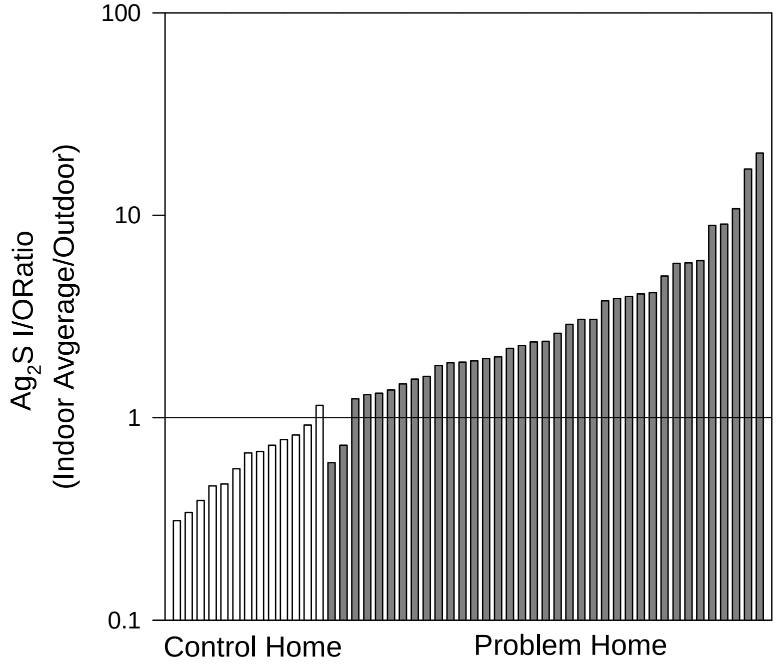

Figure 6.3 Indoor/Outdoor Ratio for Ag_2S Formation in Homes from 51-Home Study

Upon further examination of the results of the corrosion testing in Home H, the rate of copper corrosion measured at the air supply was observed to exceed the rate of silver corrosion placed at the same location. This was noted as an inconsistent result when compared with results from the 51-Home Study. In that study, data on copper and silver corrosion rates at the AHU air supply register are available for 37 homes known to be impacted by problem drywall. In homes impacted by problem drywall, the relationship between the rate of copper and silver corrosion is very stable (ratio Cu_2S:Ag_2S; median = 0.41; mean=0.47; standard deviation = 0.39) (Table 6.3). In Home H, the relationship between the rates of copper and silver corrosion does not agree with the results from homes impacted by problem drywall. The ratio observed in Home H was 2.96, which is greater than three times the standard deviation found in the 51-Home Study. Statistically, there is only a 0.01% probability of observing this result if Home H was part of the group of problem drywall impacted homes. Metal sensitivities can be used in a differential analysis to identify potential corrosive species in indoor air. Both silver and copper are highly sensitive to hydrogen sulfide (Table 6.4). Hydrogen sulfide has been shown to be associated with problem drywall and, therefore, may explain the consistent ratio of Cu_2S and Ag_2S formation in homes known to be impacted by drywall. The information in Table 6.4 may be useful in identifying other potential causative agents responsible for the observed corrosion in Home H. For example, copper is highly sensitive to SO_2 compared to silver that has a low sensitively to SO_2 as an atmospheric corrodant.

Table 6.3 Summary Statistics for Ratio of Cu_2S:Ag_2S Formation Rates at Air Handling Unit Air Supply Register in Homes Known to Be Impacted by Problem Drywall

N	Mean	Standard Deviation	Minimum	P5	P25	Median	P75	P95	Maximum
37	0.470	0.39	0.005	0.013	0.123	0.407	0.680	1.21	1.65

Cu_2S	copper sulfide
Ag_2S	silver sulfide
N	number
P	percentile

Table 6.4 Material Sensitivities to Atmospheric Corrodants

Corrodants	Silver (Ag)	Copper (Cu)
CO_2/CO_3^{2-}	L	–
NH_3/NH_4^{+}	M	M
NO_2/NO_3^{-}	N	M
H_2S	H	H
SO_2/SO_4^{2-}	L	H
HCl/Cl^{-}	M	M
$RCOOH/COOH^{-}$	L	M
O_3	M	M

H = High sensitivity
M = Moderate sensitivity
L = Low sensitivity
N = No sensitivity

* Table reproduced from Leygraf C and Graedel TE. 2000. *Atmospheric Corrosion* Hoboken, NJ: John Wiley & Sons, Inc., Table 4.1.

The results and analysis for Home H suggest that while there is a corrosive environment in the home, the results are not consistent with corrosion caused by problem drywall. This is based on the absence of the S_8 marker and differing ratio of Cu_2S and Ag_2S formation.

6.2 LIMITATIONS

The comparison data used in this study was based on a 51-Home Study. Comparisons are with respect to complaint homes and homes with confirmed problem drywall and their respective control groups. These homes originally were selected as part of the CPSC investigation into what was originally labeled the “Chinese drywall” issue. As such, a common set of parameters were identified among homes impacted with problem drywall. However, these parameters are specific to that type of problem drywall (i.e., the type of drywall problems that were originally associated with the “Chinese drywall” issue). These parameters were observed in five of the 11 homes in this study that were found to have conditions similar to those found in homes impacted by problem drywall. For the four homes with a corrosive environment but without the clear indicators of the classic problem drywall issue, it appears that the indoor corrosion could be influenced by outdoor conditions, other indoor sources, or a limited amount of problem drywall, which cannot be determined without significant additional testing. It is not known whether the domestic drywall in those homes may be contributing to the conditions in the home. If that is the case, the elemental sulfur marker may be a signature of one type of problematic drywall (i.e., “Chinese drywall”). Another possibility is that the drywall in those homes is entirely unrelated to the corrosive environment. Additional research is necessary before conclusions regarding the association between the drywall and corrosion in Homes H – K can be made. Emissions and corrosion tests conducted in controlled chamber environments can establish or refute this association.

