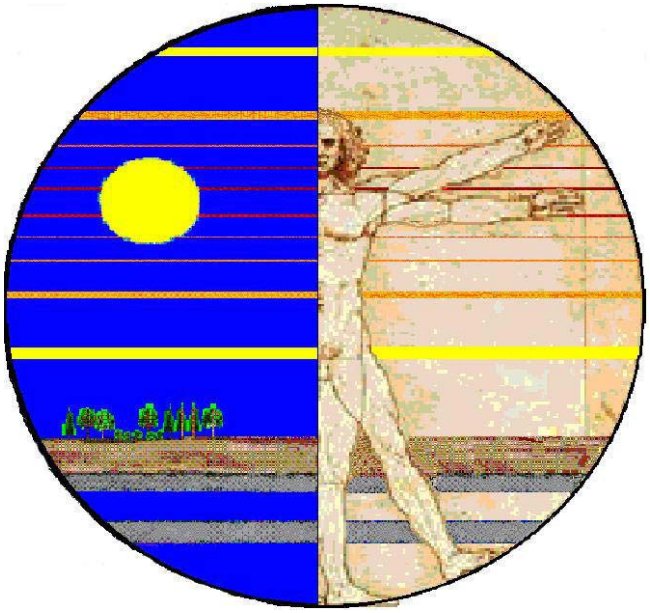
Phase II

CHINESE DRYWALL EMISSIONS:

UNCERTAINTY ANALYSIS

Mustafa M. Aral and Jiabao Guan



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ABSTRACT

In this report we provide the results of the second phase (Phase II) of the Chinese Drywall study. The Phase I and Phase II studies, in which the deterministic analysis and the uncertainty analysis of Chinese drywall emissions are investigated, are completed at the request of Agency for Toxic Substances and Disease Registry (ATSDR). These studies are conducted at Multimedia Environmental Simulations Laboratory at Georgia Tech (MESL/GT). The Phase II study that is reported here is the continuation of Phase I study which was completed and submitted to ATSDR on February 12, 2013. The findings of Phase I study were provided to ATSDR in a technical report titled "Phase I - Analysis of Chinese Drywall Emissions: A Deterministic Analysis" (Aral and Guan, 2013). In Phase II study, which is based on the deterministic analysis, we provide the uncertainty aspects of the deterministic results. It is our expectation that the uncertainty analysis will provide the reader with the expected stochastic ranges of the deterministic results given the uncertainty aspects of the model parameters used in the deterministic analysis.

From this point forward the current study will be referred to as **CHINESE DRYWALL EMISSIONS: UNCERTAINTY ANALYSIS (CDE-UA)**.

The reader should refer to Phase I study report (MESL-01-13) for the introductory material that was provided on the Chinese Drywall Emissions problem. The overarching purpose of the study was also addressed in the Phase I study report which will not be repeated here.

The study reported here is funded by ATSDR under the Cooperative Agreement 5U01TS000083-05.

1. INTRODUCTION

The reader should refer to Phase I study report (Aral and Guan, 2013) for the introductory material that was provided on the Chinese Drywall Emissions problem and the overarching purpose of the Chinese drywall emissions study. In this report we address the uncertainty analysis aspects of the Chinese drywall study which is based on the deterministic analysis reported earlier (Aral and Guan, 2013). In this analysis the purpose is to propagate the uncertainty that exists in the parameters used in the deterministic model and evaluate the effects of this uncertainty on the final results presented in the deterministic analysis. In this sense the current study is a continuation of the Phase I study which is reported earlier (Aral and Guan, 2013).

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

The most comprehensive emission data on Chinese drywall samples has originated from the laboratory tests conducted at Lawrence Berkeley National Laboratories (Maddalena et al., 2010; Maddalena 2011). In that study the 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 were varied in the experiments conducted. The LBNL experimental data was provided to MESL/GT by ATSDR and they are used here without modification as it is reported in the phase I study report (Aral and Guan, 2013).

The reader should refer to Phase I study report (Aral and Guan, 2013) for a review of the data used in both Phase I and Phase II studies. The data reported in Table 1 and Table 2 of Phase I report is repeated below for completeness. This is the complete experimental data set that was received from LBNL by ATSDR and it was transferred to MESL/GT for use in this study.

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 in μg/m^2/hr

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

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

	Temperature			Relative Humidity			Emission Factors μg/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 OF THE DETERMINISTIC ANALYSIS AND THE RESULTS

The deterministic analysis was based on the IH MOD model that 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.

In this study the IH MOD model we have selected to use 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 (1) is used for the generation phase:

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

The mathematical model for the decay phase which is associated with the ventilation in a room and is identified as given in Equation (2),

$$C(t) = C_{decay,0} \exp\left(-\frac{Q}{V}t\right) \quad (2)$$

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.

Summary of the parametric data used in the physical description of the environment used in a household is also repeated below as reported in Phase I study (Aral and Guan, 2013). This data was also submitted to MESL/GT research program by ATSDR.

<u>For Emission rate estimation the following data ranges are considered:</u>

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 household (^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

The reader should refer to Phase I study report (Aral and Guan, 2013) for a more detailed review of the data and the methodology used in the deterministic analysis phase of the study including the deterministic analysis results.

4. UNCERTAINTY ANALYSIS BASED ON THE DETERMINISTIC RESULTS PRESENTED IN PHASE I STUDY

The analyses presented in Phase I study report (Aral and Guan, 2013) for drywall emission rates and room concentrations were based on deterministic analysis in which semi-empirical models and experimental data were used. That analysis does not incorporate the impact of uncertainty factors on the results presented. In this section of the Phase II report, we present the estimates of the effect of the uncertainty factors on the numerical results presented in the Phase I study report. The uncertainty factors considered may include the limitations of the experimental data, experimental measurement errors and modeling errors. Thus, in order to evaluate the reliability of the deterministic analysis presented in Phase I study, in this section we implement a stochastic analysis of the data used in the deterministic analysis. This analysis can be performed using a two-stage analysis. First, we apply the Monte Carlo simulation to generate the statistical distributions of emission rates and steady-state contaminant concentrations in a room for cases of importance for ATSDR Health Consultation. Next, we use confidence interval theory to evaluate the confidence intervals of contaminant concentrations over time. The results of the uncertainty analysis will provide the necessary information for the risk based evaluation of the numerical results presented in Phase I study.

4.1 Monte Carlo Simulation Procedures Used for LBNL 2009 and LBNL 2010 Data

Monte Carlo technique is a stochastic algorithm that may be used to account for the impact of uncertainties in quantitative analysis. The algorithm has been widely applied in various fields including engineering, environmental modeling and health risk analysis. Monte Carlo simulation performs uncertainty analysis by building models of possible results by substituting a range of input estimates with a specified probability distribution for any factor that has an inherent uncertainty in a model or an application. The procedure repeats model computations using random samples obtained from the probability density functions that represent the uncertain parameters in the mathematical model used to represent an environmental process. The outcome of the application of the procedure yields statistical distributions of possible model outcomes which can then be evaluated using confidence interval analysis. The distributions that describe the probability of different model outcomes represent the propagation of uncertainty from inputs to outcomes. For example, as expressed in Equation (1) of Phase I report (Aral and Guan, 2013), the emission rate (*ER*) is a function of temperature (*T*), relative humidity (*RH*) and the area of drywall (*A*). The uncertainty of the *ER* can then be propagated from the uncertainties in *T*, *RH* and *A* assuming that these are the three key factors which may influence the *ER* as parameters. The assumption we are making here is that "we are not certain of the combined effects of the parameters *T*, *RH* and *A*" and we will represent them as a probability distribution rather than as deterministic parameters as was used in Phase I study. For this application the Monte Carlo simulation can be applied to address the uncertainty propagation of *ER* as shown in Figure 1, which illustrates the basic principle of Monte Carlo analysis.

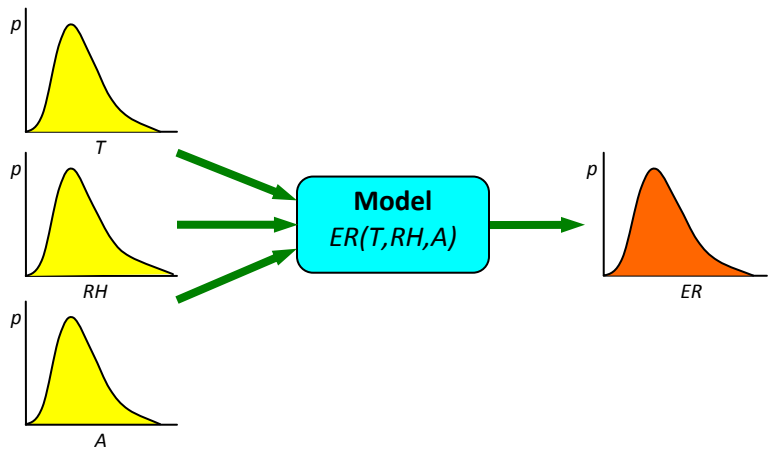


Figure 1. Schema for the Monte Carlo principle in uncertainty analysis of *ER*.

Thus, for the *ER* analysis the Monte Carlo simulation may follow the following procedures:

i. Identify parameters that are uncertain in an application that may significantly affect the *ER* outcome;
ii. Specify the parameters that may describe the model input parameters as a stochastic variable, including mean, minimum, maximum, and variance and the probability density distribution representation. In this case one may select normal, lognormal, exponential, triangle or uniform distributions;
iii. Generate the probability density functions for the model input parameters using random numbers and scaling the random numbers to fit the distribution selected;
iv. Use random samples from the probability density functions generated for the parameters of the model and repeat the deterministic computations for each combination until all possible events are used in a random manner; and,
v. Aggregate the results to obtain the statistical distributions of outcomes, in this case for *ER*.

The second phase of the analysis is the Monte Carlo simulations for the room concentrations. The Monte Carlo procedure for the second phase of the analysis can be presented as shown in Figure 2.

For room concentration analysis the Monte Carlo simulation may follow the following procedures:

i. Identify parameters that are uncertain in a room concentration calculation that may significantly affect the outcome;

ii. Specify the parameters that may describe the model input parameters as stochastic variables, including mean, minimum, maximum, and variance and the probability density distribution representation. In this case one may select normal, lognormal, exponential, triangle or uniform distributions;
iii. Generate the probability density functions for the model input parameters using random numbers and scaling the random numbers to fit the distribution selected;
iv. Use random samples from the probability density functions generated for the parameters of the model and repeat the deterministic computations for each combination until all possible events are used at least once in a random manner. This step now also includes the probabilistic outcome of the *ER* generated in the first step above; and,
v. Aggregate the results to obtain the statistical distributions of outcomes, in this case for concentrations.

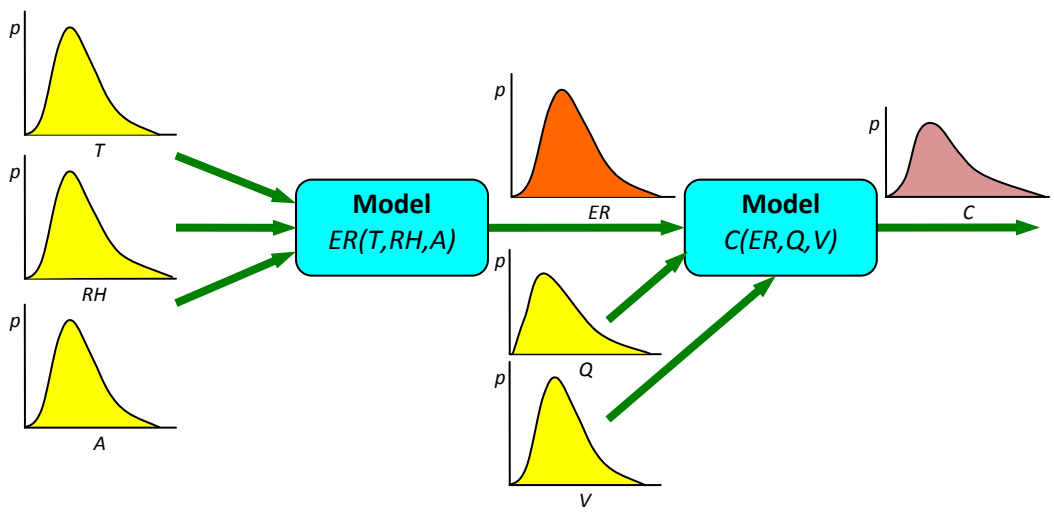


Figure 2. Schema for the two-stage Monte Carlo principle for uncertainty analysis for room concentration computations.

