

**FINAL REPORT ON AN  
INDOOR ENVIRONMENTAL QUALITY ASSESSMENT OF  
RESIDENCES CONTAINING CHINESE DRYWALL**

Prepared For:

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## Part Three

## 6.0 DISCUSSION

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### 6.1 SUMMARY

An early objective of this study was to identify reliable markers of imported drywall (and techniques for measuring the marker). These measurement techniques were then used to evaluate the presence or absence of imported drywall in sample homes. The homes were selected by CPSC staff for inclusion in this study and were located in five states in the southeastern United States. CPSC classified the homes into two types, complaint and non-complaint. EH&E was blind to the classification of the homes during the site visits and data collection phase of the study. There were 41 complaint homes selected by CPSC from their existing incident reporting database and 10 non-complaint homes recruited by CPSC for a total sample size of 51 homes. The 10 non-complaint homes were located in the same neighborhoods as the complaint homes and were selected to approximate the characteristics of the complaint homes as much as possible. EH&E visited each of the 51 homes and collected data on construction/building related characteristics such as the presence of imported drywall, locations of the types drywall, dimensions of the drywall, house and room size, type of construction, geographic location, air exchange rate and the type of heating ventilation and air conditioning systems. In addition, air samples were collected for a wide range of chemical agents including reduced sulfur gases, aldehydes, volatile organic compounds, organic and inorganic acids. To assess the corrosivity of the atmosphere inside the building, corrosion coupons composed of pre-cleaned copper and silver test strips were placed inside and outside the home. Physical parameters such as temperature and relative humidity were also measured inside and outside the home. After data collection the data were analyzed using statistical techniques that included log linear models (random and fixed effects), correlation analysis and ordinary linear regression.

The study found that the concentrations of strontium and carbonate ion (carbonate), in combination, could be used as a reliable marker of imported drywall. Portable XRF and FTIR spectrometry instruments were used to measure strontium and carbonate, respectively. The portable XRF instruments were used to make measurements in each home, and the FTIR, although portable, was used in the laboratory. These data were

used to determine which study homes contained imported drywall, how much it contained and where it was located.

Imported drywall was found to be present in 92.7% of the complaint homes and not present in any of the non-complaint homes. The differences are clear but the results could be affected by a bias in the process leading to the complaint classification, e, g., if an individual knew they have imported drywall they may be more likely to file a complaint than someone that does not have imported drywall in their home.

Corrosion was found to be greater in the complaint houses than in the non-complaint houses ( $p < 0.01$ ). The corrosion effect was significant both when quantitative measures (corrosion coupons) were used as measures of corrosion as well as when the observations of corrosion on ground wires by trained technicians onsite were used. The region where the house was located was associated with corrosion rate in certain applications. Specifically, the east coast of Florida homes had the highest corrosion rates when corrosion coupons from the air handlers were compared and used as a measure of corrosion rate. When other corrosion coupons, were used, e.g., from the bedrooms or living rooms in the analysis there was no regional effect. This finding demonstrates how sensitive these measurements may be to micro environmental effects and indicates caution must be exercised in interpreting data from limited measurements to ensure unwitting bias is not introduced. Outdoor corrosion rates were not correlated with indoor corrosion rates.

Short-term, average air exchange rates were measured in each home using carbon dioxide as a tracer gas. The results of these studies indicated that the air exchange rates for complaint and non-complaint homes were similar ( $p = 0.09$ ). The tracer gas study also showed that the houses in the sample were relatively tightly sealed with a median short-term average air exchange rate of 0.19 ACH (range 0.05 – 0.8).

Several gases/vapors that were measured in this study were present at different concentrations in homes with and without imported drywall (as determined by CPSC status or the XRF/FTIR pair of markers). These gases/vapors were also investigated for their potential to contribute to corrosion or malodor. These gases/vapors include hydrogen sulfide, carbon disulfide, and potentially inorganic and organic acids.

In homes that were both non-complaint and did not have the XRF/FTIR marker of imported drywall H<sub>2</sub>S concentration ranged from background (0.33 ppb) to levels below the minimum reported odor threshold (0.5 ppb) for samples collected with the two week passive samplers. In contrast, approximately 67% of the measurements from homes that were either complaint or had the XRF/FTIR marker of imported drywall contained two-week average concentrations of H<sub>2</sub>S that exceeded the maximum reported background concentration level. Approximately one-half of the measured H<sub>2</sub>S levels in complaint or imported drywall homes were greater than the minimum reported odor threshold. In multivariate analyses, hydrogen sulfide concentration was found to be positively and significantly associated with silver and copper corrosion rates (p=0.01).

Carbon disulfide concentrations differed between complaint and non-complaint homes, with median concentrations of 2.2 and 0.74 µg/m<sup>3</sup>, respectively. The difference however, is not statistically significant (p=0.07) although this analysis is limited due to the small sample size. Carbon disulfide concentration was also not significant when evaluated as a predictor of corrosion rates in multivariate modeling while controlling for several potential confounding variables (p=0.29). Carbon disulfide concentrations were also not significantly correlated with hydrogen sulfide concentrations (p=0.22).

Organic acids were detected at a mean concentration of 11 ppb in complaint homes and 7 ppb in non-complaint homes. The differences were not statistically significant (p=0.5). Organic acid concentrations were also not significantly correlated with corrosion rates.

Concentrations of aldehydes in the indoor air of both complaint and non-complaint homes did not differ significantly but both were generally greater than levels reported in the scientific literature for residences in various areas of the United States. For example, the average concentration of formaldehyde (active sampling) in complaint and non-complaint homes was 53 µg/m<sup>3</sup> while mean values reported in studies of homes in large cities like New York City; Houston; Elizabeth, NJ; and Los Angeles, CA, ranged from 18 and 22 µg/m<sup>3</sup>. Concentrations of other aldehydes in indoor air of homes in the present study were also generally two to four times greater than the corresponding levels reported for these cities. Most (78%) of the homes in the present study were constructed after 2005, thus variation in concentrations of aldehydes in indoor air compared to previous studies may be a function of age of construction and related

factors such as air exchange rate. For example, Hodgson et al. (2000) evaluated air exchange rates, formaldehyde, and volatile organic compound (VOC) concentrations in new manufactured houses and site built houses. The average indoor-outdoor concentrations for these fourteen residences was  $49 \mu\text{g}/\text{m}^3$  (40 ppb) with a median of  $47 \mu\text{g}/\text{m}^3$  (38 ppb) with a range from  $9 - 66 \mu\text{g}/\text{m}^3$  (7 - 54 ppb). The average air exchange rate was 0.40 per hour with a median of 0.38 per hour. The Hodgson et al. (2000) study also demonstrated that formaldehyde is emitted by materials in a new house at fairly constant rates over the period they studied, which was nine months. The levels of formaldehyde measured in their study of newly constructed houses are quite consistent with what was measured in both the complaint and non-complaint houses in this study, even though the air exchange rates are higher in the Hodgson study (Hodgson et al. 2000).