Elemental sulfur concentrations greater than 10 mg/kg in drywall have been identified as an important marker of problem drywall. In homes from the 51-Home Study, elemental sulfur was always detected in at least one sample of drywall. However, most of the homes in that study were constructed with large quantities of problem drywall. Therefore, even when analyzing only a few drywall samples for S_8, there was a small likelihood of not detecting elemental sulfur due to the chance selection of all non-problem drywall in those homes. An error of this type, were it to occur, would be referred to as a Type II error, or the possibility of not observing a result if it is truly present (i.e., not finding drywall with elemental sulfur if there is a piece of drywall in the home that does have elemental sulfur). In this study, efforts were made to minimize the opportunity for Type II error. First, a sufficient number of drywall samples (n=8) from each home were analyzed for elemental sulfur. Second, the selection of drywall samples to be analyzed for elemental sulfur was based on a procedure that used a secondary marker, strontium, to optimize the likelihood of selecting a sample with elevated elemental sulfur and at the same time ensure representative drywall samples were selected. Even with this robust study design, there is a possibility that problem drywall with elemental sulfur exists on a small number of boards in Homes H – K that was not detected.

The Interagency Task Force guidance document for identifying homes with problem drywall specifies several parameters that are necessary to be present for the home to be considered adversely impacted. However, only one of those parameters, elemental sulfur, has an established threshold level (10 mg/kg). In order to classify homes in this current study, it was necessary for EH&E to define screening level decision criteria, such as the 1,000 A/30d level for Ag_2S formation rates at the AHU air supply register. These screening level decision criteria were based on the distribution of results from the 51-Home Study in two groups of homes—those impacted by problem drywall and those that were not impacted. These screening-level criteria have not been adopted by Interagency Task Force, have not been fully validated at this time, and should be used only after careful consideration.

The focus of this report was to evaluate homes reported to be constructed with domestically produced drywall. EH&E was not able to independently confirm that all of the drywall in the impacted homes was domestically produced, as this would have required extensive removal of the interior drywall, and destructive testing of the residences was not performed as part of this study. Therefore, conclusions regarding the potential for domestic drywall to be problematic cannot be confirmed at this time without further extensive investigation and detailed documentation of the origin of the drywall in the impacted homes.

7.0 CONCLUSION

Based on: 1) the characterization of the drywall and indoor environments of these homes; 2) comparison of results in this study to existing data from homes known to be impacted by problem drywall; 3) evaluation of test results in relation to the CPSC guidance on identification of homes with corrosion from problem drywall; and 4) EH&E's extensive experience in conducting in-home investigations of homes with problem drywall, EH&E concludes that five of the homes in this study have drywall that is consistent with problem drywall.

The focus of this report was to evaluate homes reported to be constructed with domestically produced drywall. Homeowners self-reported their homes as being constructed of domestically produced drywall, and CPSC staff performed in-depth investigations to remove those homes from the study where Chinese markings were clearly present. EH&E was not able to independently confirm that all of the drywall in the impacted homes was domestically produced, as this would have required extensive removal of the interior drywall. This extremely invasive activity was excluded from the scope of work for this study. Therefore, conclusions regarding the presence of domestic drywall throughout the houses identified as being problematic cannot be confirmed at this time without further invasive investigation or detailed documentation of the origin of the drywall in the impacted homes.

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APPENDIX A

ENVIRONMENTAL TEST RESULTS TABLE

Table A.1 Environmental Test Results For Each Home, By Location

Home*	Location	S_8 (mg/kg)	Sr/CO_3^{2-} Marker** (%)	Hydrogen Sulfide† (μg/m^3)	Ground Wire Rating	Copper Sulfide† (A/30d)	Silver Sulfide† (A/30d)	Formaldehyde† (μg/m^3)	Total Sulfide in Water†† (mg/L)	AER†† (h^{-1})	Temp† (°F)	RH† (%)	Dew Point† (°F)
A (2006)	Living	800	75	1.3	3.0	350	2,600	35	<0.05	0.30	76	49	56
	Master	80	100	<0.61	3.0	220	760	38			76	47	55
	House Ave	500	39	0.80	3.0	280	1,700	36			76	48	55
	Supply	–	–	–	–	420	2,300	–	–	–	66	70	56
	Outdoor	–	–	1.3	–	<32	410	2.0	<0.05	–	80	70	69
B (2006)	Living	<5.8	0	0.97	1.7	570	2,000	42	<0.05	0.25	80	50	60
	Master	580	24	1.1	2.6	300	1,800	41			81	51	62
	House Ave	500	17	1.0	1.9	430	1,900	41			80	51	61
	Supply	–	–	–	–	180	680	–	–	–	75	62	61
	Outdoor	–	–	1.1	–	<32	700	1.8	<0.05	–	82	70	70
C (2005-2006)	Living	1,100	50	<0.52	3	230	1,500	49	<0.05	0.23	81	47	60
	Master	<5.3	0	<0.52	2.5	<32	1,900	51			81	53	63
	House Ave	810	25	<0.52	2.5	120	1,700	50			81	50	61
	Supply	–	–	–	–	420	4,100	–	–	–	78	53	60
	Outdoor	–	–	1.6	–	860	410	2.2	<0.05	–	82	68	70
D (2005-2007)	Living	220	100	0.63	3.0	300	2,700	30	<0.05	0.17	79	49	59
	Master	210	100	0.67	3.0	<32	3,900	33			79	49	59
	House Ave	180	82	0.65	3.0	160	3,300	32			79	49	59
	Supply	–	–	–	–	420	8,300	–	–	–	76	58	60
	Outdoor	–	–	0.73	–	<32	400	1.8	<0.05	–	81	65	68
E (2006)	Living	1,200	60	<0.54	3.0	220	1,400	25	<0.05	0.22	78	45	56
	Master	1,300	50	<0.53	3.0	<32	950	25			79	45	56
	House Ave	1,100	54	<0.54	3.0	120	1,200	25			79	45	56
	Supply	–	–	–	–	<32	3,100	–	–	–	75	52	57
	Outdoor	–	–	0.86	–	<32	670	1.6	<0.05	–	81	73	70
F (2005-2006)	Living	<6.3	0	<0.60	1.0	<32	230	49	<0.05	0.41	73	47	52
	Master	<5.9	0	<0.60	1.0	<32	250	56			73	57	57
	House Ave	<6.4	0	<0.60	1.0	<32	240	53			73	52	54
	Supply	–	–	–	–	<32	160	–	–	–	75	47	53
	Outdoor	–	–	<0.65	–	<32	240	2.1	<0.05	–	62	70	51
G (2002)	Living	<5.0	0	<0.61	1.0	<32	410	22	<0.05	0.16	71	49	51
	Master	<6.3	0	<0.62	1.0	<32	430	–			68	53	51
	House Ave	<5.7	0	<0.62	1.0	<32	420	22			70	51	51
	Supply	–	–	–	–	<32	320	–	–	–	68	52	49
	Outdoor	–	–	<0.67	–	<32	320	1.3	<0.05	–	59	75	49