The procedures described above would be the ideal use of the Monte Carlo analysis in uncertainty analysis. The procedures described above can be implemented for the LBNL 2010 data (LBNL 2011) since in those experiments the emission factors and the *ER* can be calculated using the regression equations given by LBNL, Equation (1) in Phase I report (Aral and Guan, 2013). However, for LBNL 2009 data (LBNL 2010) these equations cannot be used to estimate the emission factors as a function of random temperature and random relative humidity input parameters. Thus a different procedure needs to be adopted for the LBNL 2009 data as outlined in Figures 3 and 4.

As can be seen in Figure 3 the emission factors are reported in the LBNL 2009 data as experimental results and there is no other information available to generate probability density functions for the emission factors. Thus, the only uncertain input parameter that is given in Equation (1) of Phase I study report would be the cross section area. Thus a probability

distribution of the cross section can be generated and sampled to develop the probability density function for the *ER*. A schema of this process is given in Figure 3 and then the second phase of the analysis will again follow the computation process described above for room concentrations.

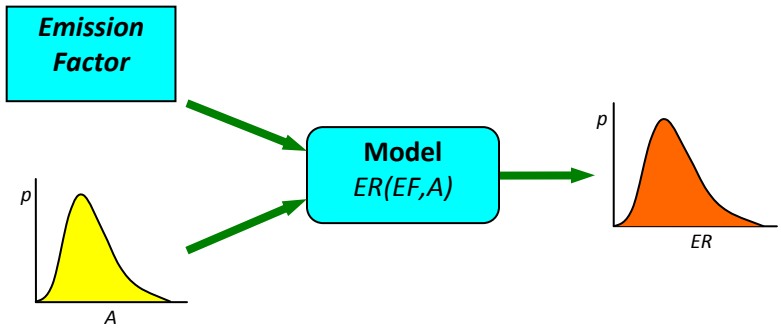


Figure 3. Schema for the Monte Carlo principle in uncertainty analysis for LBNL 2009 data (LBNL, 2010) for *ER*.

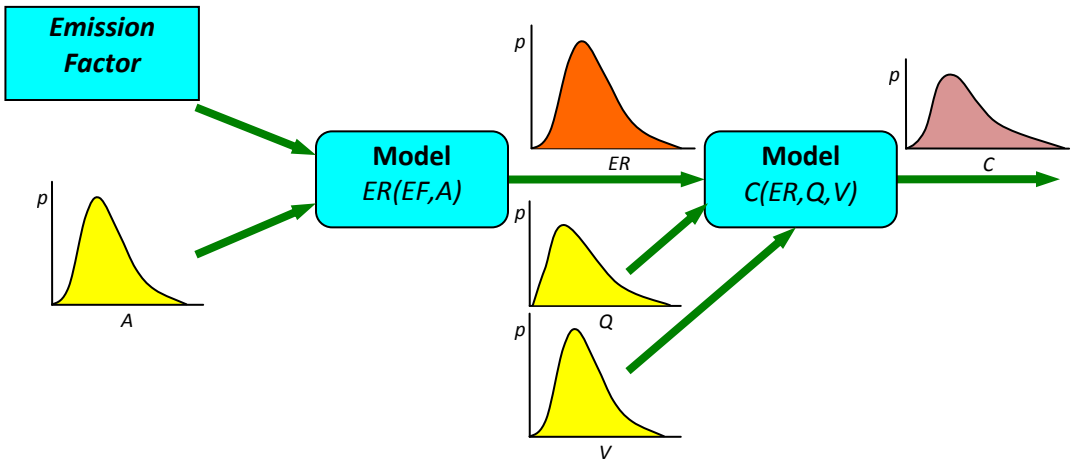


Figure 4. Schema for the two-stage Monte Carlo principle for uncertainty analysis for room concentration computations (LBNL 2009 data (LBNL 2010)).

These two procedures are used here to evaluate the uncertainty in LBNL 2009 and LBNL 2010 data based on the mathematical models that are presented in Section 3 and also in Phase I study report (Aral and Guan, 2013).

4.2 Monte Carlo Simulation of Emission Rates Based on the 2009 Data (LBNL 2010)

Table 5A of the Phase I study report (Aral and Guan, 2013) lists the expected emission rates for drywall samples based on LBNL 2009 data (LBNL 2010), which are obtained by multiplying the area of contaminated drywalls and the emission factor data. In Table 5A, the temperature used in the experiments is 25 ^{o}C and the relative humidity is 50%. As provided by ATSDR, the mean area of contaminated drywalls is 424.7 m^2. The range of the area of contaminated drywall is also given by ATSDR as [77.1, 927.7] m^2 and this is an important source of uncertainty. In Monte Carlo simulation, the parameters used to describe the probability density function of the area are given in Table 3. The resulting distribution for area is shown in Figure 5. In a typical application there is no rule of thumb to determine the required number of runs of the Monte Carlo simulation for a good representation of the variant under study. In general, if one uses more runs the Monte Carlo simulation will generate more accurate statistical results and the results obtained have higher representativeness of the parameter under study, but this also increases computational cost. However, the statistical results will not be affected when the number of runs increases above a threshold number. In our analysis, we have selected 10,000 runs based on computational time considerations. We think this is large enough to produce reliable outcomes for the current study.

Table 3. Parameters used in the estimation of emission rates for drywalls.

Variables	mean	minimum	maximum	Variance	Runs	Distribution
A (m^2)	424.7	77.1	927.7	16,000	10,000	Normal

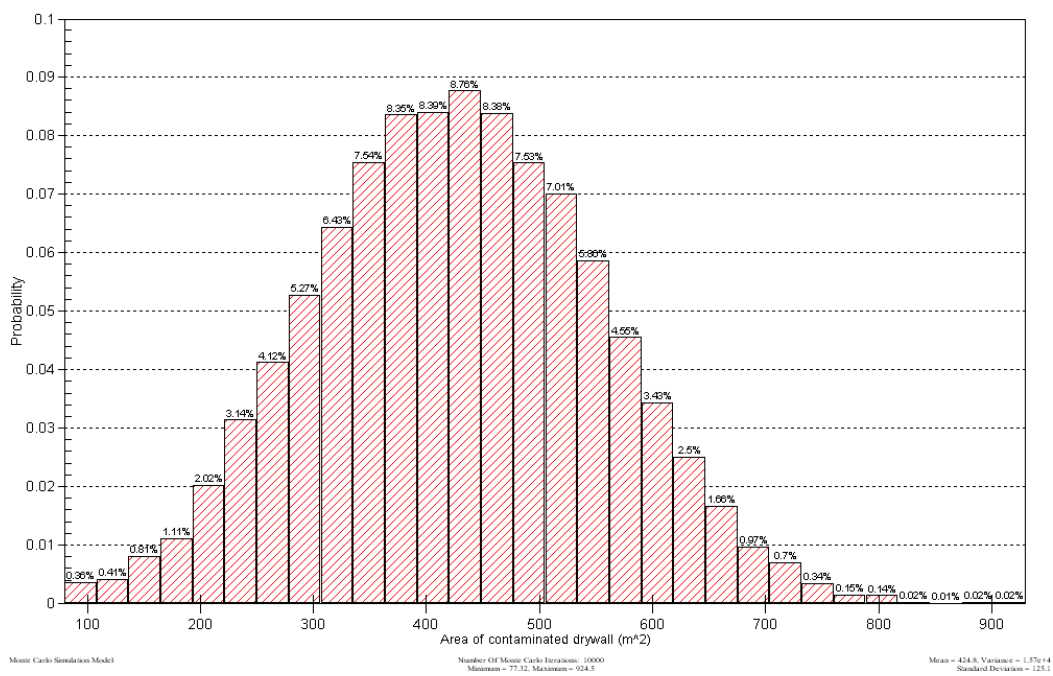


Figure 5. Results of Monte Carlo simulation for the area of contaminated drywall.

This distribution, together with the emission factors listed in Table 1, is used to calculate the distributions of emission rates of drywalls using the procedure shown in Figure 3. The mean emission rates for drywalls are listed in Table 4. In comparison with Table 5A of Phase I report (Aral and Guan, 2013), it may be noticed that emission rates for corresponding chemicals are agreeable. Figures 6 through 11 show the Monte Carlo simulation results of H_2S emission rates for drywall samples. It can be clearly seen from these figures that the statistical distributions of H_2S emission rates for drywall samples are likely to be normal distributions. We note here that these calculations are done for all chemicals (Table 4) but only the probability distributions for H_2S are shown in Figures 6 through 11 for the drywall samples as representative outcome.

Table 4. Mean emission rates for drywalls using the data developed in LBNL (2010)

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**	55613	37857	1363.6	849.6	361.1	NA	NA
	8357	83603	54628	1852.1	938.8	297.4	773.1	NA
	9672	30347	9413.3	114.7	250.6	16.99	1669.4	NA
	9673	90620	43320	297.4	675.4	25.49	3776.4	42.48
	Average for yrs. 2005 & 2006	37615	21966	671.2	416.3	169.9	1601.5	42.48
	Average for yrs. 2009	4095	5382.1	33.98	152.9	12.74	1546.2	25.49
North Am.	**8037**	NA	NA	348.3	NA	148.7	NA	NA

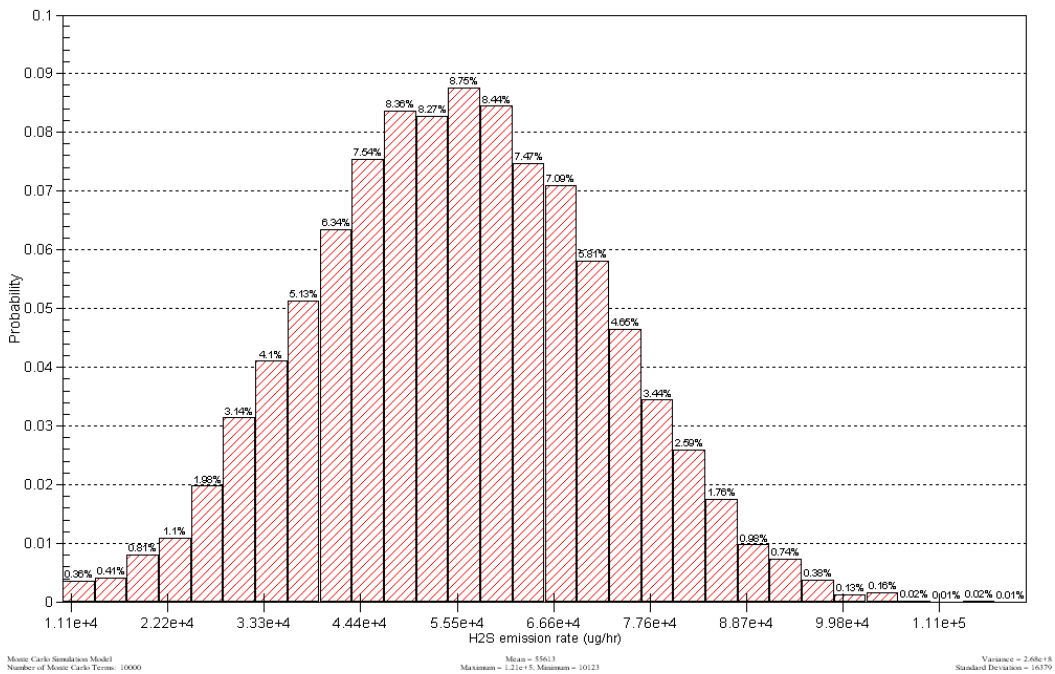


Figure 6. Monte Carlo results of H_2S emission rate for drywall sample 7339 using LBNL 2009 data.

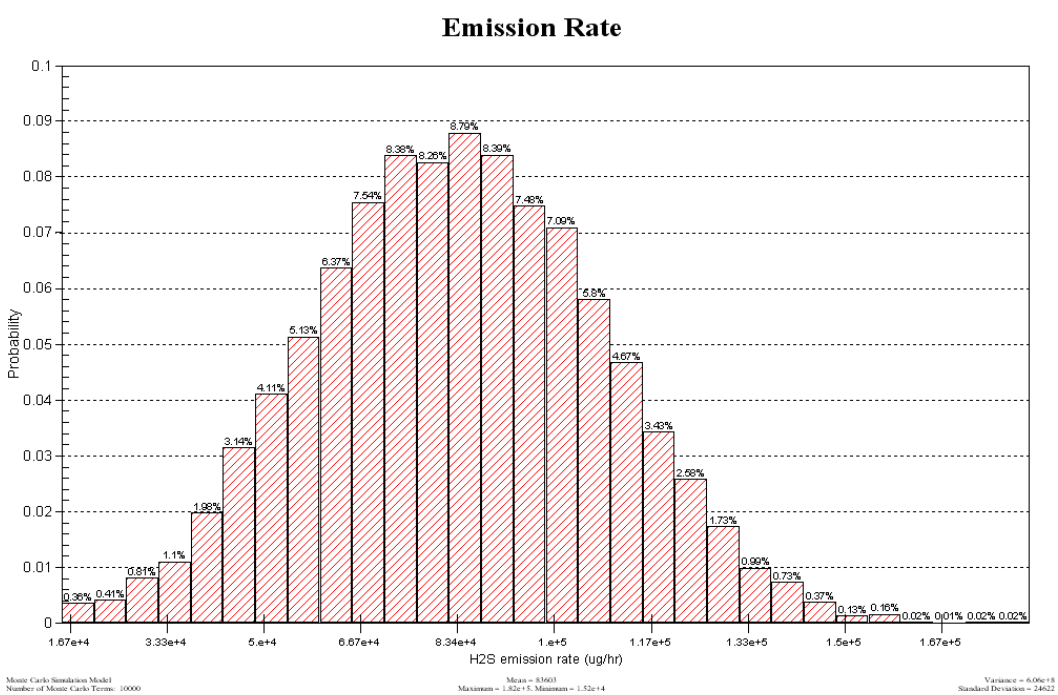


Figure 7. Monte Carlo results of H_2S emission rate for drywall sample 8357 using LBNL 2009 data.

