Phase I

ANALYSIS OF CHINESE DRYWALL EMISSIONS

A DETERMINISTIC ANALYSIS

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ABSTRACT

In this report we provide the results of the study conducted at Multimedia Environmental Simulations Laboratory at Georgia Tech (MESL/GT) on the problem of gaseous Emissions from drywalls manufactured in China and North America using deterministic analysis techniques. From this point forward the study will be referred to as **CHINESE DRYWALL STUDY DETERMINISTIC ANALYSIS (CDS-DA)**.

Exposure to drywall emissions may also results in health effects for the residents of the homes. In this study we only investigate and report our findings on the analysis of emissions and concentrations that may be encountered in a typical room in a typical home. Health risk effects of the emissions reported in the literature and also used in this study is investigated in a separate Health Consultation by the Agency for Toxic Substances and Disease Registry (ATSDR). The study reported here is funded by the ATSDR under the Cooperative Agreement 5U01TS000083-05.

1. INTRODUCTION

It is reported in the literature that there are salient differences between the Chinese drywall products and North American manufactured drywall products, AIHA (2010). The most important difference is the higher elemental sulfur content and the emission of gaseous sulfides (including hydrogen sulfide and various organosulfides) that are seen in drywall samples. It is alleged that these drywalls are originating from the Knauf Tianjin Company. In most cases, the Chinese drywall samples contain greater amounts of elemental strontium as well (USCPS, 2009). The etiological mechanisms for the production of sulfur gases have been hypothetically described, but the precise mechanism of generation of these gases has not been confirmed. It has been hypothesized that the source is the gypsum obtained from a Chinese mine that was mixed with naturally occurring sulfur minerals and organic materials which, in the presence of elevated temperature and moisture, may react to produce sulfide gases (DeMott, et al., 2010; Tuday, et al. 2009). This may be the cause of the emissions noticed in Chinese drywall installed homes.

The Consumer Product Safety Commission (CPSC) has received more than 3000 complaints alleging damage at the homes of residents (USCPS. 2010). Several hundred homes are reported to have been restored by extensive and expensive replacement of building materials, followed by an extended airing-out period. Approximately 2000 homes are involved in litigation, with initial decisions awarding remediation funding to some plaintiffs (USDCED, 2010). The majority of affected homeowners and builders are waiting for the availability of funding and a cost effective remediation protocol to resolve the indoor air pollution concern (AIHA. 2010).

Emission of individual compounds from Chinese drywall is estimated to be at low parts per billion (ppb) levels (Tuday, et al. 2009). The effects of exposure to sulfide mixtures at this range are poorly understood. While a CDC toxicological evaluation report suggested that air contaminant concentrations associated with emissions from Chinese drywall are below levels demonstrated to present a health hazard (Wilder, 2009), some occupants continue to attribute a variety of symptoms to emissions from Chinese drywall in their homes, and also there are findings contrary to this observation as it is reported in (Huang, et al., 2002). Thus, the health effects of exposure to the emissions originating from Chinese drywall installed homes are under study by various agencies and research laboratories including ATSDR/CDC and conclusive outcomes have not been reported to this date (Rosen, 2009). In the past exposure concerns associated with emissions from indoor sources have been analyzed by applying the results of basic research to the development of practical methods for assessment and control. As researchers verify the chemistry, air circulation dynamics and the health effects concern the remediation procedures that will be useful to field practitioners may eventually be generated to eliminate the health effects outcome of this problem. Currently the following remediation alternatives are recommended by AIHA (2010): (a) remove all corrosive drywall; (b) eliminate visible demolition dust; (c) eliminate residual Chinese drywall odors from remaining surfaces; and, (d) restore electrical and mechanical systems to a safe, reliable, and code-compliant condition. However, none of these strategies has been demonstrated to conclusively eliminate emissions on a permanent basis.

In this Phase I study we approach the analysis of the problem from a modeling perspective which includes deterministic analysis. The analysis is based on the data on emissions from Chinese drywall samples that are reported in the public domain literature (Maddalena et al., 2010; Maddalena, 2011).

In this analysis the effect of the decay of chemicals that are potentially mixed into the Chinese drywalls is not considered due to limitations on the data that is available on that aspect of the chemistry of the problem.

2. DATA REPORTED IN THE LITERATURE AND THE DATA USED IN THE CURRENT STUDY

Most comprehensive emission data on Chinese drywall has originated from the laboratory tests conducted at Lawrence Berkeley National Laboratories (Maddalena et al., 2010; Maddalena 2011). In that study measurement of chemical emissions from 30 samples of drywall products obtained from imported Chinese drywall is measured and these emissions were reported comparatively with the non-Chinese drywall emissions that are referred to as North American drywall sample tests. The LBNL study was conducted in two phases. In the first Phase the emission rates were estimated for constant temperature and constant relative humidity conditions. In the second phase the temperature and relative humidity was varied. The experimental data was supplied to MESL/GT by ATSDR and they are used without modification in this study. The data reported in Table 1 and Table 2 below is the complete experimental data set that was received from LBNL.