Table A.1 Continued

Home*	Location	S_8 (mg/kg)	Sr/CO_3^{2-} Marker** (%)	Hydrogen Sulfide[†] ($\mu g/m^3$)	Ground Wire Rating	Copper Sulfide[†] (A/30d)	Silver Sulfide[†] (A/30d)	Formaldehyde[†] ($\mu g/m^3$)	Total Sulfide in Water[††] (mg/L)	AER[††] (h^{-1})	Temp[†] (°F)	RH[†] (%)	Dew Point[†] (°F)
H (2004)	Living	<5.4	0	<0.57	3.0	<32	250	17	<0.05	0.63	82	62	68
	Master	<7.1	0	<0.57	3.0	<32	240	24			82	61	67
	House Ave	<6.4	0	<0.57	2.9	<32	250	20			82	62	68
	Supply	–	–	–	–	710	240	–	–	–	81	64	67
	Outdoor	–	–	<0.58	–	<32	480	1.9	<0.05	–	79	77	70
I (2004)	Living	<5.0	0	<0.56	3.0	<32	480	25	<0.05	–	74	42	50
	Master	<6.8	0	<0.55	2.7	<32	900	27			74	42	50
	House Ave	<5.5	0	<0.56	2.9	<32	690	26			74	42	50
	Supply	–	–	–	–	<32	1,800	–	–	–	68	48	48
	Outdoor	–	–	1.5	–	<32	590	0.99	<0.05	–	82	67	69
J (2005-2006)	Living	<9.4	0	1.1	2.5	290	610	42	<0.05	0.18	77	41	52
	Master	<9.9	0	1.5	2.8	280	540	39			76	43	52
	House Ave	<7.5	0	1.3	2.7	290	580	40			77	42	52
	Supply	–	–	–	–	270	560	–	–	–	67	55	51
	Outdoor	–	–	<0.56	–	<32	520	1.5	<0.05	–	79	73	69
K (2006)	Living	<5.7	0	1.1	2.7	<32	390	21	<0.05	0.19	76	49	56
	Master	<6.6	0	0.81	3.0	<32	310	25			76	48	55
	House Ave	<6.4	0	0.96	2.8	<32	350	23			76	49	55
	Supply	–	–	–	–	<32	880	–	–	–	74	54	57
	Outdoor	–	–	2.2	–	<32	400	1.7	<0.05	–	79	75	70

S_8	elemental sulfur
mg/kg	milligrams per kilograms
Sr/CO_3^{-2}	strontium per carbonate
$\mu g/m^3$	micrograms per cubic meter
A/30d	angstroms per 30 days
mg/L	milligrams per liter
AER	air exchange rate
h^{-1}	per hour
Temp	temperature
°F	degrees Fahrenheit
RH	relative humidity
<	less than
House Ave	whole house average

* (Year of construction)

** Definition of marker (%): number of bulk samples with strontium concentration (XRF) greater than 1,200 mg/kg and carbonate absorbance (FTIR) greater than 5.

[†] Two week average data

[††] House average

APPENDIX B

SAMPLING METHODS

SAMPLING METHODS

PASSIVE AIR SAMPLING METHODS

Passive air samples have been demonstrated to be a valid tool in residential exposure assessment.[1,2] For each analyte there is a specific chemiadsorbing cartridge and sampling protocol. The diffusive sampler is composed of two surfaces, a diffusive surface and an adsorbing surface. The sampling process is driven by the concentration gradient as the gaseous molecules cross the diffusive surface towards the adsorbing surface. The molecules are trapped by the selected adsorbing material in each type of passive diffusion sampler.[3] The specific passive sampling system and the analytical technique used for each class of analyte are shown in Table B.1.