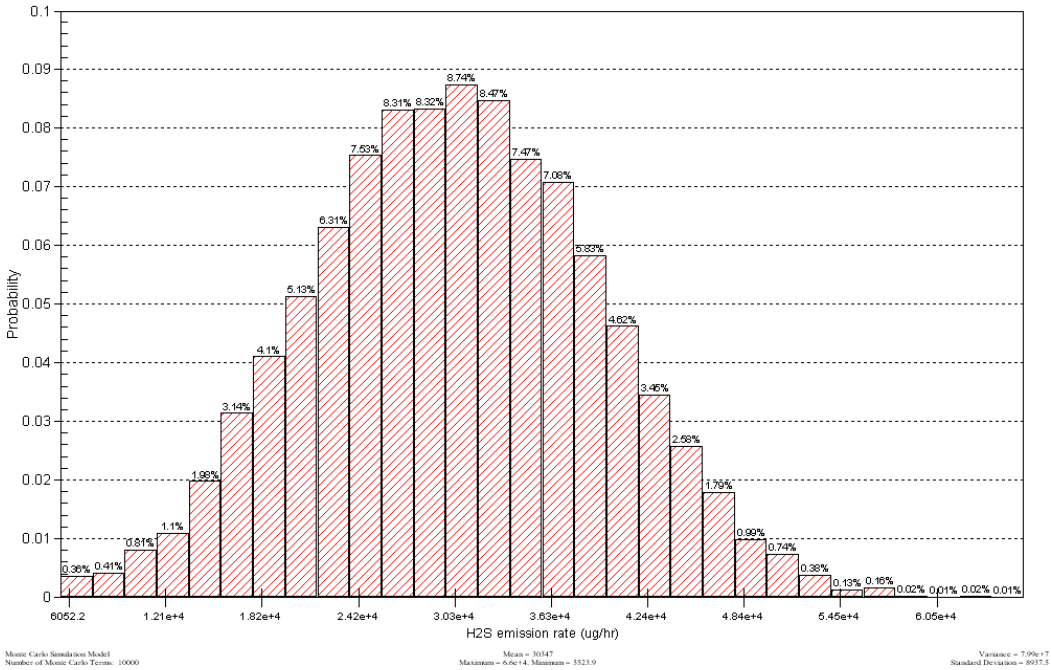


Figure 8. Monte Carlo results of H_2S emission rate for drywall sample 9672 using LBNL 2009 data.

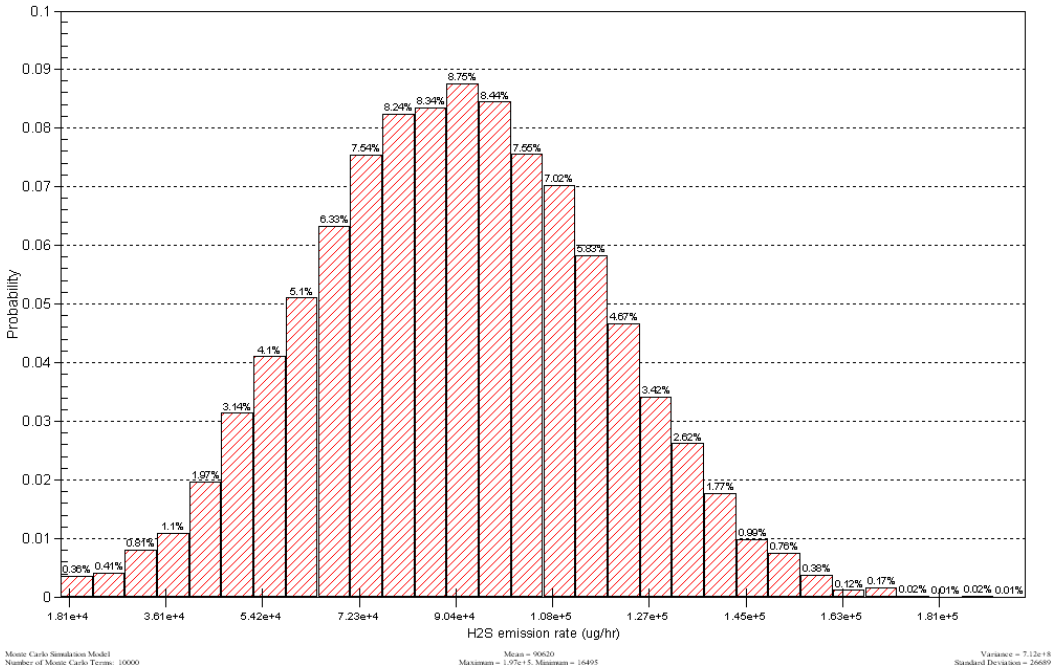


Figure 9. Monte Carlo results of H_2S emission rate for drywall sample 9673 using LBNL 2009 data.

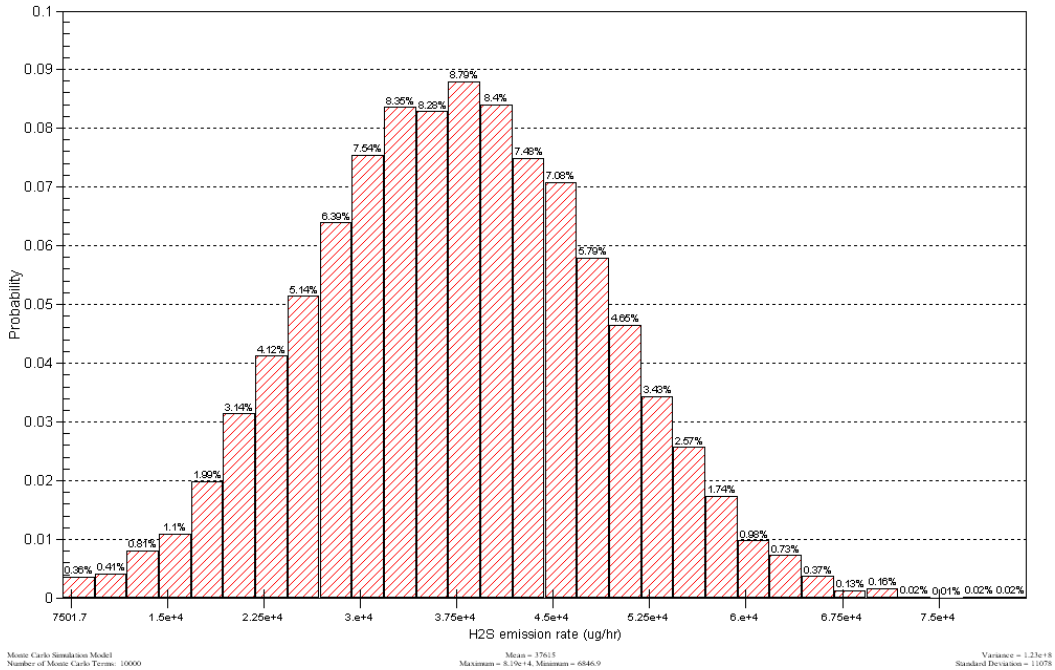


Figure 10. Monte Carlo results of H_2S emission rate for average for yrs 2005 & 2006 using LBNL 2009 data.

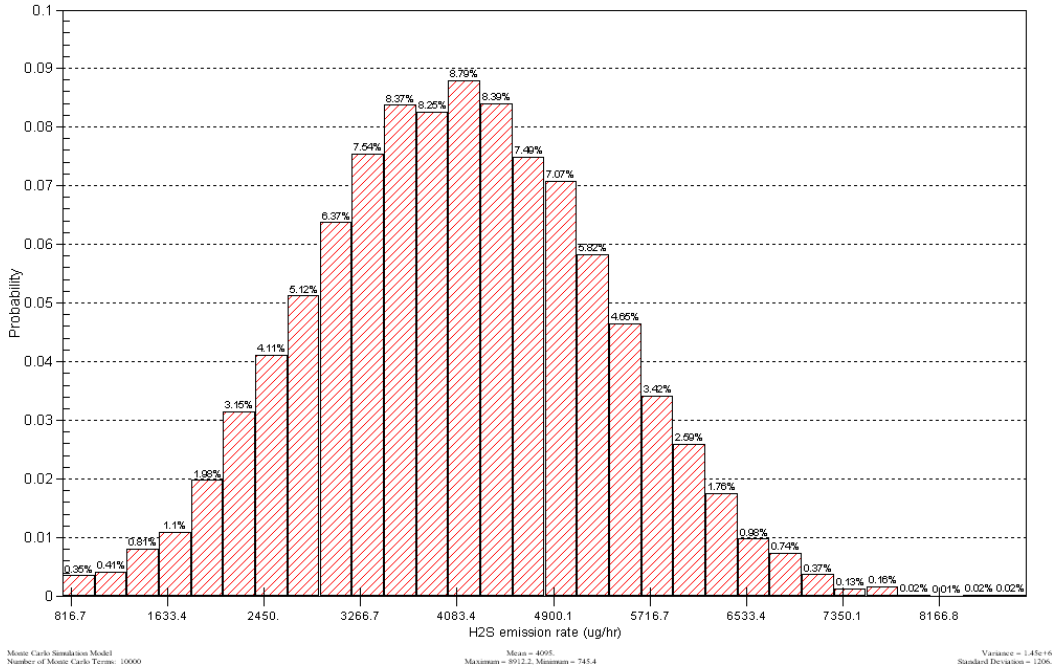


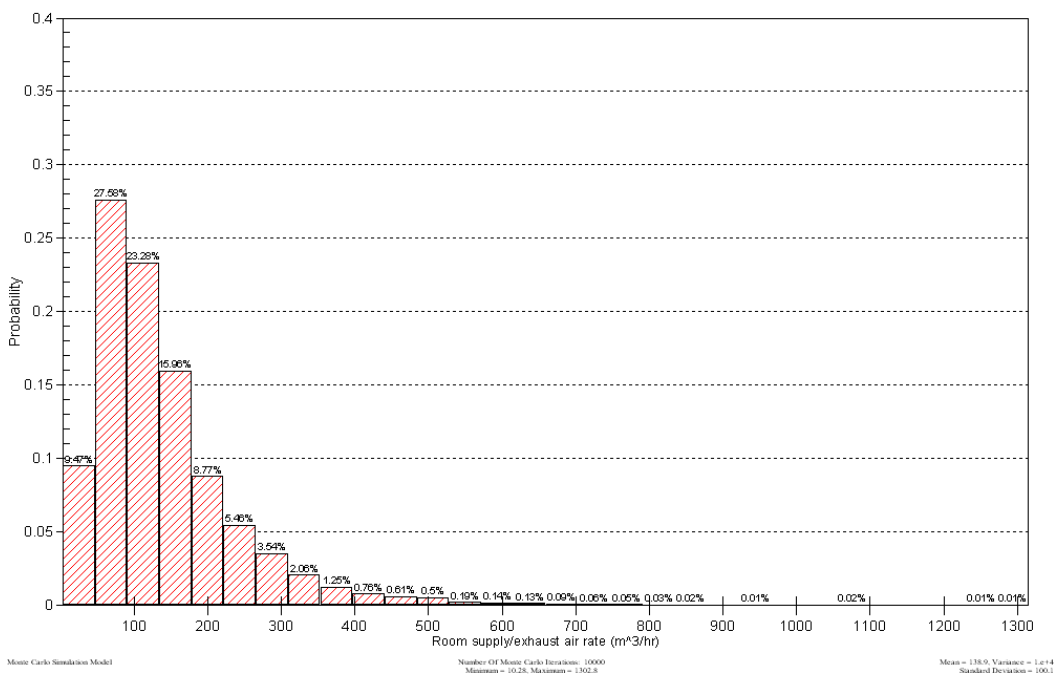
Figure 11. Monte Carlo results of H_2S emission rate for average for yr 2009 using LBNL 2009 data.