PHASE I LBNL DATA (Maddalena et al., 2010)**:**

Table 1. Emission Factors of Sulfur Gases as Reported by LBNL Phase I Study (µg/m^2/hr) (*T* = 25 ^{o}C; *RH* = 50%)

COUNTRY	MAN. DATE	CPSC ID	Sample	Hydrogen Sulfide H_2S	Carbonyl Sulfide OCS	Sulfur Dioxide SO_2	Methyl Mercaptan MM	Ethyl Merceptan EM	Dimethyl Sulfide DMS	Carbon Disulfide CS_2
China	2006	1379	C 1	126.32	2.82	72.11	1.4		0.78	2.9
China	2006	7069	C 2	23.43		16.24	0.41		0.6	1.28
China	2006	7339	C 3	130.92		89.12	2		0.85	3.21
China	2006	8357	C 4	196.81	1.82	128.6	2.21		0.7	4.36
China	2006	9707	C 5	26.31	1.38	20.48	0.15		0.56	1.44
China	2009	1491	C 6	4.89			0.41		0.04	0.06
China	2009	1493	C 7	5.17	1.88	11.77	0.38		0.02	0.05
China	2009	2631	C 8			2.26	0.06		0.02	
China	2009	2632	C 9	17.6	5.65	31.43	0.69	0.06	0.02	0.14
China	2009	2634	C 10	6.73	0.56	9.15			0.02	0.09
China	2009	2635	C 11	12.89	2.53	10.99	0.33		0.02	0.09
China	2009	2636	C 12	10.59	7.57	10.41	0.6		0.04	0.09
China	2009	2637	C 13				0.03			0.02
China	2006	7078	C 14	2.6		8.73	0.03		0.02	0.02
China	2006	9667	C 15	5.83		6.01	0.41		0.02	0.02
China	2006	9672	C 16	71.44	3.93	22.16	0.59		0.04	0.27
China	2005	9673	C 17	213.33	8.89	101.98	1.59	0.1	0.06	0.7
Chinese Ave.	2005 & 2006			88.55	3.77	51.71	0.98	0.1	0.4	1.58
Chinese Ave.	2009			9.64	3.64	12.67	0.36	0.06	0.03	0.08
N. Am.	2009	6226	NA 1			0			0.35	0.53
N. Am.	2009	7639	NA 2	4.24	8.87	0			0.47	0.85
N. Am.	2009	8036	NA 3			2.72			0.45	0.57
N. Am.	2009	8037	NA 4						0.35	0.82
N. Am.	2009	8213	NA 5			4			0.6	0.8
N. Am.	2009	8235	NA 6	0.13					0.31	0.43
N. Am.	2009	8236	NA 7	2.54					0.29	0.57
N. Am.	2009	9139	NA 8		2.34	8.21	0.23		0.6	0.63
N. Am.	2009	9175	NA 9	3.53		5.06			0.74	0.7
N. Am.	2009	9858	NA 10			9.97			0	0.15
N. Am.	2009	9961	NA 11	1.85		5.08			0.31	0.58
N. Am.	2009	9962	NA 12			1.22			0.37	0.64
N. Am.	2009	7932	NA 13			0				0

Note: Data derived from LBNL phase one study µg-S/m^2/hr to µg/m^2/hr

PHASE II LBNL DATA (Maddalena, 2011)**:**

Table 2. Emission Factors of Sulfur Gases as Reported by LBNL Phase II Study ($\mu g/m^2/hr$)