Multivariate modeling was used to assess the significance of formaldehyde concentration as a predictor of corrosion rates. In the mixed models which compare room-specific formaldehyde concentrations and corrosion rates, formaldehyde was a significant predictor of silver corrosion rates but not copper ( $p=0.01$ ;  $p=.10$ ) (see additional discussion of formaldehyde and corrosion rates in Section 6.5.3).

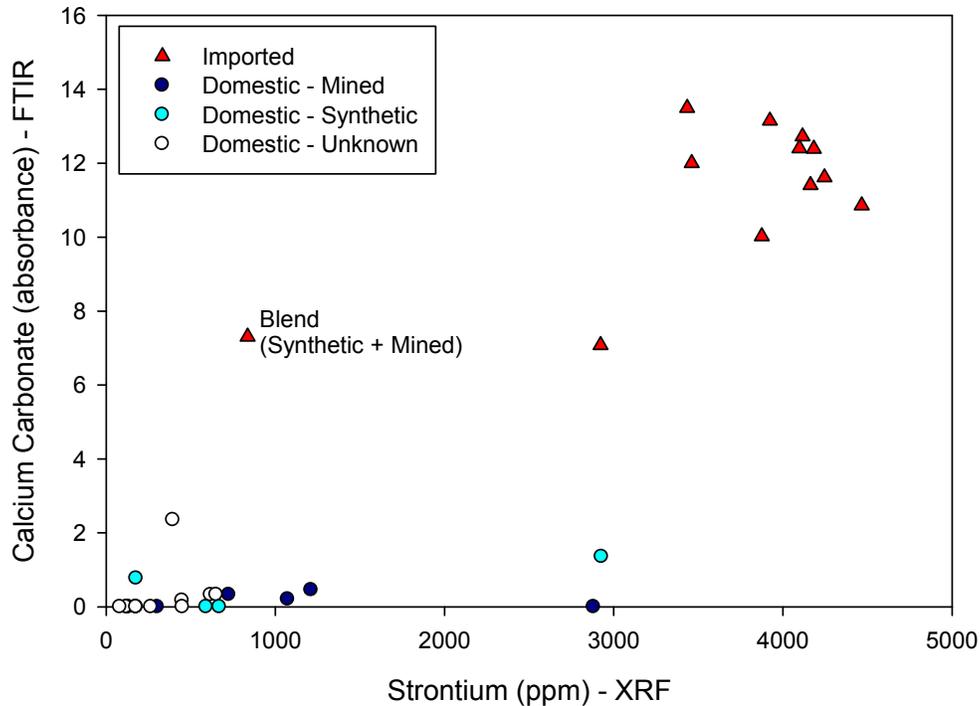
Samples for VOCs were collected at 31 of the 51 homes using SUMMA canisters and analyzed by GC/MS. Five of the 31 homes were non-complaint, the remainder were complaint homes. Several VOCs show elevated concentrations in complaint homes compared to non-complaint homes. Statistical comparisons are currently limited due to the small sample size of non-complaint homes with VOC samples ( $n=5$ ). VOCs were not significantly associated with corrosion rates.

## **6.2 SOURCE MARKERS**

### **6.2.1 Markers of imported drywall**

Laboratory-based testing of drywall samples of known origin was used to determine the utility of using real-time instruments for identifying sensitive and specific markers of imported drywall. Portable FTIR and XRF analyzers were used to quantify carbonate

and strontium concentrations, respectively. A comparison of strontium and carbonate levels was previously presented in Section 5 (Figure 5.1 reproduced here as Figure 6.1).



**Figure 6.1** Comparison of Cored Drywall Samples of Known Origin and Analyzed in a Laboratory Setting for Strontium Concentrations (ppm) Measured by XRF and Carbonate (Absorbance) Measured using FTIR

The results demonstrate that using elevated strontium concentrations alone may be a sensitive marker of imported drywall but not perfectly specific; there were two examples of domestic samples with high strontium concentrations. The analysis of known samples also indicates that carbonate alone may be sufficient to identify imported drywall. However, results from the 51 home field study indicate that there are many instances where a sample had elevated carbonate but not elevated strontium concentrations (Figure 5.2). When carbonate levels are considered in conjunction with strontium concentrations, the results demonstrate that a good indicator of imported drywall is a sample with both elevated strontium and elevated carbonate. Using both FTIR and XRF measurements of carbonate and strontium, respectively, was therefore determined to be the most sensitive and specific marker of imported drywall.

### **6.2.2 Evaluation of Portable XRF as a Field Screening Tool for Source Identification**

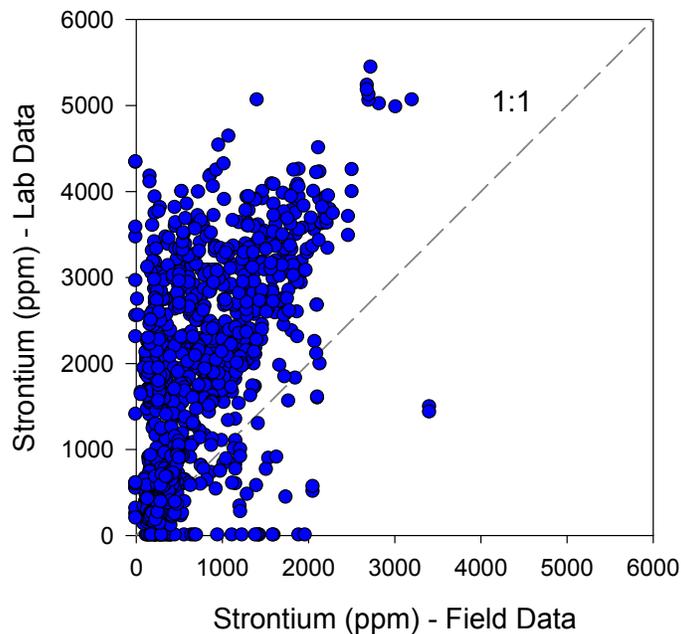
Portable XRF has been suggested as a useful tool for field identification of imported drywall, using elevated strontium concentrations as a marker. As the previously described lab analysis of core samples collected from homes demonstrates, imported drywall has elevated concentrations of strontium (greater than 1,200 ppm) compared to domestic samples. However, XRF analysis in the field can be significantly impacted by various surface materials. When drywall is measured in situ, the paint and any other of the myriad surface coatings that could be applied to walls have a muting effect on the strontium concentrations because the strontium is located at depth.