4.3 Monte Carlo Simulation of Contaminant Concentrations in a Room Based on the 2009 Data (LBNL 2010)

To perform a Monte Carlo simulation on steady-state concentrations in a room, we first generate statistical distributions for room supply/exhaust air rate (*Q*) and room volume (*V*) and the emission rates (*ER*), Figure 4. The emission rates are already generated as a Monte Carlo outcome as shown in Figures 6 through 11 for H_2S as representative distribution. The statistical distributions for both *Q* and *V* need to be generated to complete the Monte Carlo simulation. The parameters used in Monte Carlo simulation are given in Table 5 for these two variables. The results of Monte Carlo simulation for the parameters *Q* and *V* are shown in Figure 12.

Table 5. Parameters used in Monte Carlo simulation for *Q* and *V*.

Parameters	mean	minimum	maximum	Variance	Runs	Distribution
Q **(m^3/hr)**	137.74	3.26	1316.24	10,000	10,000	lognormal
V (m^3)	626.1	65.1	1645.3	60,000	10,000	normal



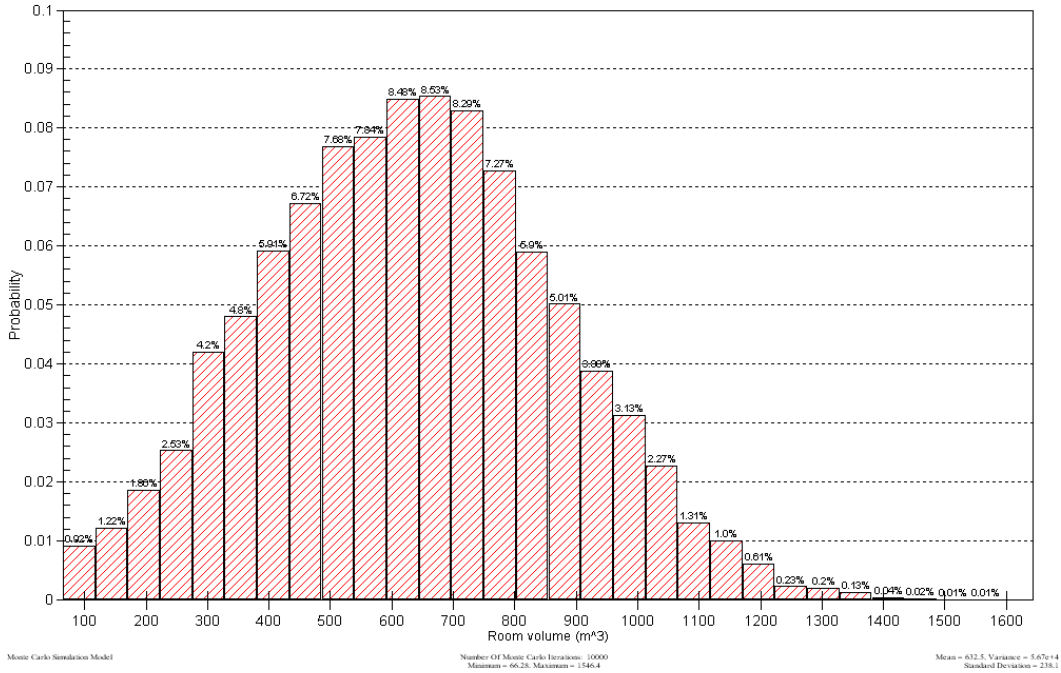


Figure 12. Statistical distributions generated for room supply/exhaust air rate and room volume.

The steady-state concentrations in a room are calculated using the procedure in Figure 4 based on Monte Carlo results of *Q* and *V* and statistical distributions of the emission rates as shown in Figures 6 – 11 for H_2S. The mean steady-state contaminant concentrations of drywall samples are listed in Table 6. The statistical distributions of steady-state H_2S concentrations in room are shown in Figures 13 to 18 for all drywall samples as sample distributions. Based on these results, we may observe that the statistical distributions of steady-state H_2S concentrations are going to be lognormal distributions since the room supply/exhaust air rate follows a lognormal distribution. Another point is that concentrations for average of yrs. 2005 and 2006 are much higher than those for average of yr. 2009.

Table 6. Expected (mean) steady-state concentrations for drywalls samples using LBNL 2009 data (LBNL 2010).

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**	592.1	403.1	14.52	9.05	3.84	NA	NA
	8357	890.1	581.6	19.72	10.00	3.17	8.23	NA
	9672	323.1	100.2	1.22	2.67	0.18	17.78	NA
	9673	964.9	461.2	3.17	7.19	0.27	40.21	0.45
	Average for yrs. 2005 & 2006	400.5	233.9	7.15	4.43	1.81	17.05	0.45

	Average for yrs. 2009	43.6	57.3	0.36	1.63	0.14	16.46	0.27
North Am.	**8037**	NA	NA	3.71	NA	1.58	NA	NA

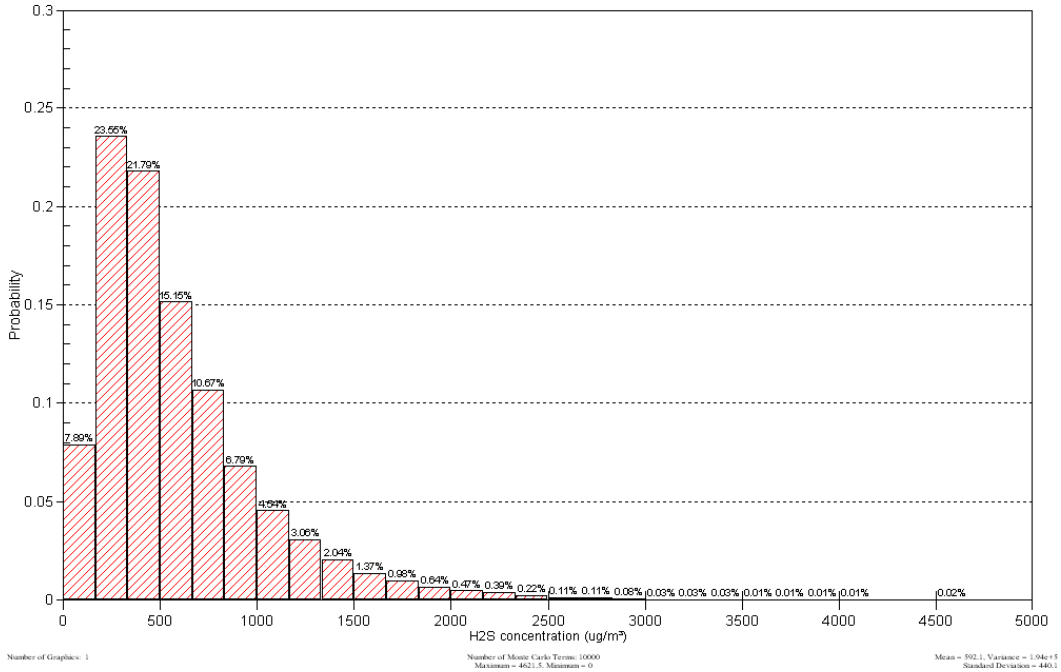


Figure 13. Monte Carlo results of H_2S concentration for drywall sample 7339 using LBNL 2009 data.

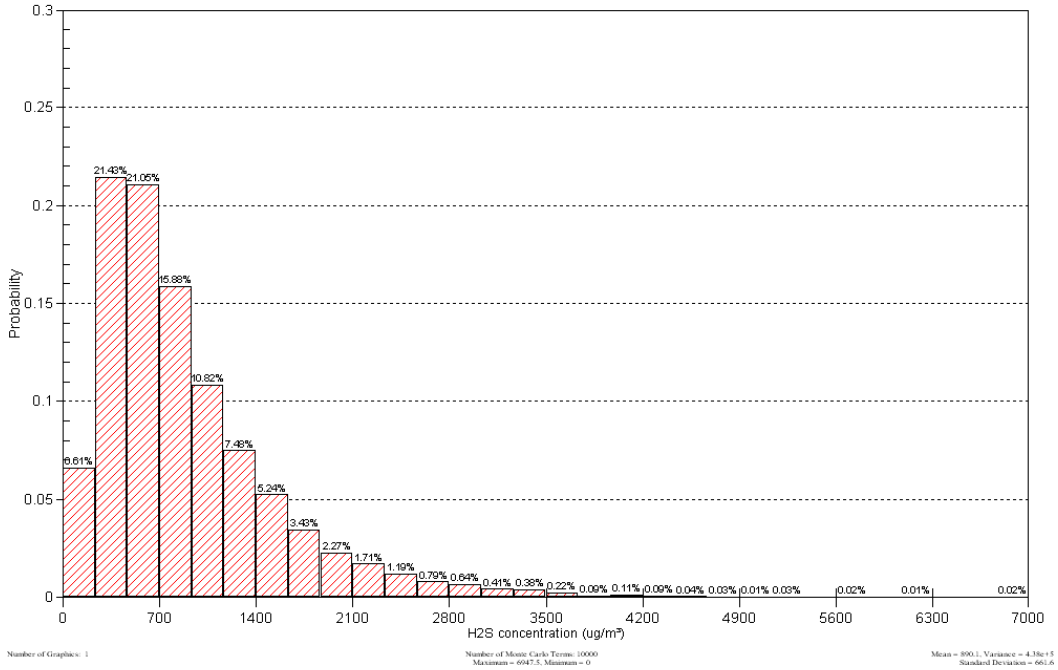


Figure 14. Monte Carlo results of H_2S concentration for drywall sample 8357 using LBNL 2009 data.

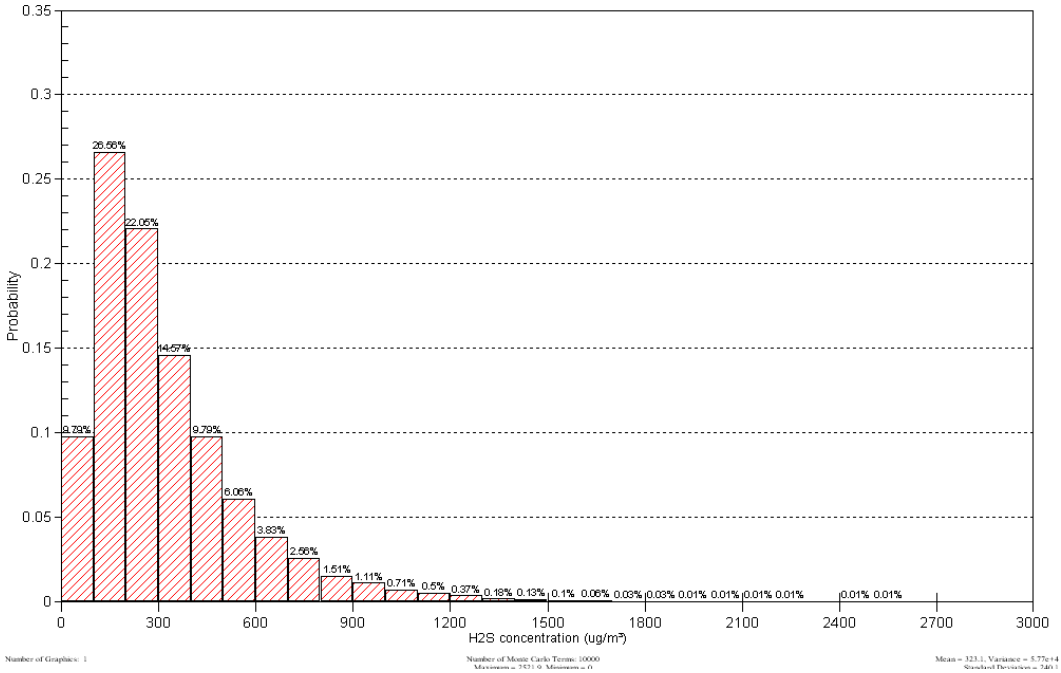


Figure 15. Monte Carlo results of H_2S concentration for drywall sample 9672 using LBNL 2009 data.