	Temperature			**Relative Humidity**			**Emission Factors $\mu g/m^2/hr$**						
Sample	**25 °C**	**32 °C**	**41 °C**	**3.40%**	**49%**	**87%**	**H_2S**	**OCS**	**SO_2**	**MM**	**EM**	**DMS**	**CS_2**
C3-01	x			x			5.29	1.49	3.29	0.32	0.04	0.02	0.05
C3-02	x				x		8.32	1.52	13.36	0.62	0.11	0.03	0.16
C3-03	x					x	8.04	3.86	6.07	0.80	0.19	0.04	1.07
C3-04		x		x			7.67	2.66	15.82	0.36	0.08	0.03	0.08
C3-05		x			x		14.05	2.47	11.91	0.94	0.23	0.04	0.42
C3-06		x				x	16.83	6.60	11.22	1.54	0.32	0.08	3.51
C3-07			x	x			15.44	1.48	39.17	0.61	0.20	0.06	0.20
C3-08			x		x		25.52	4.13	72.50	1.98	0.26	0.12	0.76
C3-09			x			x	33.47	8.55	31.99	5.30	0.42	0.18	5.22
NA4-10	x			x			1.17	0.30	1.39	0.08	0.04	0.01	0.01
NA4-11	x				x		2.63	1.10	1.59	0.12	0.05	0.02	0.01
NA4-12	x					x	1.76	3.29	2.66	0.25	0.16	0.04	0.04
NA4-13		x		x			0.70	1.46	2.22	0.20	0.05	0.02	0.01
NA4-14		x			x		4.98	2.53	8.55	0.33	0.08	0.03	0.01
NA4-15		x				x	5.91	2.15	8.24	0.88	0.15	0.06	0.06
NA4-16			x	x			2.02	1.55	1.09	0.06	0.06	0.02	0.01
NA4-17			x		x		4.77	2.55	6.82	0.50	0.12	0.03	0.01
NA4-18			x			x	11.71	4.58	2.81	1.94	0.14	0.08	0.10
C4-19	x			x			2.33	0.84	2.33	1.17	0.09	0.01	0.02
C4-20	x				x		3.67	1.49	19.29	0.38	0.18	0.02	0.07
C4-21	x					x	24.87	2.59	28.29	4.42	0.73	0.08	0.44
C4-22		x		x			9.14	1.78	21.67	0.34	0.13	0.04	0.06
C4-23		x			x		13.73	3.35	16.57	1.24	0.40	0.05	0.21
C4-24		x				x	26.65	8.28	15.01	2.08	1.03	0.10	1.93
C4-25			x	x			17.12	1.03	60.53	0.88	0.36	0.08	0.14
C4-26			x		x		28.68	3.48	106.97	1.92	0.47	0.14	0.33
C4-27			x			x	50.14	14.22	164.56	5.42	1.43	0.21	2.59
C16-28	x			x			3.79	1.26	3.38	0.22	0.07	0.02	0.02
C16-29	x				x		5.52	2.02	16.72	0.43	0.07	0.03	0.05
C16-30	x					x	10.09	5.67	8.68	1.24	0.24	0.07	0.22
C16-31		x		x			5.44	1.67	11.63	0.21	0.06	0.02	0.03
C16-32		x			x		7.43	2.97	15.11	1.10	0.10	0.17	0.08
C16-33		x				x	20.75	4.20	7.37	2.29	0.16	0.08	0.36
C16-34			x	x			15.19	2.00	55.97	0.76	0.02	0.08	0.08
C16-35			x		x		26.43	4.87	91.96	2.00	0.10	0.13	0.18
C16-36			x			x	43.44	11.17	124.85	6.54	0.35	0.31	0.55
C17-37	x			x			0.62	1.10	1.31	0.18	0.05	0.03	0.02
C17-38	x				x		8.26	1.41	7.24	0.62	0.12	0.04	0.04
C17-39	x					x	17.52	3.97	4.18	2.84	0.34	0.16	0.36
C17-40		x		x			10.24	1.41	14.99	0.33	0.06	0.03	0.04
C17-41		x			x		16.84	3.96	48.17	0.59	0.18	0.03	0.09
C17-42		x				x	17.72	2.53	13.14	1.74	0.57	0.06	0.47
C17-43			x	x			26.89	2.06	72.52	0.97	0.21	0.11	0.14
C17-44			x		x		50.86	5.38	116.94	2.41	0.49	0.13	0.26
C17-45			x			x	54.10	13.54	74.91	6.00	1.27	0.30	1.59

Note: H_2S (Hydrogen Sulfide), OCS (Carbonyl Sulfide), SO_2 (Sulfur Dioxide), MM (Methyl Mercaptan), EM (Ethyl Merceptan), DMS (Dimethyl Sulfide), CS_2 (Carbon Disulfide).

3. METHODOLOGY

In the analysis of the emissions data reported in the second phase of the experimental study (Maddalena, 2011), it is also recommended that the use of the following empirical models are suitable for the estimation of the data that involves temperature and relative humidity variations.

$$\ln(EF) = \alpha \frac{1}{T} + \beta \ln(RH) + b$$
$$ER = EF \times Area\,of\;Drywall \qquad (1)$$

where *EF* is the emission factor of chemicals such as H_2S, OCS, SO_2, MM, EM, DMS, CS_2; *ER* is the emission rate of chemicals; *T* is the temperature (^{o}K); *RH* is the relative humidity (%); α is the coefficient associated with the term (1/T); β is the coefficient associated with *RH* and *b* is the intercept. These empirical models can be used to estimate the emission factors and emission rates as a function of temperature and relative humidity for cases where the wall sample is not known in a typical home. We identify this application as the "Modeled Drywall" in this study. The model fitting parameters can be obtained using the complete database presented in Table 2. The purpose of this approach is to give the analysis presented in this study the flexibility needed to analyze the cases where one knows that there is a Chinese drywall in a home but the type of the drywall installed is unknown.

Table 3. Empirical Model Coefficients for the LBNL model

Sample		H_2S	OCS	SO_2	MM	EM	DMS	CS_2
7339 8357 9672 9673	α	-9494.127	-4723.375	-14458.28	-7608.106	-4843.822	-8106.292	-9082.319
	β	0.3325825	0.3710785	0.1940086	0.5374622	0.4498616	0.3113089	0.7252647
	b	32.553423	15.344044	49.657749	23.176156	12.767550	22.746820	25.783017

Note: The coefficients of the empirical model given above are reproduced in sufficient decimal digits for other users to be able to regenerate the results that are used in this study. Other predictions made on Emission Rates and Concentrations will be rounded to two digits.