Results from a pilot study in a complaint home indicated that elevated strontium concentrations measured via XRF in situ may still be a useful indicator of imported drywall. The apparent ability of strontium concentrations to act as a differentiator is demonstrated in Figure 6.2, which shows one wall in the pilot home that appears homogeneous in texture and finish (Figure 6.2a). In Figure 6.2b, strontium concentrations from XRF are overlaid on the picture of the wall and indicate that elevated levels of strontium were detected on the lower half of the wall. The presence of imported drywall on the lower half of the wall was confirmed on another wall in the room. Therefore, in situ measurements of strontium via XRF were able to be used to identify where domestic and imported drywall were located in an otherwise uniformly painted wall. However, as discussed below there are significant limitations on using this technique as an absolute indicator.



**Figure 6.2** Picture of One Wall from a Complaint Home (a) and Same Wall with Strontium Concentrations Measured using XRF through Paint (b) demonstrating two Different Drywall Boards in an Otherwise Uniformly Painted Wall

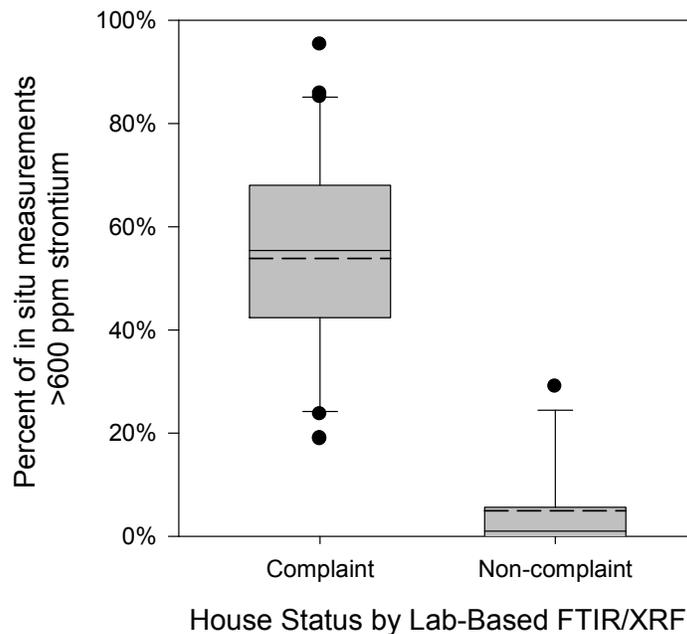
During the 51 home study, at each location where a sample was cored from the wall for laboratory analysis of the core sample, a co-located measurement using XRF was taken in situ, through the paint to allow for an assessment of the utility of portable XRF as a field tool. A point by point comparison is presented in Figure 6.3. The laboratory and field-based measurements show strong agreement, in general. However, there is no clear strontium concentration measured through the paint that could be reliably used to differentiate drywall with true elevated strontium (i.e., many false negatives). The false negatives likely occur on locations in the home that have drywall with thick layers of paint and/or plaster.



**Figure 6.3** Comparison of Strontium Concentrations of Co-located Samples Measured in the Field through Paint and/or Plaster, and Samples Measured of the Drywall Core in a Controlled Laboratory Setting

To further refine the analysis presented in Figure 6.3 and reduce the misclassification due to some walls having thick coats of paint and/or plaster, we analyzed the percent of XRF in situ samples >600 ppm (half of the 1,200 ppm value used as the cut-off in controlled laboratory analysis). This marker was created as a means of attempting to obtain an overall characterization of the home in light of the evidence that some samples may have muted strontium concentration due to wall coatings.

Results comparing the percent of in situ measurements >600 ppm strontium against house status as determined by laboratory-based analysis of core samples (i.e., no paint or plaster) are presented in Figure 6.4. These results, combined with the information presented above, suggest that while in situ measurements using XRF may not be an absolute predictor of an individual drywall measurement being from imported or domestic material (due to the potential for false negatives), the house as a whole can be reasonably well characterized using the percent of XRF samples with strontium greater than 600 ppm.



**Figure 6.4** Comparison of the Percent of Situ Samples >600 ppm Strontium and Home Status Determined Using the FTIR/XRF Marker

## 6.3 INDOOR AIR QUALITY

### 6.3.1 Concentrations of Gases

The levels of several gases measured in this investigation are of note because of (i) differences observed between homes with and without imported drywall (based on CPSC status or the XRF/FTIR pair of markers), (ii) their potential to contribute to corrosion or malodor, and (iii) their absolute levels. These gases which include hydrogen sulfide, carbon disulfide, inorganic and organic acids, and formaldehyde are discussed in this section relative to levels reported in other exposure studies and related benchmarks.

A summary of concentrations reported in the literature for gases common to this investigation and relevant comparison studies is tabulated in Appendix A.

Two-week average concentrations of hydrogen sulfide in indoor air of complaint and non-complaint homes ranged from non-detect ( $<0.7 \mu\text{g}/\text{m}^3$ ) to  $3 \mu\text{g}/\text{m}^3$ . Few published studies of indoor air quality in homes report measurements of hydrogen sulfide and other reduced sulfur gases, especially with the same degree of sensitivity as the present study. For example, Inserra et al. (2002) reported that 91% of 30-min average  $\text{H}_2\text{S}$  levels inside of homes in a community impacted by point sources of  $\text{H}_2\text{S}$  were less than the method detection limit of 30 ppb (Inserra et al. 2002). All of the  $\text{H}_2\text{S}$  levels in the present study were well below 30 ppb, yet the information available from the study by Inserra et al. does not allow any further comparison to be made. Concentrations of  $\text{H}_2\text{S}$  in ambient air as a result of emissions from natural sources have been estimated to range from 0.11 to 0.33 ppb (EPA 1993 as cited in ATSDR 2006). Similarly, the World Health Organization reports that  $\text{H}_2\text{S}$  levels in outdoor air are generally less than 0.1 ppb (WHO 1981 as cited in ATSDR 2006). With a minimum reported odor threshold of 0.5 ppb (Ruth 1986 as cited in ATSDR 2006), background concentrations of  $\text{H}_2\text{S}$  in outdoor air are not expected to be detected by olfactory means (ATSDR 2006).  $\text{H}_2\text{S}$  measured in homes that were both non-complaint and did not have the XRF/FTIR marker of imported drywall were in the range of background and below the minimum reported odor threshold. In contrast, approximately 66% of the measurements from homes that were either complaint or had the XRF/FTIR marker of imported drywall contained two-week average concentrations of  $\text{H}_2\text{S}$  that exceeded the maximum reported background level of 0.33 ppb. Likewise, approximately one-half of the measured  $\text{H}_2\text{S}$  levels in complaint or imported drywall homes were greater than the minimum reported odor threshold of 0.5 ppb.