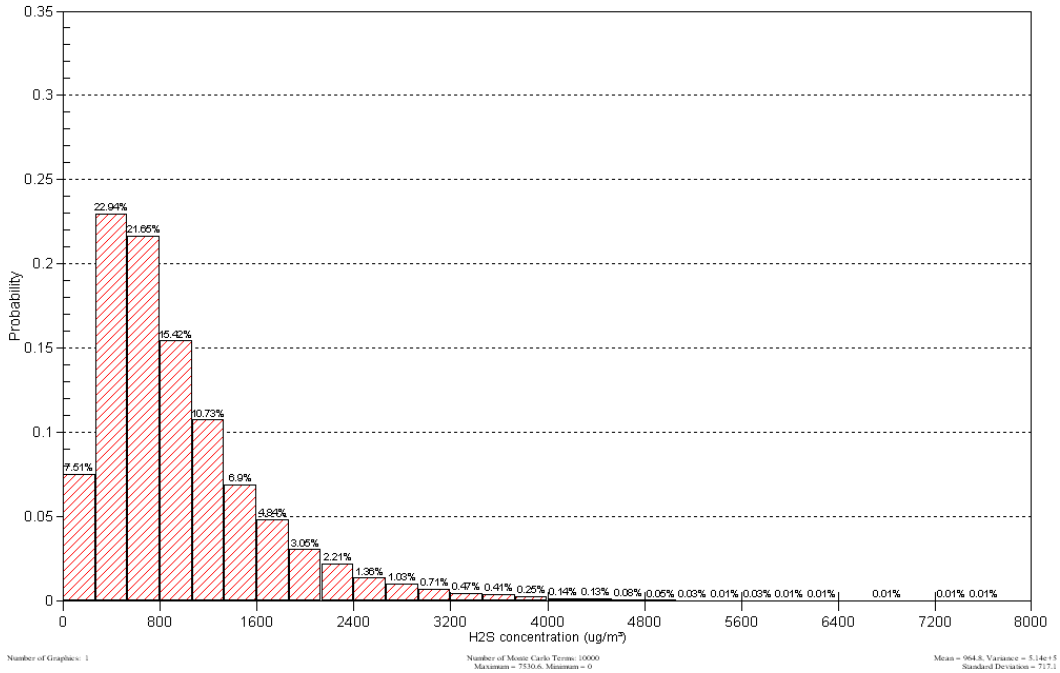


Figure 16. Monte Carlo results of H_2S concentration for drywall sample 9673 using LBNL 2009 data.

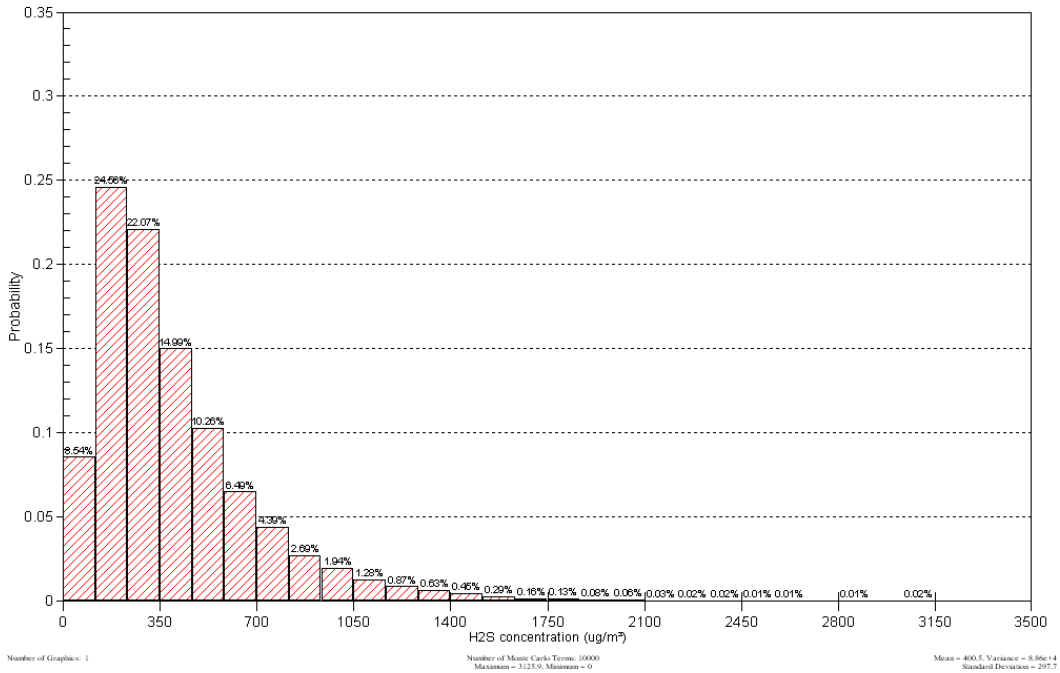


Figure 17. Monte Carlo results of H_2S concentration for average for yrs 2005 & 2006 using LBNL 2009 data.

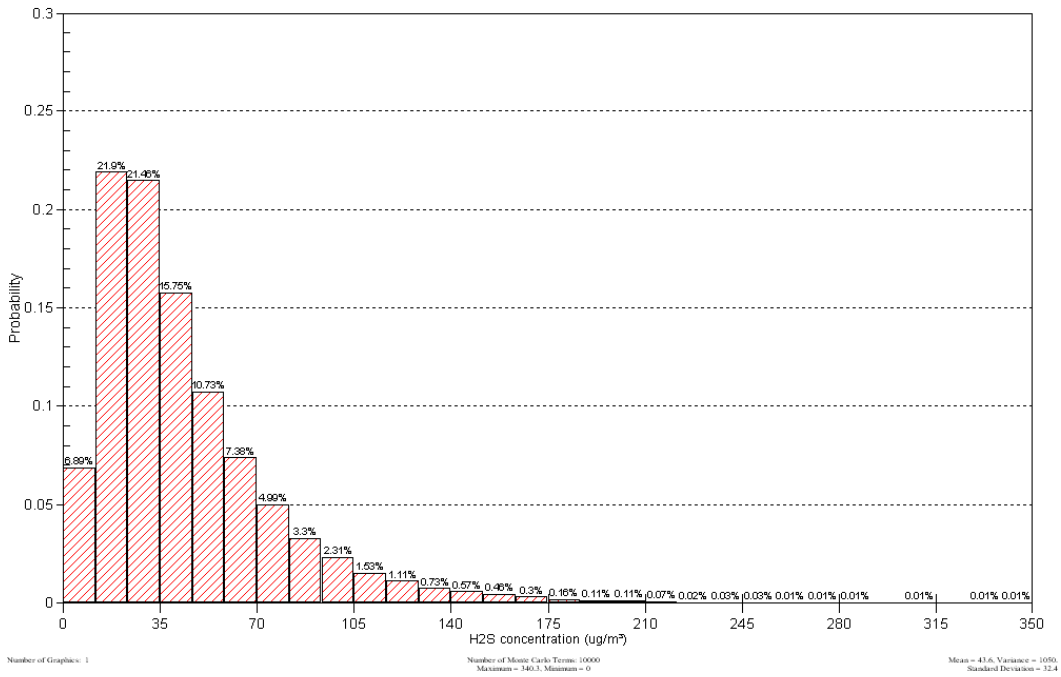


Figure 18. Monte Carlo results of H_2S concentration for average for yr 2009 using LBNL 2009 data.

4.4 Monte Carlo Simulation of Emission Rates Based on the 2010 Data (LBNL 2011)

For the 2010 experimental data (LBNL 2011), we can perform the uncertainty analyses for emission rates of drywall samples and room concentrations using two different cases which include: (A) using the emission rates at mean ambient temperature (*T*) at 25 ^{o}C and mean relative humidity (*RH*) at 49%; and, (B) using the emission rates at mean ambient temperature (*T*) at 25.4 ^{o}C and mean relative humidity (*RH*) at 60%.

Case A: Monte Carlo Analysis at mean ambient temperature *T* = 25 ^{o}C and mean relative humidity *RH* = 49%

In this case, the Monte Carlo simulation procedures are exactly the same as that used for the 2009 data (LBNL, 2010). The distribution of the area of contaminated drywall shown in Figure 5, together with the emission factors listed in Table 2, is used to calculate the distributions of emission rates of drywalls using the procedure shown in Figure 3. The mean emission rates for drywalls are listed in Table 7. When compared with the results given in Table 5B of Phase I report (Aral and Guan, 2013) these results are consistent with the deterministic analysis results. Figures 19 to 24 show the Monte Carlo simulation results of H_2S emission rates for all drywall samples. It can be clearly seen from these figures that the statistical distributions of H_2S emission rates for drywall samples are likely to be normal distributions.

Table 7. Expected (mean) emission rates for drywalls using the data developed in LBNL (2011) for Case A.

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**	3534.2	5675.2	68.0	263.4	12.7	645.7	46.7
	8357	1559.0	8194.2	29.7	161.4	8.5	632.9	76.5
	9672	2344.8	7102.5	21.2	182.7	12.7	858.1	29.7
	9673	3508.8	3075.5	17.0	263.4	17.0	599.0	51.0
	Modeled drywall	2736.7	6011.8	34.0	217.7	12.7	683.9	51.0
North Am.	**8037**	1117.2	675.4	4.2	51.0	8.5	467.3	21.2

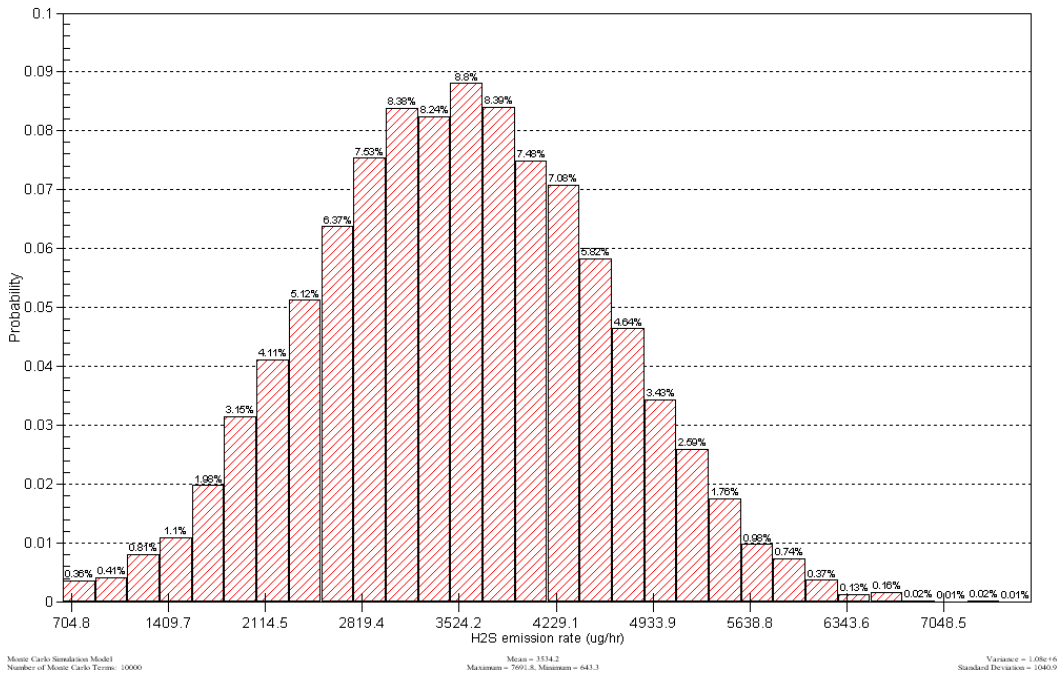


Figure 19. Monte Carlo results of H_2S emission rate for drywall sample 7339 using LBNL 2010 data for Case A.

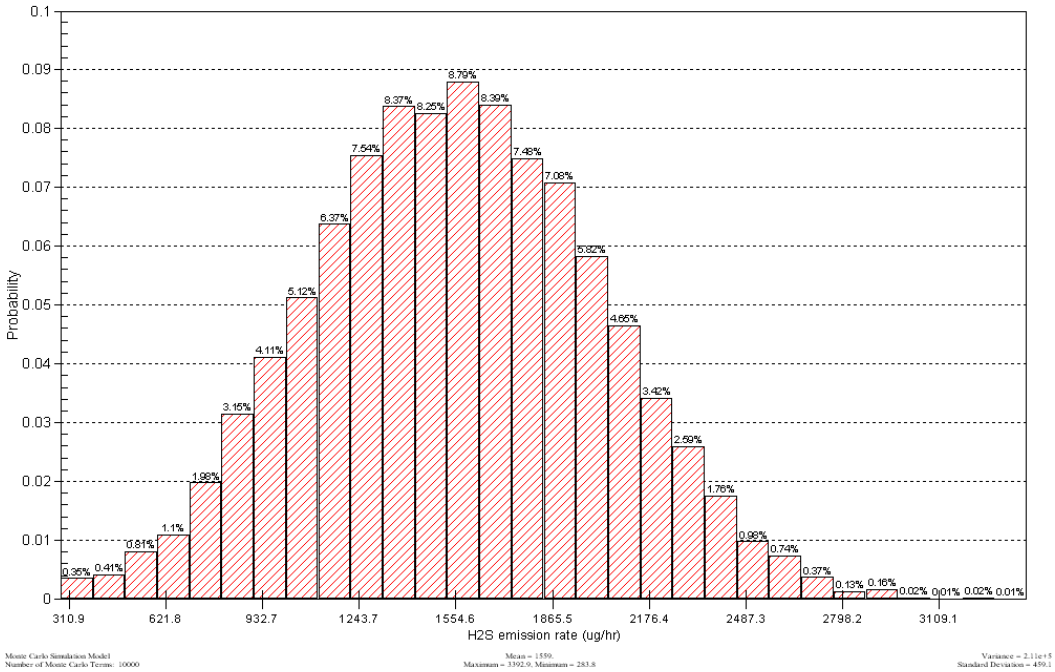


Figure 20. Monte Carlo results of H_2S emission rate for drywall sample 8357 using LBNL 2010 data for Case A.