The error analysis of the Empirical Model is given in Table 4A which indicates a good fit with the experimental data. Error analysis for individual wall are given in Table 4B

Table 4A. Error analysis of Empirical Model

Error	H_2S	OCS	SO_2	MM	EM	DMS	CS_2
Multiple R	0.88	0.84	0.87	0.90	0.73	0.86	0.82
R^2	0.77	0.71	0.76	0.82	0.54	0.74	0.67
Adjusted R^2	0.76	0.70	0.75	0.80	0.51	0.72	0.65
Standard Error	0.46	0.41	0.61	0.46	0.70	0.45	0.88

Table 4B. Error analysis of Empirical Model for drywalls 8357 and 9673

Drywall	Error	H_2S	OCS	SO_2	MM	EM	DMS	CS_2
8357	Multiple R	0.87	0.86	0.87	0.87	0.89	0.92	0.89
	R^2	0.77	0.74	0.76	0.76	0.79	0.84	0.79
	Adjusted R^2	0.69	0.65	0.69	0.67	0.72	0.79	0.72
	Standard Error	0.56	0.55	0.70	0.68	0.49	0.43	0.85
9673	Multiple R	0.90	0.89	0.94	0.89	0.94	0.71	0.87
	R^2	0.81	0.79	0.88	0.79	0.89	0.51	0.76
	Adjusted R^2	0.74	0.72	0.84	0.72	0.85	0.34	0.68
	Standard Error	0.67	0.42	0.61	0.59	0.42	0.69	0.79

The temperature and relative humidity dependent drywall specific emission factors can now be computed to estimate deterministic emission rate and emission factor model input for rooms where there is an unknown Chinese Drywall installed. These input parameters will be used to estimate the concentration distributions in a room using a version of the IH MOD model developed at MESL/GT.

The IH MOD model is developed by the **American Industrial Hygiene Association** (AIHA) **Exposure Assessment Strategies Committee** (EASC) and has been published as IH MOD application in a workbook of models described in the document "*Mathematical Models for Estimating Occupational exposure to Chemicals*" (AIHA, 2009). IH MOD uses Microsoft Excel to calculate algorithms for airborne concentrations of chemicals in a **deterministic mode** only.

The IH MOD model we have selected to use in this study is the "**Well Mixed Model with Constant Emissions Rate**" application. This is a suitable model when decay rate of the gaseous source is not known and is not considered.

The "**Well Mixed Model with Constant Emissions Rate**" application is based on the following mathematical model. In this model Equation (2) is used for the generation phase:

$$C(t) = \frac{G + C_{in}Q}{Q + k_L V}\left[1 - \exp\left(-\frac{Q + k_L V}{V}t\right)\right] + C_0 \exp\left(-\frac{Q + k_L V}{V}t\right) \qquad (2)$$

The mathematical model for the decay phase related to ventilation is identified as given in Equation (3),

$$C(t) = C_{decay,0} \exp\left(-\frac{Q}{V}t\right) \qquad (3)$$

The parameters of this mathematical model are defined as:

G: Generation rate *ER* which is equal to *EF* x area of drywall) Equation 1 (µg/hr);
V : Total room volume minus volume of solid objects in room (m^3);
K_L: Loss mechanism value (fraction/min);
Q : Work space ventilation (m^3/hr);
C_0 : Contaminant concentration in the work space at the start (µg/m^3). Often assumed to be zero;
C_{in} : Contaminant concentration in the air entering the work space (µg/m^3). Often assumed to be zero;
$C_{decay,0}$: Contaminant concentration at the beginning of decay phase (µg/m^3);

Maximum time for the simulation which is equal to the time specified by the user to run the calculations (simulation time); and, time at the end of generation of emissions is equal to time specified by the user at which time the Generation (G) will cease and purging of the room begins.

<u>Deterministic Analysis:</u>

i. We first calculate the emission rate using the wall specific data or the empirical model is used for cases where the wall type is not known (Modeled Drywall case). During this step a temperature and moisture content value is needed and will be entered;
ii. The user than transfers the emission rate generated to the IH MOD application;
iii. The concentration estimates in a room are then calculated in a deterministic manner; and,
iv. The results obtained can be plotted, viewed in text format or can be transferred to other platform to perform the analysis of the results if desired.

4. NUMERICAL RESULTS FOR DRYWALL EMISSIONS AND ROOM CONCENTRATIONS

In this section we provide the analysis for several drywall types first in the following sequences; (a) Analysis based on emission data reported in Maddalena et al., (2010) report; and Analysis based on emission data reported in Maddalena, (2011) report.

Summary of the Data Used in the physical description of the environment used in a household is as follows. This data was submitted to MESL/GT research program by ATSDR.

For Emission rate estimation the following data ranges are considered:

Area of contaminated drywall (A) for a typical household (m^2):

Min: 77.1 m^2;
Max: 927.7 m^2;
Mean: 424.7 m^2.

Room volume (V) (m^3):

Min: 65.1 m^3;
Max: 1,645.3 m^3;
Mean: 626.1 m^3

Ambient temperatures (T) within a house hold (^oC):

Min: 69.4^{o}F = 20.8 ^{o}C
Max: 88.1^{o}F = 31.2 ^{o}C
Mean: 77.7^{o}F = 25.4 ^{o}C.

Relative humidity in a room in a house hold (RH%) (percentage):

Min: 40%;
Max: 80%;
Mean: 60%.