With regard to carbon disulfide and additional reduced sulfur gases other than hydrogen sulfide, a search of the published literature did not identify measurements in residential indoor air. Among these gases, only carbon disulfide was found to differ between complaint and non-complaint homes in this investigation; median concentrations of  $2.2$  and  $0.74 \mu\text{g}/\text{m}^3$ , respectively. According to the ATSDR, most people can detect the burnt match odor characteristic of carbon disulfide at concentrations between

62 and 310  $\mu\text{g}/\text{m}^3$  (ATSDR 2004). Thus, the concentrations of carbon disulfide measured in this study are below the reported odor threshold for this substance.

Information on acid gas concentrations in homes that can be compared to results from the present study are available in a small number of published studies all of which were conducted in the northeastern United States. Formic acid, for example, was detected at a mean concentration of 11 ppb in complaint homes and 7 ppb in non-complaint homes. Reiss (Reiss et al. 1995) reported mean formic acid values of 9.8 ppb in the summer and 17.8 ppb in the winter for homes in Massachusetts, and Zhang (Zhang et al. 1994) reported a mean of 8.8 ppb in New Jersey. Concentrations of other acids measured in complaint and non-complaint homes were also similar to background levels reported in the published literature.

The indoor air levels of formaldehyde and other aldehydes were similar for complaint and non-complaint homes although generally greater than levels reported in the scientific literature for residences in various areas of the United States. For example, the average concentration of formaldehyde (active sampling) in complaint and non-complaint homes was 53  $\mu\text{g}/\text{m}^3$  while mean values reported for homes in the TEACH (New York City and Los Angeles) and RIOPA (Houston, Los Angeles, and Elizabeth, NJ) studies were 18 and 22  $\mu\text{g}/\text{m}^3$ , respectively (NUATRC 2000; Weisel et al. 2004). Concentrations of other aldehydes in indoor air of homes in the present study were also generally two to four times greater than the corresponding levels reported for the TEACH and RIOPA studies. Most (78%) of the homes in the present study were constructed after 2005, thus variation in concentrations of aldehydes in indoor air compared to previous studies may be a function of age of construction and related factors such as air exchange rate. For example, Hodgson et al. (2000) evaluated air exchange rates, formaldehyde, and VOC concentrations in new manufactured houses and site built houses. The average indoor-outdoor concentrations for those fourteen residences was 49  $\mu\text{g}/\text{m}^3$  (40 ppb) with a median of 47  $\mu\text{g}/\text{m}^3$  (38 ppb) with a range from 9 – 66  $\mu\text{g}/\text{m}^3$  (7 – 54 ppb). The average air exchange rate was 0.40 per hour with a median of 0.38 per hour. The Hodgson et al. (2000) study also demonstrated that formaldehyde is emitted by materials in a new house at fairly constant rates over the period they studied, which was nine months. The levels of formaldehyde measured in their study of newly constructed houses are quite consistent with what was measured in both the complaint

and non-complaint houses in this study, even though the air exchange rates are higher in the Hodgson study.

Concentrations of VOCs in the indoor air of complaint homes were nominally greater than in non-complaint homes, although a statistical test of equality of the central tendency is limited by the modest sample size in each group. Nonetheless, the concentrations of VOCs found in homes of both groups were in the range of levels reported in the published scientific literature such as the TEACH (NUATRC 2009) and RIOPA (Weisel et al. 2004), and Hodgson et al. (2000) studies. For example, toluene concentrations averaged 29.15  $\mu\text{g}/\text{m}^3$  and 10.99  $\mu\text{g}/\text{m}^3$  in complaint and non-complaint homes. In comparison, the average concentration in the TEACH and RIOPA studies were 18.26 and 20.28  $\mu\text{g}/\text{m}^3$ , respectively. In addition, the nominal differences between concentrations of VOCs for complaint and non-complaint homes was similar to the differences observed across homes and cities in the TEACH and RIOPA studies. For example, the average concentration of benzene in non-complaint homes was 1.06  $\mu\text{g}/\text{m}^3$  and 5.05  $\mu\text{g}/\text{m}^3$  in complaint homes. In comparison, concentrations of benzene ranged from <0.4  $\mu\text{g}/\text{m}^3$  to 39  $\mu\text{g}/\text{m}^3$  across homes in New York City and from 2.5  $\mu\text{g}/\text{m}^3$  to 5.3  $\mu\text{g}/\text{m}^3$  between average levels in Los Angeles and New York City. A larger number of observations would be required to ascertain whether any true differences in VOC concentrations exist between homes with and without imported drywall. However, the available information suggests that concentrations of VOCs in both groups of homes are similar and typical of residential buildings.

### **6.3.2 The Role of Air Exchange and Ventilation**

Home ventilation rate, measured in air changes per hour (ACH), is an important determinant of concentrations of gases in the indoor environment. Air exchange rates in residential buildings vary considerably based on the type of construction, seasonal variability in weather, and geographic region (ASHRAE 2005).

Short-term air exchange rates were measured in each home during the sampling period. A short-term test only provides a snapshot of typical conditions in a home, yet the results can still provide useful insights if gross-level differences across homes existed. The median ventilation rate for all homes in the study was 0.19 (range 0.05 – 0.8), with no

significant differences between complaint and non-complaint homes or across study region.