Table B.1 Summary of Target Parameters, Passive Air Sampling

Analyte	Radiello Badge Type	Analytical Method*
Formaldehyde	165	Aldehydes by Radiello 165, HPLC-UV
Hydrogen sulfide	170	Hydrogen sulfide by Radiello 170 Spectrophotometer at 665 nm

HPLC high performance liquid chromatography
UV ultra violet
nm nanometer

* Analytical methods provided by Fondazione Salvatore Laboratory, Radiello Manual, Supelco Edition.

The concentrations of hydrogen sulfide (H_2S) and formaldehyde measured in each study home were calculated using Equation 1:

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[2] WHO. 2000. *Environmental Health Criteria 214: Human Exposure Assessment, International Program on Chemical Safety.* Geneva: World Health Organization.

[3] Sigma-Aldrich. 2006. *Radiello® Manual*. Bellefonte, PA: Sigma-Aldrich Co.

$$C = \frac{m}{Q_k * t} * 1{,}000{,}000 \qquad \text{(Equation 1)}$$

where:

C = concentration in μg/m^3
m = mass in μg
Q_k = analyte specific sampling rate, adjusted for temperature at the sampling site, in ml/min
t = sample duration in minutes
1,000,000 = conversion factor, ml/m^3

Sampling rates for indoor samples were adjusted to account for different temperatures and their potential effect on the sampling rate by using the mean indoor temperature measured in each home. For outdoor samples, the sampling rates were adjusted using the mean outside temperature over the sampling period.[4] The reported passive sampling results were adjusted for temperature in accordance with Equation 2, which is provided by the supplier of the passive diffusion samplers.[5]

$$Q_k = Q_{298} * \left(\frac{K}{298}\right)^{\exp} \qquad \text{(Equation 2)}$$

where:

Q_k = analyte specific sampling rate, adjusted for temperature at the sampling site, in ml/min
Q_{298} = analyte specific sampling rate at 298 K (25 °C) in ml/min
K = temperature at the sampling site, in degrees kelvin
exp = diffusion sampler-specific factor (provided by manufacturer)

Analyte specific sampling rates at 298 K (Q_k) and the sampler-specific factor (exp) are listed in Table B.2, and are all provided by the manufacturer, based on a standard temperature of 298 K.[6] No sampling rate adjustments for relative humidity or wind speeds are recommended because rates have been shown to be constant over wide ranges of relative humidity and wind speed conditions.[7]

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[4] The outdoor samples at one home were adjusted based on the mean temperature obtained from the nearest National Weather Service weather station due to data logger malfunction.

[5] Sigma-Aldrich. 2006.

[6] Sigma-Aldrich. 2006.

[7] Sigma-Aldrich. 2006.

Table B.2 Sampling Rates for Targeted Analytes for Passive Sampling

Compound	CAS #	Sampling Rate in ml/min at 298 K (Q_{298})	exp
Formaldehyde	50-00-0	99	0.35
Hydrogen sulfide	7783-06-4	69	3.8

CAS#	Chemical Abstract Service number
ml/min	milliliters per minute
K	degrees kelvin
exp	sampler-specific factor provided by manufacturer

All analysis of the diffusive sampling media was conducted by Air Toxics Ltd. located in Folsom, California.

RELATIVE HUMIDITY/TEMPERATURE

The temperature sensor has a range of -20 degrees Celsius (°C) to 70 °C (-4 to 158 degrees Fahrenheit [°F]) with accuracy of ± 0.4 °C at 25 °C (± 0.7 °F at 77 °F). The sensor is factory rated to achieve a resolution of 0.1 °C at 25 °C (0.2 °F at 77 °F). The relative humidity sensor has a range of 25% to 95% with accuracy of ± 3.5% from 25% to 85%. The sensor is factory rated to achieve a resolution of 0.07%. As recommended by the manufacturer, the accuracy of the temperature and relative humidity sensors is verified annually.

PROJECT ORGANIZATION(S) AND RESPONSIBILITIES

The Environmental Health & Engineering, Inc. (EH&E) project manager was responsible for overall implementation, documentation, and delivery of the project and had the responsibility of ensuring the accuracy, precision, and completeness of all data presented. The Project Executive was responsible for technical oversight of the overall project and for ensuring that highest data quality objectives were met by the Project Manager and the project team. Prior to release, all deliverables at EH&E are reviewed and approved by qualified Senior Level staff, with relevant qualifications and expertise, whose responsibilities include ensuring the accuracy and appropriateness of technical information presented. All members of the project team were trained in, and responsible for, data validation and quality control checks during each of their tasks.

QUALITY ASSURANCE AND QUALITY CONTROL SAMPLES

As detailed above, in addition to the primary samples collected during the study, a number of quality control samples were collected and analyzed in each sample set to evaluate the quality and reasonableness of the data collected during the study. The types and frequency of quality assurance quality control (QA/QC) samples collected during the study are outlined in Table B.3.

Table B.3 Quality Assurance and Quality Control Samples Collected During the Project

Sample Type	Frequency	Definition
Duplicate sample	Minimum of one per sample set and one per every 10 primary samples	A sample collected concurrently with a primary field sample to assess repeatability of methods.
Field blank	Minimum of one per sample set and one per every 10 primary samples	A sample prepared by the field team that represents the procedure for preparing for integrated sampling, and is handled as such, but is not actually used for sampling. This is sent in a blinded fashion to the laboratory. The results of the field blanks can be used to determine whether there was any contamination in the preparation, handling or shipping process in the field, or during the analysis of the samples by the laboratory.
Shipping Blank	Minimum of one per sample set and one per every 10 primary samples	An unused sample that is not handled in the field other than to have it incorporated into a regular sample shipment and sent in a blind fashion to the laboratory. The results of shipping blanks can be used to determine whether there was any contamination during the shipping process.