For concentration calculations the following data ranges are considered:

Q (m^3/hr) = Air exchanges/hr x Room Volume (m^3)

Min: 0.05 (AE/hr) x 65.1 (m^3) = 3.26 m^3/hr
Max: 0.8 (AE/hr) x 1,645.3 (m^3) = 1,316.24 m^3/hr
Mean: 0.22 (AE/hr) x 626.1 (m^3) = 137.74 m^3/hr

Initial Contaminant concentration in room at t_0 is set to zero. Contaminant concentration in supply air is set to zero. Concentration Loss mechanism value in a wall/room environment (fraction/min), K_L, is set as zero to model the most adverse conditions in a household.

Deterministic Analysis at Constant Temperature (25°C) and Humidity (50%) Based on** *Maddalena et al., (2010)* **data:

As can be seen in Table 1, emissions of sulfur gases were reported first for room temperature (25°C) and room relative humidity (50%) conditions. This emissions data is directly used in Equation (2) to determine the expected concentrations in a room for specific drywall samples. In this case the empirical model parameters are not used to estimate the variable temperature and humidity dependent conditions in a room. Thus, to represent the average condition as an approximation the average of the emission factors reported in the LBNL study is calculated for the years (2005-2006) and (2009) and these average values were used in the estimation of the concentrations in a room, Equation (2). This would provide information on the expected concentration estimates for an average case for years (2005-2006) and (2009). The outcome of this analysis is summarized in Table 5A for Emission rates and Table 6A for concentrations Equation (2).

Table 5A. Emission rates for drywalls using the data developed in Maddalena et al., (2010) (From Table 1, T = 25 °C; RH = 50%)

Drywall Type	Sample	H_2S (µg/hr)	SO_2 (µg/hr)	CS_2 (µg/hr)	MM (µg/hr)	DMS (µg/hr)	OCS (µg/hr)	EM (µg/hr)
Chinese Drywall	**7339**	55601.72	37849.26	1363.29	849.40	361.00		
	8357	83585.21	54616.42	1851.69	938.59	297.29	772.95	
	9672	30340.57	9411.35	114.67	250.57	16.99	1669.07	
	9673	90601.25	43310.91	297.29	675.27	25.48	3775.58	42.47
	Average for yrs. 2005 & 2006	37607.19	21961.24	671.03	416.21	169.88	1601.12	42.47
	Average for yr. 2009	4094.11	5380.95	33.98	152.89	12.74	1545.91	25.48
North Am.	**8037**			348.25		148.65		

Table 6A. Expected steady-state concentrations for Chinese drywalls and North American drywall for each chemical using the data provided in Maddalena et al., (2010) (From Table 1, T = 25 °C; RH = 50%)

Drywall Type	Sample	H_2S (µg/m^3)	SO_2 (µg/m^3)	CS_2 (µg/m^3)	MM (µg/m^3)	DMS (µg/m^3)	OCS (µg/m^3)	EM (µg/m^3)
Chinese Drywall	**7339**	403.67	274.79	9.90	6.17	2.62		
	8357	606.84	396.52	13.44	6.81	2.16	5.61	
	9672	220.27	68.33	0.83	1.82	0.12	12.12	
	9673	657.77	314.44	2.16	4.90	0.19	27.41	0.31
	Average for yrs. 2005 & 2006	273.03	159.44	4.87	3.02	1.23	11.62	0.31
	Average for yr. 2009	29.72	39.07	0.25	1.11	0.09	11.22	0.19
North Am.	**8037**			2.53		1.08		

Note: The term "average" in Tables 5A and 6A implies the average of all drywall samples manufactured in (2005 & 2006) and 2009.

Deterministic Analysis at Constant Temperature and Humidity Based on** Maddalena, **(2011) data:

Given the discrete data, we estimate emission rates for all Chinese drywall samples 7339, 8357, 9672, 9673, the "Modeled Drywall" sample and the North American drywall sample 8037 and also calculate the concentrations based on these emission rates. This analysis is presented in two stages: (i) in order to compare the emission rates and concentrations between the LBNL 2009 and LBNL 2010 experiments we have used the experimental data provided in Table 2 at $T = 25\ ^oC$; $RH = 49\%$ and calculated the emission rates and concentrations (Maddalena, 2011). Notice that he we have assumed that 1% difference in relative humidity will not change the emission factors estimated in the LBNL study. The results for this analysis (LBNL 2010 experiments (Maddalena, 2011)) are presented in Table 5B for emission rates and in Table 6B for concentrations. Thus Tables 5A & 5B and 6A & 6B correspond to same temperature and relative humidity conditions for emissions and concentrations respectively that are related to the two experiments conducted by LBNL at different times. These results are given for all wall samples that are considered in this study;

Table 5B. Emission rates for drywalls using the data developed in Maddalena, (2011) (T = 25 ^{o}C; RH = ~50%)

Drywall Type	Sample	H_2S (µg/hr)	SO_2 (µg/hr)	CS_2 (µg/hr)	MM (µg/hr)	DMS (µg/hr)	OCS (µg/hr)	EM (µg/hr)
Chinese Drywall	7339	3533.50	5673.99	67.95	263.31	12.74	645.54	46.72
	8357	1558.65	8192.46	29.73	161.39	8.49	632.80	76.45
	9672	2344.34	7100.98	21.24	182.62	12.74	857.89	29.73
	9673	3508.02	3074.83	16.99	263.31	16.99	598.83	50.96
	Average Drywall	2736.13	6010.57	33.98	217.66	12.74	683.77	50.96
North Am.	8037	1116.96	675.27	4.25	50.96	8.49	467.17	21.24

Note: The term "average drywall" implies the use of average of all drywall emission factors as an estimate.