Typical air exchange rates for residential buildings in North America 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). This suggests that the homes in this study, both complaint and non-complaint, are on the lower end of the distribution of typical air exchange rates found in North America. The lack of variability in air exchange rates from homes in this study (i.e., most on low end of typical range) may partly explain why air exchange rate, while known to be an important variable in determining indoor gas concentrations, was not a significant predictor of gas concentrations or corrosion in the regression analyses in this study.

## **6.4 CORROSION**

### **6.4.1 Corrosion Classification Coupons**

Corrosion classification coupons were used as an integrated measure of effect. The levels of corrosion observed on the classification coupons represent the combined effect of all variables in the home, including both measured and unmeasured characteristics. The corrosion rates measured accounted for conditions in the home at the time of the indoor air sampling and allowed for a determination of effect to be seen even if the corrosion detected was due to a potentially un-quantifiable synergistic effect between low-level indoor air contaminants.

The corrosion classification coupons deployed in the 51 homes in this study were comprised of two metal strips—one copper and one silver. Using two different metals allows for the potential to identify and/or rule-out the presence of airborne contaminants based on differential rates of corrosion between the two metals. For example, Table 6.1 lists the material sensitivities of silver and copper to various corrosive agents.

<b>Table 6.1</b> Material Sensitivities to Atmospheric Corrodants		
<b>Corrodants</b>	<b>Silver (Ag)</b>	<b>Copper (Cu)</b>
CO <sub>2</sub> /CO <sub>3</sub> <sup>2-</sup>	L	–
NH <sub>3</sub> /NH <sub>4</sub> <sup>+</sup>	M	M
NO <sub>2</sub> /NO <sub>3</sub> <sup>-</sup>	N	M
H <sub>2</sub> S	H	H
SO <sub>2</sub> /SO <sub>4</sub> <sup>2-</sup>	L	H
HCl/Cl <sup>-</sup>	M	M
RCOOH/COOH <sup>-</sup>	L	M
O <sub>3</sub>	M	M
H = High sensitivity M = Moderate sensitivity L = Low sensitivity N = No sensitivity  * Table reproduced from (Leygraf and Graedel 2000) Table 4.1.		

From this table we can infer that if the corrosion observed in the homes was due to SO<sub>2</sub>, then copper corrosion would be expected to be elevated compared to silver corrosion. As there was generally good agreement between copper and silver corrosion in the same homes, corrosive agents that act on silver and copper at differential rates (such as SO<sub>2</sub>) are unlikely to be the primary cause of effect in the study homes. Similarly, the information in Table 6.1 can be used to add further evidence that hydrogen sulfide is a primary corrosive agent in this study because both silver and copper are highly sensitive to H<sub>2</sub>S—a finding supported by field measurements which recorded high rates of corrosion for both metals observed in this study.

#### **6.4.2 Differences in Corrosion Rates by Location in a Home**

In general, co-located measurements of corrosion levels measured in rooms were moderately to highly correlated. Corrosion rates measured at the AHU supply vents was significantly greater than levels measured in the rooms. Atmospheric corrosion is dependent upon corrosive species contacting the metal surface, which is most commonly governed by the process of dry deposition where contact at the surface occurs via turbulent diffusion (Leygraf and Graedel 2000). The vertical flux ( $\Phi$ ) of a contaminant is dependent upon the concentration of the contaminant in air (C) and deposition velocity ( $V_{dep}$ ), expressed in terms of flux units ( $m^3/h/m^2$ ):

$$\Phi = C \cdot V_{\text{dep}} \quad (\text{Equation 6.1})$$

Measured deposition velocities are typically much greater outdoors than indoors as a result of increased air movement (Leygraf and Graedel 2000). The increased corrosion rate observed at the AHU supply vent compared to the rooms may be explained, therefore, by the increased  $V_{\text{dep}}$  in the supply duct air stream due to increased volume of air passing the corrosion coupon (i.e., increased mass-transfer rates).

### 6.4.3 Hydrogen Sulfide and Formaldehyde

The results of the multivariate modeling (Section 5.3.8.3) indicate that both indoor formaldehyde and hydrogen sulfide concentrations were associated with silver and copper corrosion. Formaldehyde and its related acid (formic acid), can cause corrosion on copper and silver, with silver having a lower sensitivity to formic acid (Table 6.1) (Leygraf and Graedel 2000).

Reduced sulfur gases in air, even at low concentrations, are able to initiate corrosion and disrupt the protective cuprous oxide layer that forms on copper thereby enabling other corrosive agents (i.e., formaldehyde, formic acid) to more readily act on the metal. While silver does not form an oxide layer in typical temperature ranges (Campbell and Thomas 1939; Graedel et al. 1985), synergistic effects have been seen between hydrogen sulfide and other airborne corrosive agents (Leygraf and Graedel 2000).

The results from the field study support this hypothesis. The multivariate modeling results suggest that for silver corrosion there was an interactive effect between hydrogen sulfide and formaldehyde; the level of silver corrosion associated with formaldehyde was dependent upon the presence of hydrogen sulfide. This same interactive effect would be expected to be seen for copper but was not. One possible explanation relates to the mass increase rates for silver and copper. Copper and silver both have fast mass increase rates, but, in an experimental study, silver was shown to have a mass increase rate an order of magnitude faster than copper, showing mass responses within several minutes after hydrogen sulfide was introduced (Forslund et al. 1997).

Further support of a multi-component model of corrosion can be found in the literature. A study of corrosion rates of copper by sulfurous gases determined a copper corrosion rate of 29 Angstrom per ppb of hydrogen sulfide per 30 days ( $0.04 \text{ \AA ppb } 30\text{d}^{-1}$ ) (Graedel et al. 1983). Using the 75<sup>th</sup> percentile of hydrogen sulfide concentration in homes with imported drywall (0.79 ppb), the estimated rate of corrosion due to hydrogen sulfide would be 23  $\text{\AA}$  per 30 days. In this study, the average rate of copper corrosion in homes with imported drywall was  $\sim 350 \text{ \AA } 30\text{d}^{-1}$  in room air and  $1400 \text{ \AA } 30\text{d}^{-1}$  at the AHU air register, values that are 1 to 2 orders of magnitude greater than predicted based on hydrogen sulfide alone. Accounting for corrosion rates associated with another reduced sulfur, carbon disulfide, does not alter this finding; adding the 75<sup>th</sup> percentile air concentration for carbon disulfide (3.13 ppb) and the copper corrosion rates reported by Graedel et al (Graedel et al. 1983) does not significantly increase the copper corrosion rate (<0.1%). Therefore, the copper corrosion observed in homes may not be solely attributable to the concentration of reduced sulfur gases observed in this study. Additional work would be necessary to confirm this observation.