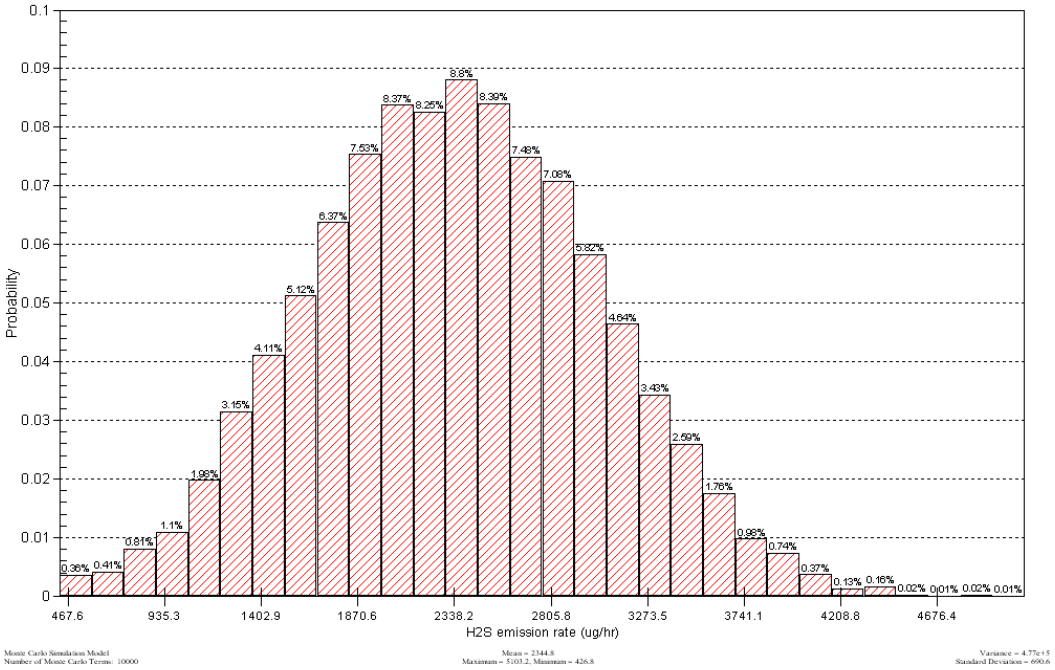


Figure 21. Monte Carlo results of H_2S emission rate for drywall sample 9672 using LBNL 2010 data for Case A.

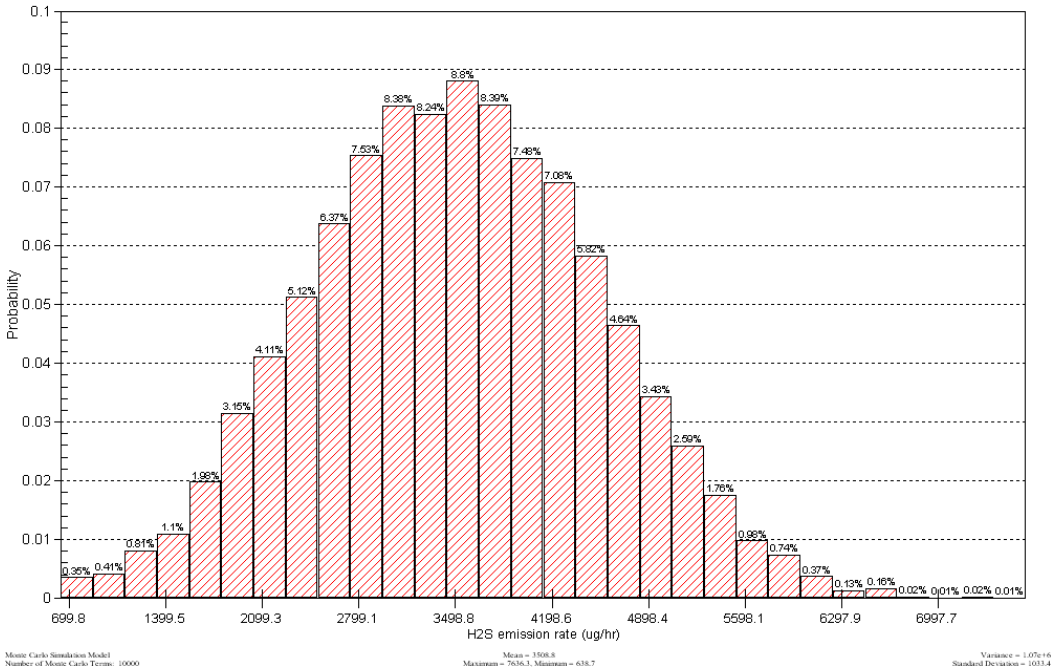


Figure 22. Monte Carlo results of H_2S emission rate for drywall sample 9673 using LBNL 2010 data for Case A.

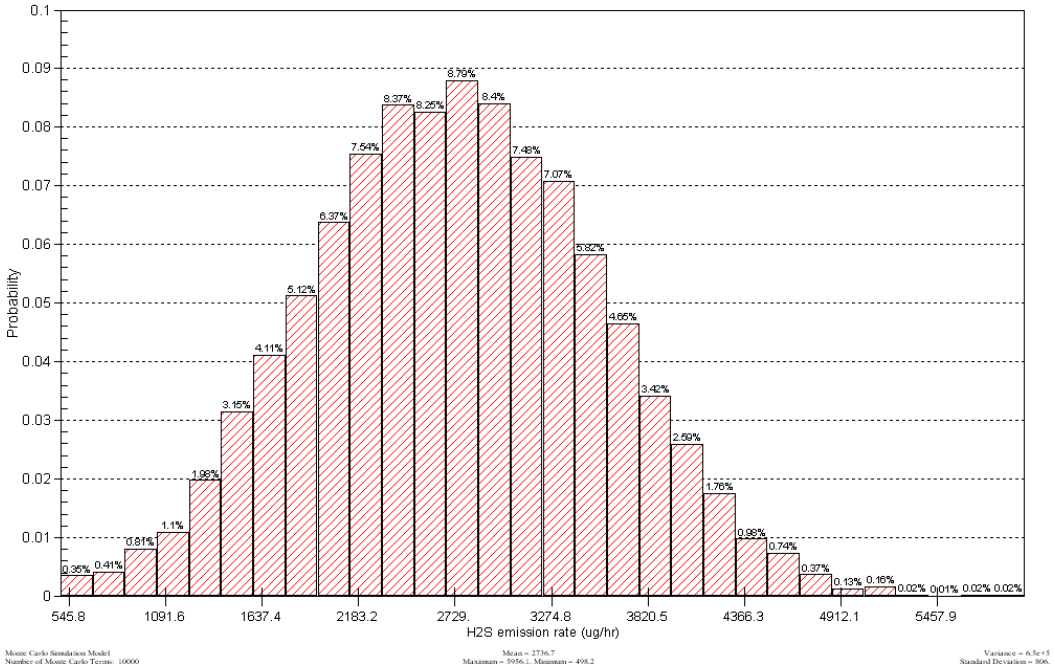


Figure 23. Monte Carlo results of H_2S emission rate for modeled drywall using LBNL 2010 data for Case A.

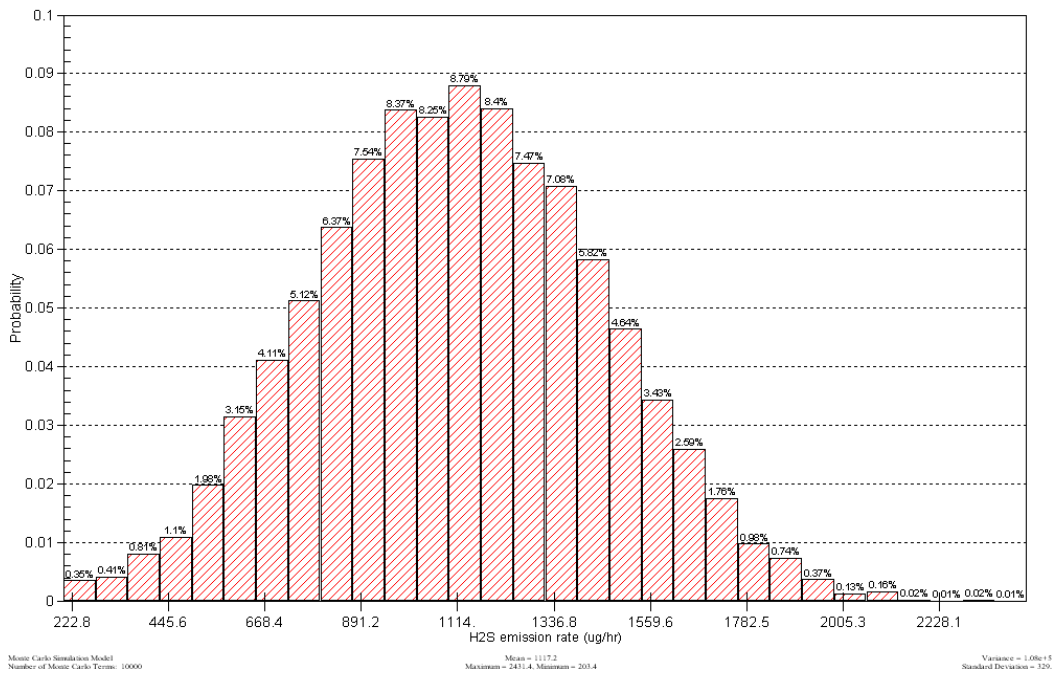


Figure 24. Monte Carlo results of H_2S emission rate for drywall sample 8037 using LBNL 2010 data for Case A.

Case B: Monte Carlo Analysis at mean ambient temperature *T* = 25.4 °C and mean relative humidity *RH* = 60%

In this case there are no experimental data available at *T* = 25.4 °C and *RH* = 60%. Equation (1) of Phase I study report, obtained from the 2010 data (LBNL 2011), will be used to estimate the emission rates of drywall samples for this case. To estimate statistical distributions for emission rates in a Monte Carlo sense, we have used the statistical distributions for input variables that appear in the empirical emission rate model discussed earlier in the Phase I study. These input variables include the area of contaminated drywall (*A*), the ambient temperature (*T*) and relative humidity in a room (*RH*). The parameters of input variables used in Monte Carlo simulation are listed in Table 8. The distribution of the area of contaminated drywall is shown in Figure 5 and the distributions of the ambient temperature (*T*) and relative humidity in a room are show in Figure 25.

Table 8. Parameters used in estimation of emission rates for drywalls.