Table 6B. Expected steady-state concentrations for Chinese drywalls and North American drywall for each chemical using the data provided in Maddalena, (2011) (T = 25 ^{o}C; RH = ~50%)

Drywall Type	Sample	H_2S (µg/m^3)	SO_2 (µg/m^3)	CS_2 (µg/m^3)	MM (µg/m^3)	DMS (µg/m^3)	OCS (µg/m^3)	EM (µg/m^3)
Chinese Drywall	7339	25.65	41.19	0.49	1.91	0.09	4.69	0.34
	8357	11.32	59.48	0.22	1.17	0.06	4.59	0.56
	9672	17.02	51.55	0.15	1.33	0.09	6.23	0.22
	9673	25.47	22.32	0.12	1.91	0.12	4.35	0.37
	Average Drywall	19.87	43.64	0.25	1.58	0.09	4.96	0.37
North Am.	8037	8.11	4.90	0.03	0.37	0.06	3.39	0.15

Note: The term "average drywall" implies the use of average of all drywall emission factors as an estimate.

and, (ii) the second analysis we present below are calculated at T = 25.4 °C; RH = 60%. These are the temperature and relative humidity values selected by ATSDR for this analysis and they represent normal average conditions in a home. In this case empirical models are used to estimate the *EF*s, Equation (1). For this case the numerical results obtained for Emission Rates are given in Table 7 below.

Table 7. Emission rates for drywalls using regression models (T = 25.4 °C; RH = 60%)

Drywall Type	Sample	H_2S (µg/hr)	OCS (µg/hr)	SO_2 (µg/hr)	MM (µg/hr)	EM (µg/hr)	DMS (µg/hr)	CS_2 (µg/hr)
Chinese Drywall	7339	3717.12	1275.12	2870.34	330.15	59.91	15.12	213.78
	8357	3984.54	1175.30	5350.08	469.06	155.00	15.68	91.25
	9672	3161.40	1373.92	3197.61	340.85	66.68	21.77	43.59
	9673	3272.21	1021.78	2171.90	402.04	82.20	22.96	48.25
	Modeled Drywall	3518.25	1204.36	3213.58	381.67	84.46	18.55	80.03
North Am.	8037	1139.76	678.37	1455.07	118.56	38.62	12.67	9.63

Note: The term "modeled drywall" implies the use of Empirical model Equation (1).

Using these emission rates and the IH MOD application one can calculate the steady state concentrations of gases in a deterministic manner. In this calculation, we use the mean values of the parameters described above, which are Q = 137.736 m^3/hr, V = 626.1 m^3, C_0 = 0, C_{air} = 0, k_L = 0, and ER are as summarized in Table 7. The steady state concentrations obtained for Chinese drywall samples and North American drywall are given in Table 8.

Table 8. Expected steady-state concentrations in a room for Chinese drywalls and North American drywall for each chemical based on Emission rates given in Table 7. (T = 25.4 °C; RH = 60%)

Drywall Type	Sample	H_2S (µg/m^3)	OCS (µg/m^3)	SO_2 (µg/m^3)	MM (µg/m^3)	EM (µg/m^3)	DMS (µg/m^3)	CS_2 (µg/m^3)
Chinese Drywall	7339	26.99	9.26	20.84	2.40	0.44	0.11	1.55
	8357	28.93	8.53	38.84	3.41	1.13	0.11	0.66
	9672	22.95	9.98	23.22	2.48	0.48	0.16	0.32
	9673	23.76	7.42	15.77	2.92	0.60	0.17	0.35
	Modeled Drywall	25.54	8.74	23.33	2.77	0.61	0.14	0.58
North Am.	8037	8.28	4.93	10.56	0.86	0.28	0.09	0.07

Note: The term "modeled drywall" implies the use of Empirical model Equation (1).

Deterministic Analysis as a Function of Temperature and Humidity Based on (**Maddalena**, 2011) Data:

We have also evaluated the variation of emission rates and room concentrations as a function of temperature and humidity based on the discrete data reported in Maddalena (2011). Since there are several combinations of this analysis we have only selected to evaluate some of the important combinations of the parameters (Drywall type, Temperature and Relative Humidity). The preliminary analysis conducted indicates that the "Chinese drywall sample 8357 and 9673" are the critical drywall for most of the chemical emissions. Thus we have selected these drywall samples to evaluate the effect of temperature and relative humidity variations on the emission rates and also the room concentrations. It is also important to compare this effect for the emission rates and room concentration results originating from the "Modeled Drywall" drywall case and also the "North American Drywall" case. Thus we have also evaluated the emission rates and room concentrations for these two drywall samples as well. This analysis was done for all chemicals of concern, namely H_2S, OCS, SO_2, MM, EM, DMS, CS_2.

The emission rate results for the three drywall samples selected are given in Table 9 for three different temperatures and three different humidity values for all chemicals. These temperature and humidity values correspond to the Maddalena (2011) laboratory test conditions for all samples. The room concentration results for the same three drywall samples are given in Table 10 again for three different temperatures and three different humidity values for all chemicals.