SAMPLE HANDLING

EH&E followed the requirements for holding times and sample preservation outlined in the respective reference sampling methods used. After each day of sampling, samples were shipped to the laboratory via overnight express delivery within the holding time specified by the analytical method.

SAMPLE CUSTODY

All project samples were handled in accordance with appropriate chain of custody procedures. Compliance was overseen by the field team leader. The field team leader was also responsible for ensuring that all unused sample media, as well as collected samples, were cared for properly before, during, and after sampling. At the time of use, each sample was assigned a unique sample identification label. Each sample label was recorded on the field sample log sheets prior to sample collection. All log sheets were stored in a master field binder during the study.

CALIBRATION PROCEDURES

All measuring, monitoring, and sampling instrument calibrations, except those requiring factory calibrations, were performed in EH&E's Field Operations Support Center (FOSC) prior to shipment of instruments to the field. All instruments that are factory calibrated are checked periodically in the FOSC by comparing them against other, recently calibrated instruments. Prior to use in the field, each instrument was zeroed and span-checked with appropriate gases to insure that they were operating within specification (and adjusted as necessary). Table B.4 summarizes the calibration procedures for instruments used in the study.

Table B.4 Calibration Procedures

Parameter	Instrument Type	Instrument	Calibration Method	Frequency
Air temperature	Thermistor, data logger	HOBO® U10-003 (Onset Computer Corp)	Calibrations performed by the manufacturer	Annual
Relative humidity	Thin-film capacitive sensor, data logger	HOBO® U10-003 (Onset Computer Corp)	Calibrations performed by the manufacturer	Annual
Carbon dioxide	Non-dispersive infrared sensor	Q-Trak Model 8551 Indoor Air Quality Monitor	Multipoint with standard gas mixtures ranging from 0 to 2000 ppm (nominal) along linear response curve.	Pre and post field measurements

RECORDKEEPING

Written Documentation

All data and documentation generated during the study, except that generated in electronic formats (raw data files, digital photographs), was transcribed into the appropriate collection forms which are subsequently stored in a single data collection binder. Hardcopies of final analytical laboratory reports (and the completed chains of custody) were also received and retained in EH&E's central filing system. Any changes in data entries are done in a manner that does not obscure the original entry. The reason for the revision is indicated, dated, and signed at the time of change. All original hard copy records for the project are retained (together) in a central file system at EH&E's main office.

Electronic Documentation

Electronic documentation generated in the field during the study included digital photographs, x-ray fluorescence (XRF) data files, carbon dioxide measurements and temperature and relative humidity data files. All files generated during the field phases of the study were downloaded and stored temporarily on a field computer under the control of the field team leader. Electronic files were then transferred from the field computer onto EH&E's central server routinely (typically at the end of each day). In order to track the various electronic data files, a standardized filing and naming system was used to clearly differentiate between files by type and the home in which they were collected. Also, field personnel documented the location of digital photographs, XRF measurements, and real-time data monitor deployments on the appropriate field forms.

DATA REDUCTION, VALIDATION, AND REPORTING

A systematic, standardized approach was implemented by EH&E to analyze, validate, and report the data collected during the study, including incorporating the following steps:

- Senior level staff at EH&E reviewed and verified the overall study approach, data collection strategy, methodology, appropriateness of all calculations and statistical analysis, and deliverables.
- EH&E developed a database (Microsoft Access), where all field data and laboratory results were stored.
- All (100%) field log entries and calculations were reviewed by independent staff members prior to entry into the study database.

- All (100%) of the data entry into the study database was reviewed and verified by independent, qualified personnel.
- To minimize database entry errors, EH&E requested that, when possible, all laboratory reports be provided in electronic data delivery (EDD) formats, such as Microsoft Excel so that the data could be directly imported into the central study database.
- After the database was populated, the number and sample identification labels in the database were compared with those on the field log sheets and the analytical laboratory reports (using a program coded in SAS 9.1).
- As discussed above, data summary and analysis was completed using SAS 9.1. All programming codes developed and executed for processing the data were independently reviewed by qualified personnel.
- In the limited instances where data entry or recording errors were identified during the QA/QC review processes described above, the entry was corrected in all relevant locations (back to the original entry). Corrections were noted on all original documentation.
- All of the final results underwent QA/QC review, including completeness and reasonableness checks.

QUALITY ASSURANCE AND QUALITY CONTROL—DATA

As described above, a number of measures were implemented to ensure the collection of reproducible and accurate data during the study. This section describes the measures used to evaluate the completeness, precision, and accuracy of the data collected during the study. The completeness of the data set was evaluated by analyzing the capture efficiency for each environmental parameter targeted in the study. Accuracy was evaluated by reviewing results of blank samples. Precision was evaluated by examining the strength of the association between paired primary and duplicate samples. Paired duplicates were averaged and no blank correction was done for purposes of analysis.

Completeness

The completeness of sampling data from the study was evaluated by examining the overall data capture efficiency for each sample group and sample type collected in the field (primary samples, duplicate samples, and field blanks and shipping blanks). Table B.5 summarizes the data capture efficiency during the study.

Table B.5 Summary of Data Capture Efficiency for Samples

	Number of Valid Samples*				Number of Void Samples				Capture Efficiency (%)	
Sample Type	**S**	**D**	**FB**	**SB**	**S**	**D**	**FB**	**SB**	**S/D**	**All**
Hydrogen Sulfide	33	11	11	11	0	0	0	0	100	100
Formaldehyde	32	11	6	5	1	0	0	0	98	98
Coupons	44	11	6	–	0	0	0	0	100	100
Water Sulfide	22	4	4	–	0	0	0	0	100	100
Overall data capture efficiency									**99.5**	**99.5**

S	primary samples
D	duplicates
FB	field blanks
SB	shipping blanks
S/D	samples/duplicates

Overall, data capture efficiency was 99.5%. One formaldehyde sample went missing during the two week sample period. Although not listed in Table B.6, no carbon dioxide (CO_2) data monitoring results were excluded from the analysis and only one outdoor temperature/humidity data logger output was excluded from the analysis.