Variables	mean	minimum	maximum	Variance	Runs	Distribution
A (m^3)	424.7	77.1	927.7	16,000	10,000	normal
T (°C)	25.4	20.8	31.2	2.5	10,000	normal
RH (%)	60	40	80	36	10,000	normal

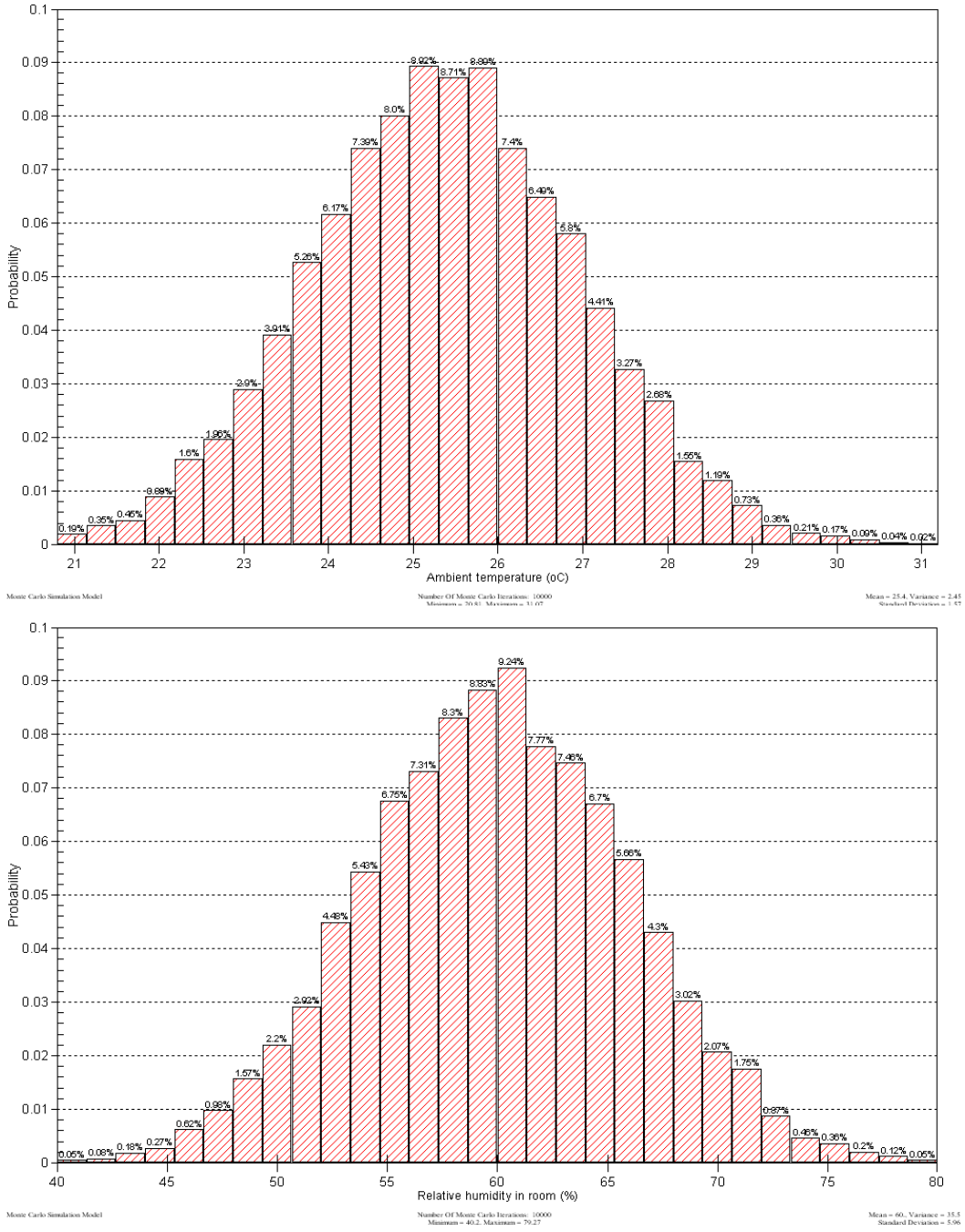


Figure 25. Monte Carlo results for ambient temperature and relative humidity in a room for Case B Monte Carlo analysis.

Using these statistical distributions, the emission rates for all drywalls are estimated using Equation (1) of Phase I study report (Aral and Guan, 2013) based on the procedure given in Figure 2 in a Monte Carlo sense. The mean values of emission rates obtained in the Monte Carlo simulation are listed in Table 9. The results of H_2S emission rates for drywalls are shown in

Figures 26 to 31 for each drywall sample. These results show that H_2S emission rates follow normal distributions.

Table 9. Mean emission rates for drywalls using the data developed in LBNL (2011) for Case B.

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**	3739.2	1275.6	2923.3	332.1	60.2	15.2	215.9
	8357	4026.9	1177.9	5482.8	471.4	155.5	15.9	92.5
	9672	3191.3	1375.1	3291.0	344.0	66.6	22.0	43.8
	9673	3348.9	1026.0	2285.3	404.7	82.9	23.1	48.9
	Modeled drywall	3558.8	1206.4	3309.6	384.2	84.6	18.7	80.9
North American	**8037**	1143.6	680.2	1454.2	119.0	38.6	12.7	9.6

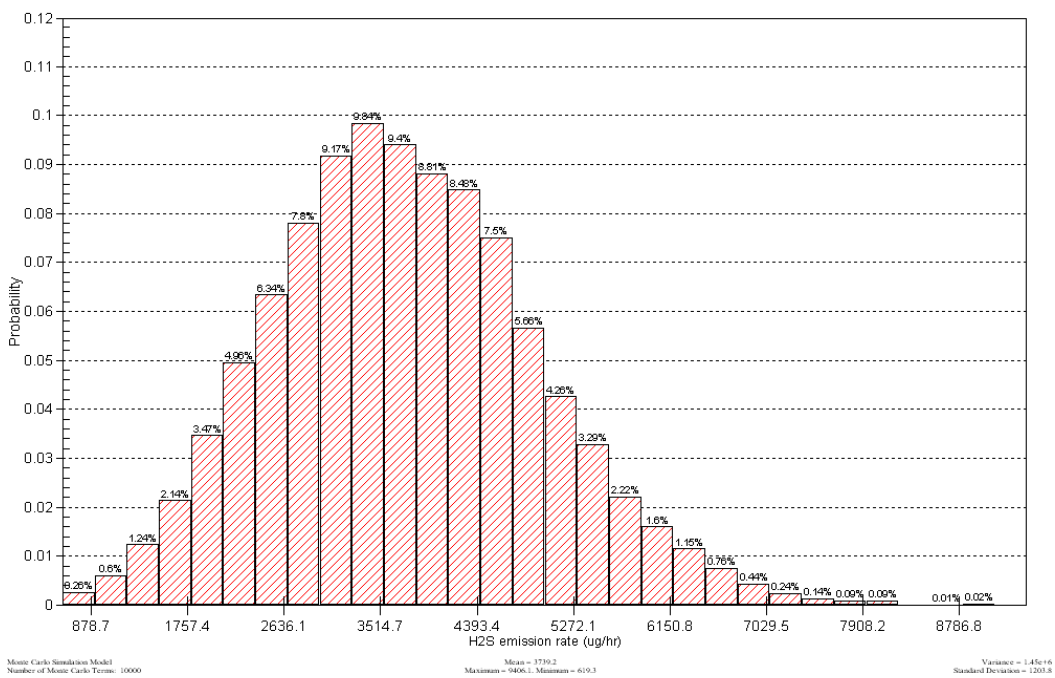


Figure 26. Monte Carlo results of H_2S emission rate for drywall sample 7339 using LBNL 2010 data for Case B.

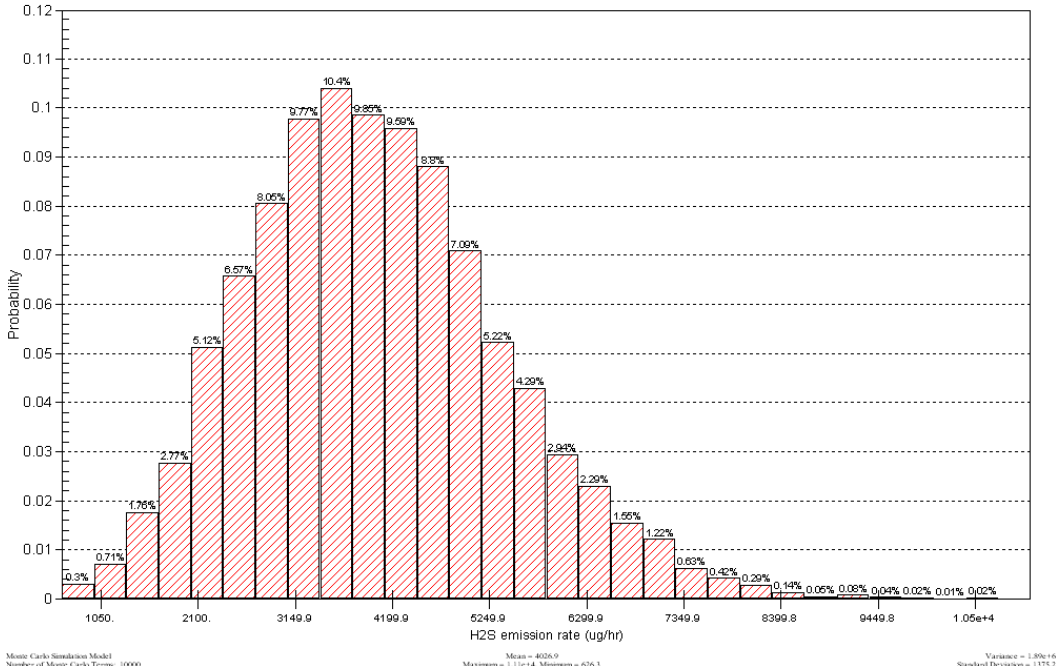


Figure 27. Monte Carlo results of H_2S emission rate for drywall sample 8357 using LBNL 2010 data for Case B.

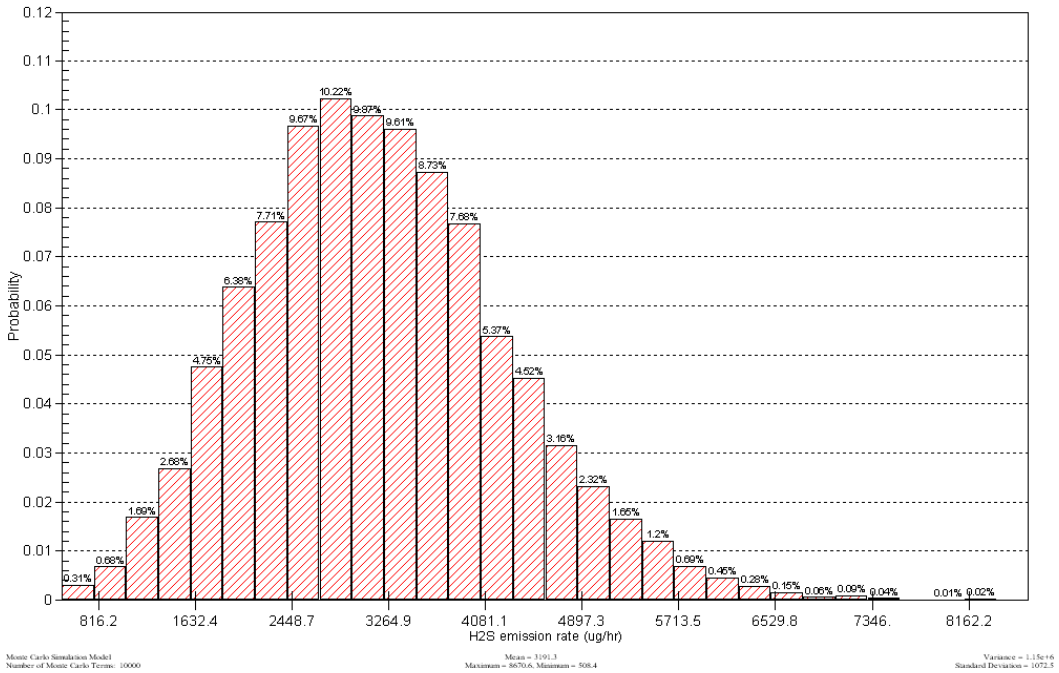


Figure 28. Monte Carlo results of H_2S emission rate for drywall sample 9672 using LBNL 2010 data for Case B.

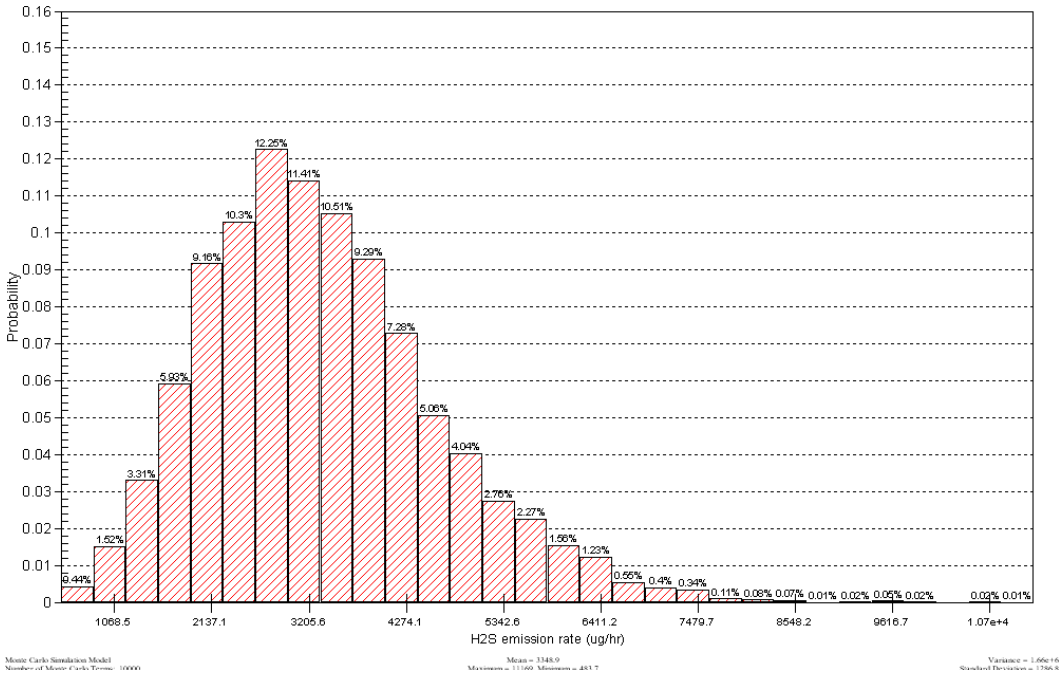


Figure 29. Monte Carlo results of H_2S emission rate for drywall sample 9673 using LBNL 2010 data for Case B.