These results are also not presented in figures since ATSDR personnel only uses the tabulated results in their Health Consultation. This presentation format of the results was requested by the ATSDR research personnel.

Table 9. Emission Rates of Four Drywall Samples as a Function of Temperature and Relative Humidity (µg/hr)

	CH DW	8357		CH DW	9673		Average	Drywall		NA DW	8037	
H_2S	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	989.55	1558.65	10562.29	263.31	3508.02	7440.74	1277.29	2736.13	6425.71	496.90	1116.96	747.47
Temp. 32°C	3881.76	5831.13	11318.26	4348.93	7151.95	7525.68	3449.63	5526.41	8701.04	297.29	2115.01	2509.98
Temp. 41°C	7270.86	12180.40	21294.46	11420.18	21600.24	22976.27	7924.90	13960.95	19233.60	857.89	2025.82	4973.24
OCS	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	356.75	632.80	1099.97	467.17	598.83	1686.06	497.96	683.77	1708.36	127.41	467.17	1397.26
Temp. 32°C	755.97	1422.75	3516.52	598.83	1681.81	1074.49	798.44	1353.73	2294.44	620.06	1074.49	913.11
Temp. 41°C	437.44	1477.96	6039.23	874.88	2284.89	5750.44	697.57	1896.29	5041.19	658.29	1082.99	1945.13
SO_2	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	989.55	8192.46	12014.76	556.36	3074.83	1775.25	1094.66	6010.57	5013.58	590.33	675.27	1129.70
Temp. 32°C	9203.25	7037.28	6374.75	6366.25	20457.80	5580.56	6806.88	9742.62	4962.62	942.83	3631.19	3499.53
Temp. 41°C	25707.09	45430.16	69888.63	30799.24	49664.42	31814.28	24228.07	41235.18	42078.21	462.92	2896.45	1193.41
MM	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	496.90	161.39	1877.17	76.45	263.31	1206.15	200.67	217.66	987.43	33.98	50.96	106.18
Temp. 32°C	144.40	526.63	883.38	140.15	250.57	738.98	131.66	410.90	812.24	84.94	140.15	373.74
Temp. 41°C	373.74	815.42	2301.87	411.96	1023.53	2548.20	341.88	882.31	2469.63	25.48	212.35	823.92
EM	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	38.22	76.45	310.03	21.24	50.96	144.40	26.54	50.96	159.26	16.99	21.24	67.95
Temp. 32°C	55.21	169.88	437.44	25.48	76.45	242.08	35.04	96.62	220.84	21.24	33.98	63.71
Temp. 41°C	152.89	199.61	607.32	89.19	208.10	539.37	83.88	140.15	368.43	25.48	50.96	59.46
DMS	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	4.25	8.49	33.98	12.74	16.99	67.95	8.49	12.74	37.16	4.25	8.49	16.99
Temp. 32°C	16.99	21.24	42.47	12.74	12.74	25.48	12.74	30.79	33.98	8.49	12.74	25.48
Temp. 41°C	33.98	59.46	89.19	46.72	55.21	127.41	35.04	55.21	106.18	8.49	12.74	33.98
CS_2	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	8.49	29.73	186.87	8.49	16.99	152.89	11.68	33.98	221.91	4.25	4.25	16.99
Temp. 32°C	25.48	89.19	819.67	16.99	38.22	199.61	22.30	84.94	665.72	4.25	4.25	25.48
Temp. 41°C	59.46	140.15	1099.97	59.46	110.42	675.27	59.46	162.45	1056.44	4.25	4.25	42.47

Note: The term "average drywall" implies the use of average of all drywall emission factors as an estimate.

Table 10. Room Concentrations for Four Drywall Samples as a Function of Temperature and Relative Humidity ($\mu g/m^3$)