Accuracy

Laboratory Measurements

Review of field and shipping blanks analysis were used to assess the accuracy of air and water sample measurements. For purposes of comparison of the sample data analyzed in this report, the nominal laboratory reporting limit, expressed as quantity per sample and as quantity per unit volume of air sampled, was used as the metric of comparison to determine when results were below detection. The reporting limits presented are as reported by the respective analytical laboratory.

No blank correction was done in EH&E's analysis of the study data, except for any blank corrections performed by the laboratory as part of their standard reporting procedures. All field and media blank results were below detection for all samples (and analytes) analyzed during the study, with the exception of silver sulfide (Ag_2S), which was detected in the field blanks (maximum of 285 angstroms per 30 days [A/30d]), collected during the study. This represents background rates of Ag_2S formation in homes.

EH&E also reviewed the quality assurance procedures implemented by the analytical laboratories to evaluate the accuracy of the laboratory measurements. In accordance with the standard or published methodologies employed for the sampling and analysis, laboratory quality control measures included blanks, duplicates, standards, and continuing calibration verification (CCV). These quality control metrics demonstrated excellent compliance with the accuracy requirements specified in the respective reference methods. EH&E also evaluated the laboratory results to determine if there was potential sample media saturation; no saturation occurred during the study. Finally, the laboratory reports were reviewed to determine if sample handling (e.g., temperature control issues) or holding time exceedances occurred during the study; no issues were found. No analytical quality assurance exceptions were noted; therefore, no data adjustment or exclusion was warranted.

Direct-Read Instruments

The accuracy of the XRF instruments was ensured using several measures. First, the XRF analyzer was calibrated by the manufacturer prior to delivery to EH&E using standard reference materials that include many elements, including strontium. The manufacturer's calibration procedure specifically includes an assessment of the concentration of strontium in the standard reference material and values reported by the analyzer. In addition, internal instrument background checks were run on each instrument before use.

The accuracy of the XRF readings was evaluated in this study by examining repeat XRF strontium readings obtained each day during the laboratory analysis period from a reference material with a known strontium concentration: National Institute for Standards and Technology (NIST) Standard Reference Material 2702 (SRM 2702), 119.7 ± 3.0

milligrams per kilograms (mg/kg) strontium. A total of 22 XRF readings of the reference material were taken in the field, which indicated a mean of 113.7 mg/kg with a coefficient of variation (CV) of 6.8%. During XRF laboratory testing, repeat measurements of the NIST material as well as three other reference materials, with known strontium concentrations, were obtained. The repeat laboratory XRF measurements are summarized in Table B.6.

Table B.6 Summary of Repeat XRF Laboratory Measurements

Reference Material (Known Sr Concentration, mg/kg)	**Number of measurements**	**Mean XRF**	**Coefficient of Variation (%)**
CPSC14 (570)	12	580	1.1
CPSC19 (1500)	12	1500	3.0
CPSC26 (2,720)	12	3100	1.3
SRM 2702 (120)	12	120	2.1
		Overall CV	**1.9**

XRF	x-ray fluorescence
Sr	strontium
mg/kg	milligrams per kilograms
CPSC	U.S. Consumer Product Safety Commission
SRM	Standard Reference Material
CV	coefficient of variation

Overall, the repeat XRF strontium measurements in both field and laboratory studies, indicated strong agreement with the reference materials and a high degree of accuracy. This is consistent with a recent, extensive study undertaken by EH&E, which has indicated excellent accuracy of measurements of strontium by XRF analyzers compared to analysis by ICP-AES (slope = 0.85-0.95, R^2 = 0.96-0.99, $p<0.01$).[8]

For Fourier transform infrared spectroscopy (FTIR), internal calibration programs were run on the instrument monthly in accordance with manufacturer's recommendations.

The accuracy of real-time temperature, relative humidity, and dew point monitors was ensured in accordance with manufacturer's recommendations (annual calibration against a primary standard). Accuracy of the CO_2 monitors was maintained using a primary

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[8] EH&E. 2010. *Draft Identification of Problematic Drywall: Source Markers and Detection Methods*, prepared for the U.S. Consumer Product Safety Commission. Needham, MA, USA: Environmental Health & Engineering, Inc. May 28, 2010.

calibration procedure, with NIST-traceable zero and span gases, prior to field deployment, where the instrument response was set or calibrated to a primary standard device, zero or span gas, or mercury thermometers and hygrometers. Each day during the field study, the performance of each sensor was measured or verified against these primary standards. This method allows both the repeatability (precision) and the instrument accuracy to be recorded.

PRECISION

Measurement precision for targeted analytes was characterized by analysis of the duplicate samples collected during the field study. Numerous methods have been developed to characterize the precision of environmental measurement systems from duplicate measurements. Estimates of precision attained from the various methods are reported to be a function of the magnitude that the differences between duplicate samples deviate from normality.[9] The initial evaluation of precision was a review of detection agreement between samples and corresponding duplicates; there was 100% detection agreement between paired sample and duplicate readings. Both a primary and secondary method was used to estimate the precision of the measurements in this study in order to ensure that a robust determination of precision was obtained. The precision estimates discussed below included all duplicate pairs where both measurements were above the laboratory reporting limit.