## 6.5 HEALTH CONSIDERATIONS

This assessment of indoor environmental quality in homes provides new information that is relevant to understanding the potential for human health effects to occur in association with the imported drywall that is under investigation by CPSC and its federal and state partners. The principal contrasts in exposure conditions between homes with and without imported drywall that were observed in this field study were: (1) levels of hydrogen sulfide and possibly carbon disulfide and selected hydrocarbons in indoor air; (2) rates of silver and copper corrosion; and (3) malodor. Factors such as formaldehyde concentrations and air exchange rate that were approximately equal between complaint and non-complaint homes but notable because of their magnitude and potential to influence health symptoms are considered in this discussion as well.

Hydrogen sulfide is a flammable, colorless gas with a characteristic odor of rotten eggs that may cause irritation to the eyes, nose, or throat at low concentrations and can be poisonous at elevated concentrations (ATSDR 2006). Health-based benchmarks for hydrogen sulfide exposures in non-occupational settings have been recommended by ATSDR and EPA. The ATSDR minimum risk level (ATSDR 2008) of 20 ppb for

inhalation exposure to hydrogen sulfide over an intermediate duration (more than 14 days and less than a year) is based on the prevalence of damage to olfactory neurons observed in mice exposed to 10, 30 and 80 part per million of hydrogen sulfide for 6 hours per day, 7 days per week for 10 weeks reported by Brenneman et al. (Brenneman et al. 2000). ATSDR also recommends a minimum reporting limit (MRL) of 70 ppb for acute exposure (duration of one to 14 days) based on suggestive evidence of bronchial obstruction among asthmatics exposed to 2 ppm hydrogen sulfide for 30 minutes reported by Jappinen et al. (Jappinen et al. 1990). The EPA inhalation reference concentration (RfC) for hydrogen sulfide of  $2 \times 10^{-3}$  milligrams per cubic meter (1.4 ppb) was also derived from the Brenneman (2000) study of mice. Most of the two-week average concentrations of hydrogen sulfide measured in complaint homes included in this study were below these health-based benchmarks.

Concentrations of carbon disulfide and hydrocarbons measured in whole air samples collected with SUMMA canisters were nominally about 1.5 to 2 times greater in complaint homes than in non-complaint homes. As discussed in Section 6.2, the strength of conclusions about systematic differences in VOCs levels between complaint and non-complaint homes are constrained by the number of non-complaint homes (5) from which these types of samples were obtained. The MRL for carbon disulfide of 300 ppb ( $936 \mu\text{g}/\text{m}^3$ ) recommended by ATSDR is based upon reports of reduced motor nerve conduction velocity in humans after prolonged occupational exposure to the chemical (ATSDR 1996). The EPA derived the RfC for carbon disulfide of  $700 \mu\text{g}/\text{m}^3$  from an observational study of workers in the viscose rayon industry (EPA 2002). With a maximum house-wide average concentration of  $9.1 \mu\text{g}/\text{m}^3$ , the levels of carbon disulfide in complaint and non-complaint homes were well below the ATSDR and EPA health-based benchmarks. Similar conclusions can be reached for hydrocarbons that were also assessed through the SUMMA canister sampling and analysis. For instance, the median concentration of n-hexane in complaint homes was  $4.13 \mu\text{g}/\text{m}^3$  compared to  $0.95 \mu\text{g}/\text{m}^3$  in non-complaint homes, levels that are more than 500 times below the MRL of  $2,117 \mu\text{g}/\text{m}^3$  and 150 times below RfC of  $700 \mu\text{g}/\text{m}^3$ . Moreover, the target organs and health endpoints from which MRLs and RfCs are derived typically differ across VOCs and differ from the symptoms reported by occupants of complaint homes such as respiratory irritation, headache, and eye irritation. Thus while effects of concurrent exposure to multiple VOCs are possible, the variety of health endpoints that form the

basis of health-based benchmarks complicates an assessment of risk associated with cumulative exposure. Additional analysis would be needed to evaluate the potential for cumulative effects of these gases further.

As described in Section 5.2.3, corrosion of silver and copper coupons was accelerated in complaint homes compared to non-complaint homes. The levels of hydrogen sulfide found in complaint homes may not be sufficient cause for the rate of corrosion observed in these buildings (see Section 5.3). The accelerated corrosion could be the product of synergistic effects of hydrogen sulfide with formic or acetic acid or other species that are ubiquitous in indoor environments, perhaps potentiated by dew points in the vicinity of ambient indoor temperatures as described in Section 5.3.8.1. The mixtures of corrosive species found in the air of these homes have not been studied in relation to health based considerations based upon a literature search completed by EH&E. Nevertheless, the acid gases found in these homes including hydrogen sulfide, nitrogen dioxide, acetic acid, and formic acid, are well known to be irritating to the eyes and respiratory tract (Klaassen et al. 1986; Lewis 2000) although typically at higher concentrations in air than were observed in this investigation. Hence, a close examination of the acid gas and health literature may be valuable for further evaluation of the health implications of the corrosion observed in these homes.

Malodor perceived in indoor air is another distinct difference that was observed between the complaint and non-complaint homes included in this study. Hydrogen sulfide has a low odor threshold, was enriched in indoor air of complaint homes, and therefore could be responsible for contributing to the malodors in complaint homes (see Section 6.2).

Symptoms of eye, nose, and throat irritation are often cited by occupants of polluted indoor environments (Cometto-Muñiz 2001; Molhave 2001). Studies conducted by Fanger (Fanger 201), and Molhave (Molhave et al. 1986) have shown that emissions associated with building materials, furnishings, and equipment contribute to the pollution and sensory load of the indoor environment. Liu et al. (Liu et al. 2007) found that people who had been exposed to moderate to strong odors from home renovations were approximately four times more likely to experience discomfort than those who had been exposed to emissions that generated “weak” odors. A paper by (Schiffman and Williams 2005) cites three mechanisms by which odors may produce health symptoms. Although

their paper focuses primarily on the impact of ambient odors on community health, it does provide a useful construct by which to consider the possible impact of malodors on occupants of homes containing suspect Chinese drywall. Schiffman and Williams (2005) describe these mechanisms as:

- Mechanism One: Irritation, rather than the odor, causes the health symptoms.
- Mechanism Two: Health symptoms occur at odorant concentrations that are not irritant.
- Mechanism Three: A co-pollutant in an odorous mixture is responsible for the reported health symptoms.