	CH DW	8357		CH DW	9673		Average	Drywall		NA DW	8037	
H_2S	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	7.18	11.32	76.68	1.91	25.47	54.02	9.27	19.86	46.65	3.61	8.11	5.43
Temp. 32°C	28.18	42.33	82.17	31.57	51.92	54.64	25.04	40.12	63.17	2.16	15.36	18.22
Temp. 41°C	52.79	88.43	154.60	82.91	156.82	166.81	57.54	101.36	139.64	6.23	14.71	36.11
OCS	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	2.59	4.59	7.99	3.39	4.35	12.24	3.62	4.96	12.40	0.93	3.39	10.14
Temp. 32°C	5.49	10.33	25.53	4.35	12.21	7.80	5.80	9.83	16.66	4.50	7.80	6.63
Temp. 41°C	3.18	10.73	43.85	6.35	16.59	41.75	5.06	13.77	36.60	4.78	7.86	14.12
SO_2	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	7.18	59.48	87.23	4.04	22.32	12.89	7.95	43.64	36.40	4.29	4.90	8.20
Temp. 32°C	66.82	51.09	46.28	46.22	148.53	40.52	49.42	70.73	36.03	6.85	26.36	25.41
Temp. 41°C	186.64	329.83	507.40	223.61	360.57	230.97	175.90	299.37	305.49	3.36	21.03	8.66
MM	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	3.61	1.17	13.63	0.56	1.91	8.76	1.46	1.58	7.17	0.25	0.37	0.77
Temp. 32°C	1.05	3.82	6.41	1.02	1.82	5.37	0.96	2.98	5.90	0.62	1.02	2.71
Temp. 41°C	2.71	5.92	16.71	2.99	7.43	18.50	2.48	6.41	17.93	0.19	1.54	5.98
EM	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	0.28	0.56	2.25	0.15	0.37	1.05	0.19	0.37	1.16	0.12	0.15	0.49
Temp. 32°C	0.40	1.23	3.18	0.19	0.56	1.76	0.25	0.70	1.60	0.15	0.25	0.46
Temp. 41°C	1.11	1.45	4.41	0.65	1.51	3.92	0.61	1.02	2.67	0.19	0.37	0.43
DMS	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	0.03	0.06	0.25	0.09	0.12	0.49	0.06	0.09	0.27	0.03	0.06	0.12
Temp. 32°C	0.12	0.15	0.31	0.09	0.09	0.19	0.09	0.22	0.25	0.06	0.09	0.19
Temp. 41°C	0.25	0.43	0.65	0.34	0.40	0.93	0.25	0.40	0.77	0.06	0.09	0.25
CS_2	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp. 25°C	0.06	0.22	1.36	0.06	0.12	1.11	0.08	0.25	1.61	0.03	0.03	0.12
Temp. 32°C	0.19	0.65	5.95	0.12	0.28	1.45	0.16	0.62	4.83	0.03	0.03	0.19
Temp. 41°C	0.43	1.02	7.99	0.43	0.80	4.90	0.43	1.18	7.67	0.03	0.03	0.03

Note: The term “average drywall” implies the use of average of all drywall emission factors as an estimate.

In order to evaluate the variation of emission rates and room concentrations for all drywall samples which was not included in the analysis given in Table 9 and Table10, we have selected the most critical chemical of concern, which is H_2S (this is a chemical of concern for ATSDR Health Consultation) and completed a similar analysis for all drywall samples of concern. These results are presented in Table 11 for three different temperatures and three different humidity values for the chemical H_2S.

Table 11. Emissions and Room Concentrations for Chemical H_2S as a Function of Temperature and Relative Humidity

	EMISSIONS (μg/hr)					CONCENTRATIONS (μg/m³)		
Dry Wall 7339	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Dry Wall 7339	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	2246.66	3533.50	3414.59		Temp = 25 °C	16.31	25.65	24.79
Temp = 32 °C	3257.45	5967.04	7147.70		Temp = 32 °C	23.65	43.32	51.89
Temp = 41 °C	6557.37	10838.34	14214.71		Temp = 41 °C	47.61	78.69	103.20
Dry Wall 8357	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Dry Wall 8357	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	989.55	1558.65	10562.29		Temp = 25 °C	7.18	11.32	76.68
Temp = 32 °C	3881.76	5831.13	11318.26		Temp = 32 °C	28.18	42.33	82.17
Temp = 41 °C	7270.86	12180.40	21294.46		Temp = 41 °C	52.79	88.43	154.60
Dry Wall 9672	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Dry Wall 9672	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	1609.61	2344.34	4285.22		Temp = 25 °C	11.69	17.02	31.11
Temp = 32 °C	2310.37	3155.52	8812.53		Temp = 32 °C	16.77	22.91	63.98
Temp = 41 °C	6451.19	11224.82	18448.97		Temp = 41 °C	46.84	81.49	133.94
Dry Wall 9673	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Dry Wall 9673	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	263.31	3508.02	7440.74		Temp = 25 °C	1.91	25.47	54.02
Temp = 32 °C	4348.93	7151.95	7525.68		Temp = 32 °C	31.57	51.92	54.64
Temp = 41 °C	11420.18	21600.24	22976.27		Temp = 41 °C	82.91	156.82	166.81
Average Drywall	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Average Drywall	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	1277.29	2736.13	6425.71		Temp = 25 °C	9.27	19.86	46.65
Temp = 32 °C	3449.63	5526.41	8701.04		Temp = 32 °C	25.04	40.12	63.17
Temp = 41 °C	7924.90	13960.95	19233.60		Temp = 41 °C	57.54	101.36	139.64
Dry Wall NA 8037	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%		Dry Wall NA 8037	R. Hum. 3.4%	R. Hum. 49%	R. Hum. 87%
Temp = 25 °C	496.90	1116.96	747.47		Temp = 25 °C	3.61	8.11	5.43
Temp = 32 °C	297.29	2115.01	2509.98		Temp = 32 °C	2.16	15.36	18.22
Temp = 41 °C	857.89	2025.82	4973.24		Temp = 41 °C	6.23	14.71	36.11

Note: The term "average drywall" implies the use of average of all drywall emission factors as an estimate.

The results presented in this section are based on deterministic analysis and this concludes the deterministic analysis phase of CDS-DA study conducted at MESL/GT during the first phase of the study.

5. DISCUSSION OF DETERMINISTIC ANALYSIS RESULTS

The analysis presented in Section 4 shows that estimated emission rates and concentrations in a room where a Chinese drywall is installed will be higher than the estimated emission rates and concentrations where North American drywall sample is installed.

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