The primary method for estimating precision was based upon guidance from the EPA.[10] In this method, precision is calculated as the root mean square of the scaled relative differences between pairs of duplicate samples (Equation 3). The one standard deviation estimate of precision derived from this method provides a concentration range within which the actual concentration is expected to occur 68% of the time.

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[9] Hyslop NP and White WH. 2009. Estimating precision using duplicate measurements. *Journal of Air & Waste Management Association*. 59:1032-1039.

[10] EPA. 2008. *Quality Assurance Handbook for Air Pollution Measurement Systems Volume II Ambient Air Quality Monitoring Program*. Research Triangle Park, NC: U.S. Environmental Protection Agency.

$$Root\ mean\ square = \sqrt{\frac{1}{n}\sum_{i=1}^{n} D_i^2} \times 100\%\,, \qquad \text{(Equation 3)}$$

where $$D_i = \frac{(C_{i1} - C_{i2})\big/\sqrt{2}}{(C_{i1} + C_{i2})\big/2}$$

The secondary method used to estimate precision of the study data was the CV computed from an ordinary least squares regression of the paired duplicate samples. In this case, the CV is calculated as the root mean square error of the regression model divided by the mean of the dependent variable (the second sample of each duplicate pair).

Precision estimates for each parameter targeted during the study are provided in Table B.7; note that all water (sulfide) measurements were below detection and are not presented. Duplicate bulk S_8 measurements were not collected in this study, however precision of S_8 measurements have been evaluated and reported in the EH&E report titled *Draft Identification of Problematic Drywall: Source Markers and Detection Methods*.[11]

Table B.7 Primary Estimate of Measurement Precision for the Study

Parameter	Number of Pairs	Precision (%)
Hydrogen Sulfide	3	6.2
Formaldehyde	11	10
Copper Sulfide	3	12
Silver Sulfide	11	20
Strontium (XRF)	91	2.4
Carbonate (FTIR)	67	18

XRF	x-ray fluorescence
FTIR	Fourier transform infrared spectroscopy

The high precision shown in Table B.7 is illustrated in the scatter plots presented in Figures B.1 – B.6. The secondary estimates of precision inset in the figure agree well

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[11] EH&E. 2010.

with the corresponding primary estimates, all of which demonstrate a high level of precision.

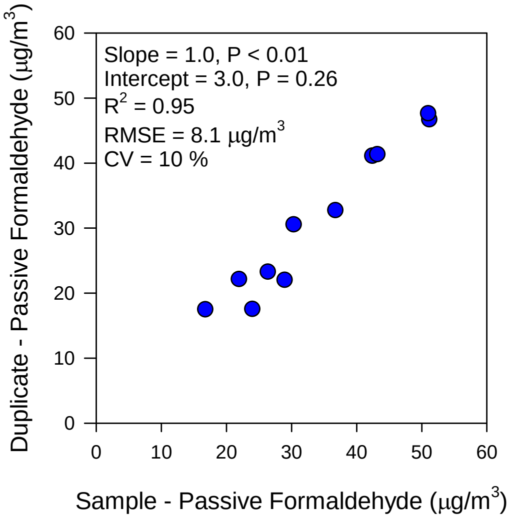

Figure B.1 Comparison of Paired Sample and Duplicate Air Sample Measurements of Passive Formaldehyde

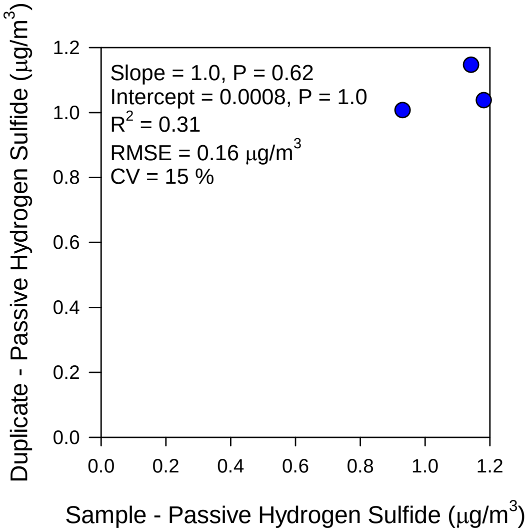

Figure B.2 Comparison of Paired Sample and Duplicate Air Sample Measurements of Passive Hydrogen Sulfide

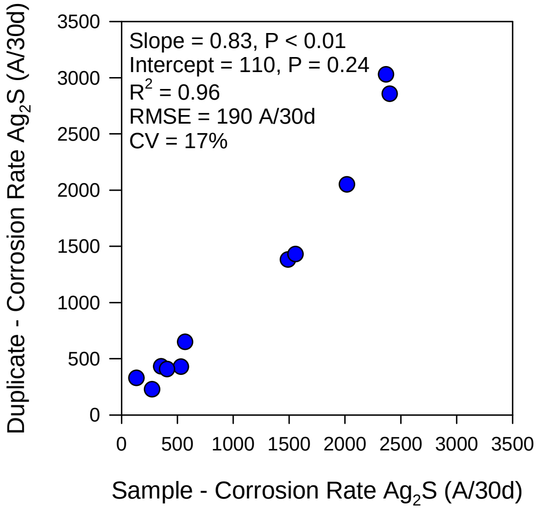

Figure B.3 Comparison of Paired Sample and Duplicate Air Sample Measurements of Corrosion Rate (Formation of Ag2S)