The first mechanism proposed details a direct association between symptoms and the compounds producing the malodors. In this case irritation, rather than the odor, is the cause of the health symptoms. The associated odor is not the cause, but rather serves as an exposure marker. Of interest is the fact that this mechanism is not dependent upon only one chemical being above its odorant threshold; irritation may be induced by a number of chemicals that each individually may be below the concentrations that cause irritation, but taken in aggregate may exceed the irritant threshold (Cometto-Muñiz et al. 1999; Cometto-Muñiz et al. 1997).

In the second mechanism it is postulated that health symptoms can occur from odors, even when the odorant is below the irritant threshold. Schiffman and Williams (2005) acknowledge that the mechanism responsible for health complaints in the absence of irritation is not well understood, however they cite several community-based studies in which low levels of hydrogen sulfide were associated with health complaints (Haahtela et al. 1992; Jaakkola et al. 1991; Jaakkola et al. 1990).

The third mechanism acknowledges that the odorant is not the only source of pollutant or irritant that is in the indoor environment. Other co-pollutants may originate from the source of the odorant material, from other sources within the residence such as VOCs and formaldehyde from wood products or NO<sub>2</sub> associated with gas stoves (Andersson et al. 1997; Hodgson et al. 2000), or be transported from outdoors such as ozone or vehicular pollutants . In this case the odorant may focus occupants' attention on the

indoor air and the irritant symptoms, but may only be a minor contributor to the health concerns that are really attributable to other materials present in the indoor environment.

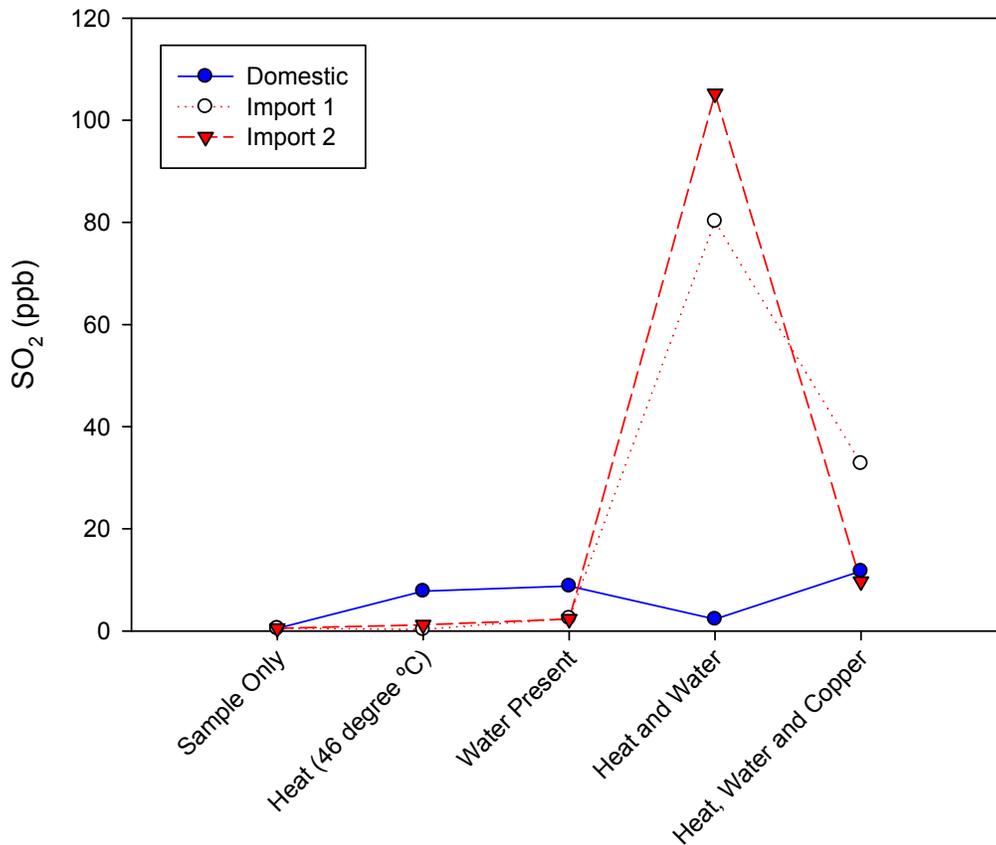
One additional effect of malodor is that occupants are aware of the status of a building with respect to construction with imported drywall. Knowledge of the drywall status of a building could bias beliefs about relationships between health symptoms and occupancy of that space. This type of bias is commonly described as dependent error in the vernacular of epidemiology (Rothman et al. 2008). Under this scenario, symptoms such as upper respiratory irritation experienced by occupants of complaint homes could be incorrectly ascribed to construction with imported drywall, as opposed to other factors. At least one well known respiratory irritant, formaldehyde, was found at elevated concentrations in the indoor air of both complaint and non-complaint homes. Yet, homes without the malodor do not have a history of health complaints with CPSC. The low air exchange rate in complaint and non-complaint homes could also be a factor in dependent error because of the potential for other common respiratory irritants to accumulate within these residences. Further research would be needed to evaluate the role of odor in reported health effects in greater detail.

## **6.6 COMPARISON TO CHAMBER STUDIES**

Results of chamber studies of imported drywall reported to date are generally consistent with the observations made during the field investigation with some notable exceptions. Accelerated corrosion of copper evidenced by visual inspection and SEM/EDS was reported when clean copper tubing was stored with imported drywall (Unified Engineering Inc. 2009). Similarly, the rate of corrosion measured on both copper and silver test coupons during the field investigation was substantially and significantly greater in homes with imported drywall than in homes with domestic drywall (see Section 5.2.3). The type of corrosion observed in the chamber studies also agrees with the results of the field investigation. Specifically, analysis of corrosion material in the chamber studies and the field investigation indicate production of  $\text{Cu}_2\text{S}$  (and  $\text{Ag}_2\text{S}$  in the field study coupons) rather than sulfates, chlorides or other common forms of copper corrosion. These results are consistent with sulfidation via  $\text{H}_2\text{S}$  and carbonyl sulfide although only the former species was found at elevated levels in indoor air of homes with imported drywall (Graedel et al. 1983), whereas chamber studies have identified both

H<sub>2</sub>S and carbonyl sulfide in headspace analysis (CAS 2009; EPA 2009; Unified Engineering Inc. 2009).