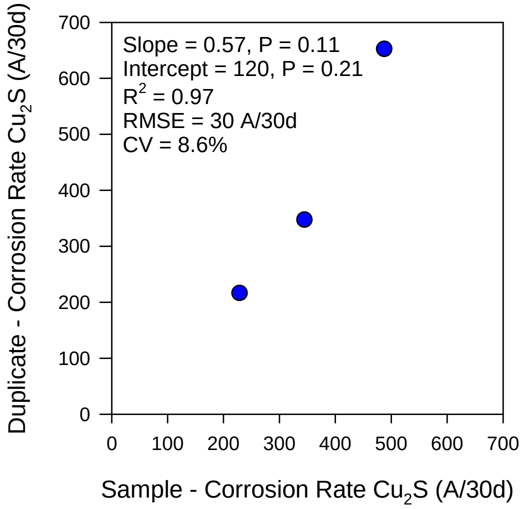

Figure B.4 Comparison of Paired Sample and Duplicate Air Sample Measurements of Corrosion Rate (Formation of Cu2S)

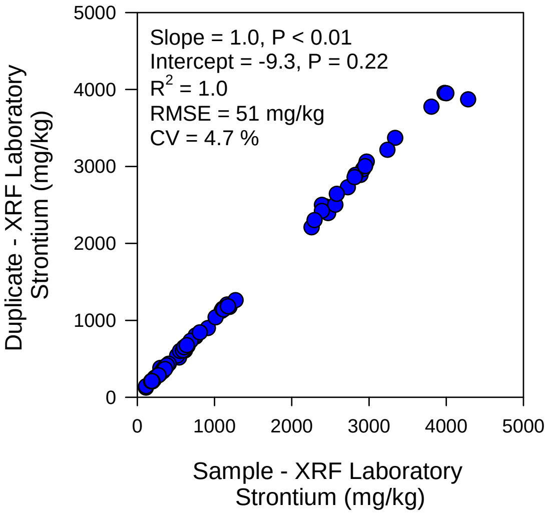

Figure B.5 Comparison of Paired Sample and Duplicate XRF Laboratory Strontium Measurements

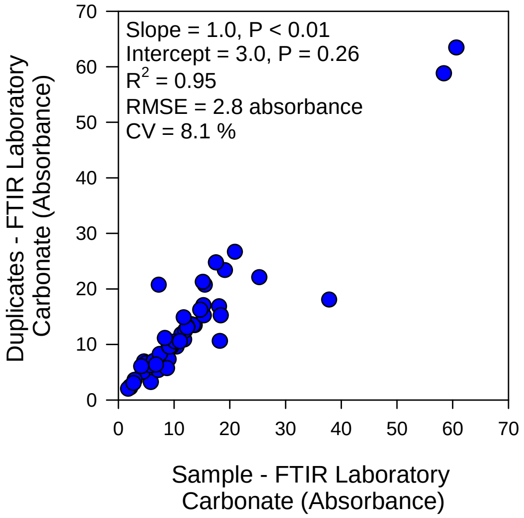

Figure B.6 Comparison of Paired Sample and Duplicate FTIR Laboratory Carbonate Measurements

The precision of the FTIR instrument used in testing at EH&E's laboratory was also examined by evaluating the agreement between measurements repeated daily from two reference drywall samples, which indicated CVs of 8.5% and 4.1%, and indicate strong agreement.

In addition to the calibration procedures implemented prior to, and in the field (described above), the precision and reasonableness of real-time monitoring data (temperature, relative humidity, dew point temperature, and CO_2) was evaluated utilizing several measures. For the temperature, relative humidity, and dew point temperature measurements, the CV between the daily average values at each measurement location within each Home was used as an indicator of agreement (CV=[standard deviation/mean]$*$100). The mean CV of indoor temperature, relative humidity and dew point temperatures over the two week period was 1.8%, 7.4%, and 4.6%, respectively.

The precision of air exchange rate measurements was evaluated using linear regression analysis between each of the two coincident air exchange rate estimates within each home, which were based on CO_2 readings. The agreement between in-home CO_2 measurements were excellent (all R^2s were above 0.94 and CVs ranged from 3.4% – 8.9%). Note that the CO_2 measurements from one home (Home I) were excluded from the air-exchange estimate calculations because the estimate did not meet the fit test criteria (R^2 less than 0.70).

The precision of the FTIR instrument used in testing at EH&E's laboratory was also examined by evaluating the agreement between measurements repeated daily from the same sample of drywall. The CV of the two validation samples, CPSC19 and CPSC26, from the repeat readings for carbonate, indicated good agreement 8.5% and 4.1% respectively.

PROCEDURES FOR STATISTICAL ANALYSIS OF DATA

Statistical analyses of the study data were performed using SAS® statistical software, version 9.1 (Cary, North Carolina). Field blank samples were analyzed to determine if field samples should be blank corrected. Based on statistical analysis of the field and shipping blank data samples did not require corrections for blanks. Values below the laboratory reporting limit, generally defined as 3x the method detection limit, were substituted using one-half of the reporting limit in statistical analyses. As described in Appendix A, regression analysis indicated good agreement between paired primary samples and duplicates; samples and duplicates were averaged for all statistical analyses.

Statistical analysis included compiling descriptive statistics and box plots. Box plots depict the mean, median, 10th, 25th, 75th, and 90th percentiles, as well as individual points beyond the 10th and 90th percentiles. The statistical probability analysis in the Discussion section (Section 6.0) was determined by taking the natural log of the ratio of Cu_2S to Ag_2S formation rates for samples from the 51-Home Study and calculating the mean and standard deviation (the natural log was used to satisify normality assumptions). A t-score was calculated for the ratio observed in Home H (natural log transformed), and the probability of observing that result was determined based on the t-distribution.