In contrast to the agreement note here, some corrosive species reported to be released from imported drywall tested in chamber studies were not observed at elevated concentrations during the field investigation. For instance, carbonyl sulfide has been observed in some chamber tests (Unified Engineering Inc. 2009) but was not found in homes of this field investigation. The absence of carbonyl sulfide in samples obtained from homes could be explained by several reasons. First, carbonyl sulfide may have been present at concentrations below the method detection limit of the grab sampling procedure (see Table 4.2). Second, some species present in chamber studies may not be produced in the field because of differences in environmental conditions between the lab and actual homes. The chamber studies are typically performed at elevated temperatures (e.g., 37 °C, 98 °F), while the average indoor temperature of homes included in the present study was 25.5 °C (78 °F). Third, species evolved from imported drywall could be rapidly scavenged by sinks inside of homes that are not present in the chamber studies. For example, hydrogen sulfide and carbonyl sulfide are known to rapidly react with copper (Graedel et al. 1985), which could result in limited direct evidence of their presence within homes. Measurements of sulfur dioxide made during exploratory experiments conducted in EH&E's laboratory also support this explanation. As shown in Figure 6.5, sulfur dioxide was measured at elevated concentrations in the air of a sealed and heated glass container that held imported drywall and water. Yet, no notable differences in sulfur dioxide concentrations compared to the control conditions were observed when a piece of clean copper tubing was also present inside the jar, although the copper tubing rapidly showed evidence of corrosion, thereby supporting the scavenging of the reactive gases from the air. Additional investigation is required to ascertain the reasons that fully explain differences between the field investigation and chambers studies that have been reported to date.



**Figure 6.5** Sulfur Dioxide (SO<sub>2</sub>) Concentrations inside Small-volume Chamber Studies Comparing Two Imported and One Domestic Drywall Sample Under Varying Environmental Conditions.

## 6.7 LIMITATIONS

This study was designed to characterize the air quality in homes that had health and/or corrosion complaints suspected to be associated with certain types of drywall. This “suspect” drywall is believed to originate and be imported from the People’s Republic of China. However, at this time there is insufficient evidence to support or refute the assertion that all Chinese-origin or imported drywall exhibits the health or corrosive characteristics reported in complaint homes.

The intent of this sampling and analysis program was to elucidate the relationships between suspect drywall and environmental conditions existing in the home that could be characterized by use of objective measurements such as the rate of corrosion on metal surfaces. A variety of sampling and inspectional techniques were utilized in this study. This study was designed as an in situ investigation in which the house was

characterized in the “lived in” condition. (Certain exceptions to this “lived in” characterization, where the houses were unoccupied during the testing, are discussed in the body of the report.) So as to not possibly miss an important interaction effect, no attempt was made to restrict occupant activities, manipulate the mechanical systems or remove materials from the residence prior to, or during, sampling. Thirteen of the 51 homes in this study were unoccupied during the sampling (12 complaint homes). Unoccupied homes represent a different environment than occupied homes and thus could potentially be an important factor when looking for associations between sources, the environment and effects. To examine the potential for occupancy status to impact the study findings, we compared several key parameters (hydrogen sulfide, formaldehyde, air exchange rate, dew point, temperature) by occupancy status and found that only temperature was significantly different across the two groups (similar results were observed when the analysis was restricted to comparing occupied status within complaint homes only). Additionally, consistent results were observed in all regression models when they were re-run controlling for occupancy status.

Formaldehyde was observed to be a predictor of silver corrosion but this study cannot rule out the possibility that formaldehyde is a surrogate for some other agent. For example, formaldehyde is corrosive to some metals, although its related acid (formic acid) is known to be more corrosive. Similarly, formaldehyde concentrations were positively associated with indoor air temperature. Therefore, the effect of formaldehyde on corrosion could be a true effect, or formaldehyde could be a marker for formic acid, temperature or some other variable.

The indoor environment of the complaint homes is complex, dynamic and in many ways challenging to characterize due to the low concentrations of the contaminants present and the highly reactive nature of many of the species of interest. It is also probable that there are important interactions between the materials emitted from the suspect drywall and airborne compounds present in the indoor environment that may be associated with other sources, as well as specific home characteristics, that could cause, or be a significant contributor to, the complaints reported.

## 7.0 CONCLUSIONS

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The objective of the in-home investigation was to characterize the indoor environment in representative complaint homes in detail, obtain air samples and other objective measurements that could be used for future risk assessments and examine homes for evidence of health stressors that could plausibly be related to drywall based on complaints and scientific information compiled by CPSC and EH&E. The following associations were observed based on the results of the 51-home study:

- Study homes with imported drywall had elevated rates of objectively quantified corrosion

*CPSC complaint homes were found to have elevated rates of corrosion as measured objectively by metal coupon and visual inspection, compared to non-complaint homes. This finding remained when house status was determined using an objective marker of imported drywall (FTIR/XRF).*

- Imported drywall found in these homes was associated with increased levels of hydrogen sulfide in indoor air

*Homes with imported drywall had significantly greater hydrogen sulfide concentrations compared to homes with domestic drywall.*

- Hydrogen sulfide concentrations in air were associated with higher dew points for complaint homes

*A positive association was observed between elevated dew points and hydrogen sulfide concentrations for homes with imported drywall. Hydrogen sulfide was present where the dew point reached typical room temperatures and condensation of water vapor would be expected.*

- Hydrogen sulfide and formaldehyde concentrations in indoor air were associated with corrosion rates

*Hydrogen sulfide was associated with corrosion rates in these study homes. For silver, a potential interactive effect was seen with formaldehyde; the effect of formaldehyde on corrosion rates was dependent upon the presence of hydrogen*

*sulfide. Formaldehyde may be associated itself or may be a marker of some other factor associated with corrosion (e.g., formic acid).*

- Objective markers of imported drywall can be quantified using portable FTIR and XRF analyzers

*FTIR and XRF analyzers provide an additional metric for characterizing homes with imported drywall that can be used in conjunction with objectively measured estimates of corrosion rates and malodor.*

- Air exchange rates in the study homes were all on the low-end of typical air exchange rates in homes

*Both complaint and non-complaint homes were newly constructed homes with air exchange rates consistent with the low end of the distribution for North American housing stock (i.e., tightly constructed homes). These low air exchange rates may play an important role in the effect of gases and indoor environmental conditions on corrosion and possible exposures to indoor contaminants.*

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