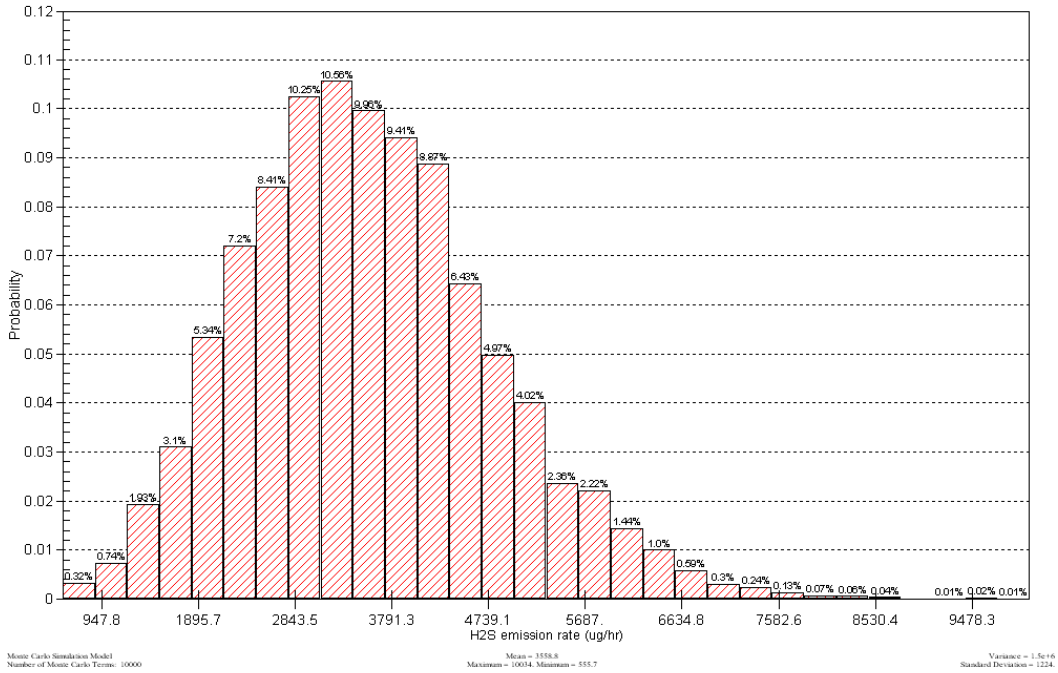


Figure 30. Monte Carlo results of H_2S emission rate for modeled drywall using LBNL 2010 data for Case B.

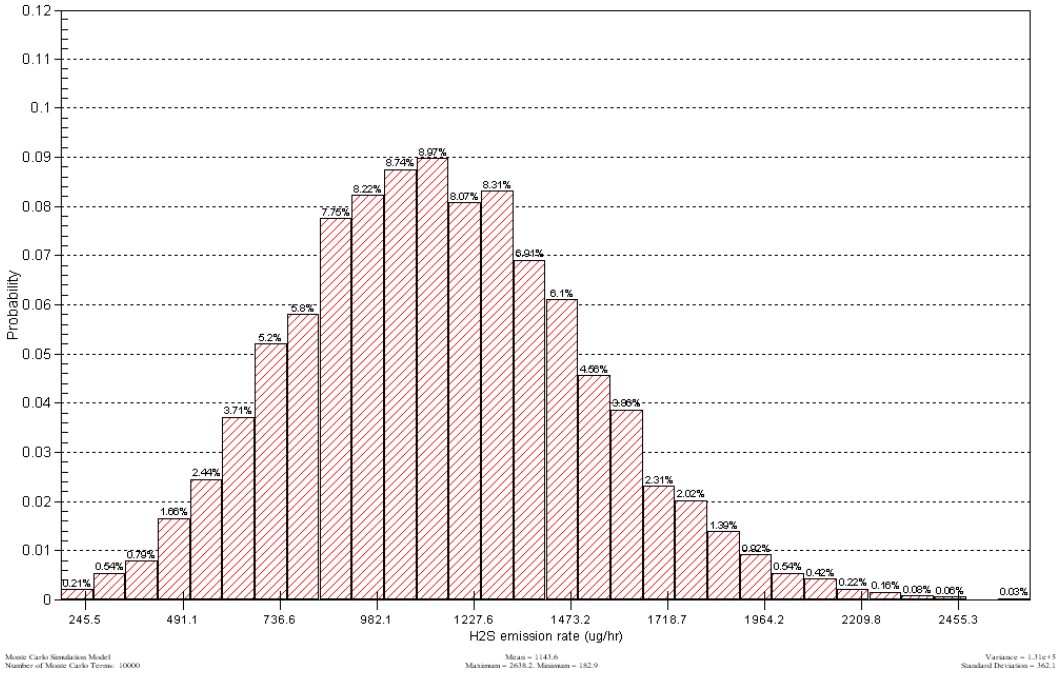


Figure 31. Monte Carlo results of H_2S emission rate for drywall sample 8037 using LBNL 2010 data for Case B.

4.5 Monte Carlo Simulation of Contaminant Concentrations in a Room Based on the 2010 Data (LBNL 2011)

Monte Carlo simulation for contaminant concentrations in a room based on the 2010 Data (LBNL 2011) includes two cases: (A) Monte Carlo simulations at mean ambient temperature (*T*) at 25 ^{o}C and mean relative humidity (*RH*) at 49%; and, (B) Monte Carlo simulations at mean ambient temperature (*T*) at 25.4 ^{o}C and mean relative humidity (*RH*) at 60%.

Case A: Monte Carlo Analysis at mean ambient temperature *T* = 25 ^{o}C and mean relative humidity *RH* = 49%

In this case, we apply the procedure of Monte Carlo simulation shown in Figure 4 to obtain statistical distribution of steady-state concentrations in a room. As shown in Equation (1), the concentration in a room is a function of emission rate (*ER*), room supply/exhaust air rate (*Q*) and room volume (*V*). The emission rates are already obtained as a Monte Carlo outcome based on statistical distributions of the parameters of the empirical model used in the simulation of the Emission Rates. The statistical distributions on room supply/exhaust air rate (*Q*) and room volume (*V*) are generated based on the specified parameters used in Monte Carlo simulation as listed in Table 5 and the resulting statistical distributions are shown in Figure 12. Using this procedure, we obtain the mean steady-state concentrations for all drywall samples as listed in Table 10. The resulting statistical distributions for H_2S concentrations are shown in Figures 32 and 37 for all drywall samples. The calculations are done for all chemicals as seen in Table 10.

Table 10. Mean steady-state concentrations for drywalls using the data developed in LBNL (2011) for Case A.

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**	37.63	60.43	0.72	2.80	0.14	6.87	0.50
	8357	16.60	87.25	0.32	1.72	0.09	6.74	0.81
	9672	24.97	75.62	0.23	1.94	0.14	9.14	0.32
	9673	37.36	32.75	0.18	2.80	0.18	6.38	0.54
	Modeled drywall	29.14	64.01	0.36	2.32	0.14	7.28	0.54
North Am.	**8037**	11.90	7.19	0.05	0.54	0.09	4.98	0.23

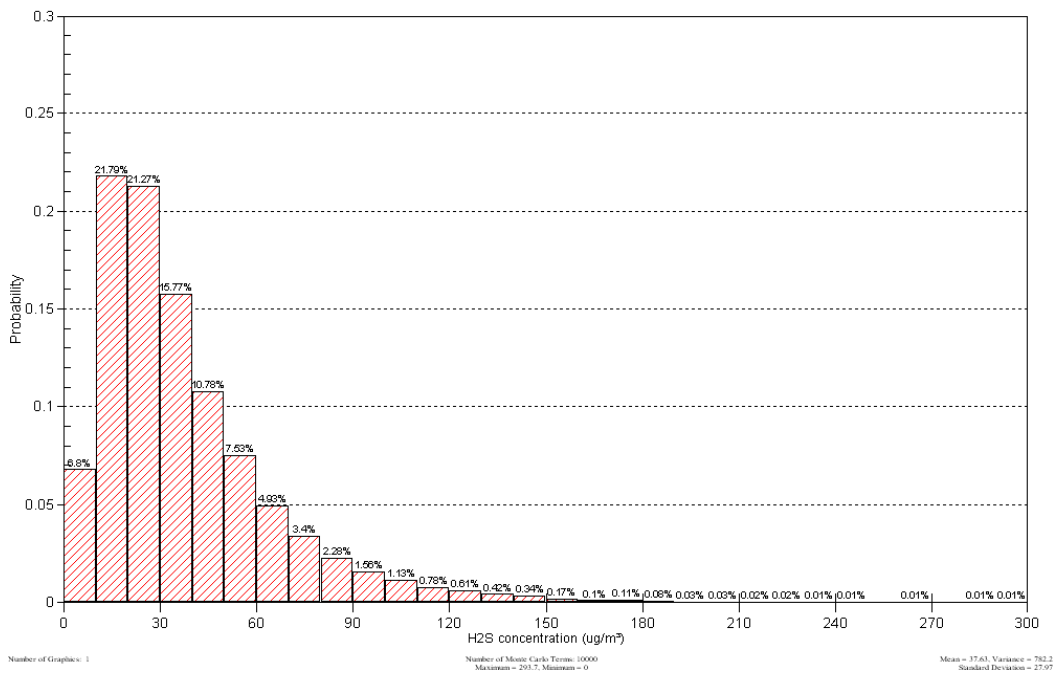


Figure 32. Monte Carlo results of H_2S concentration for drywall sample 7339 using LBNL 2010 data for Case A.

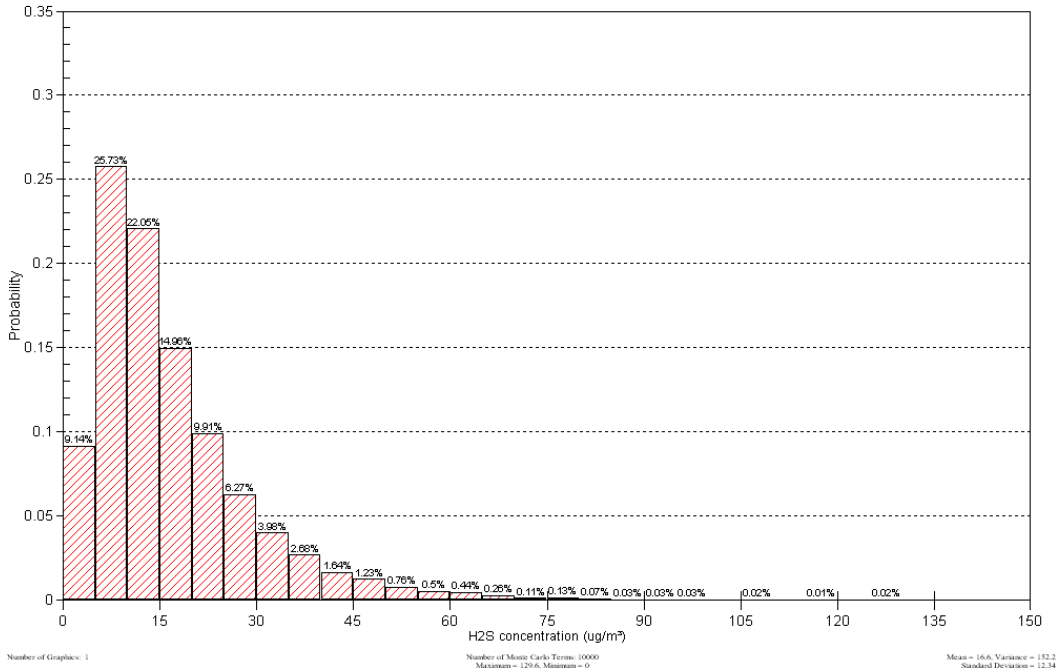


Figure 33. Monte Carlo results of H_2S concentration for drywall sample 8357 using LBNL 2010 data for Case A.

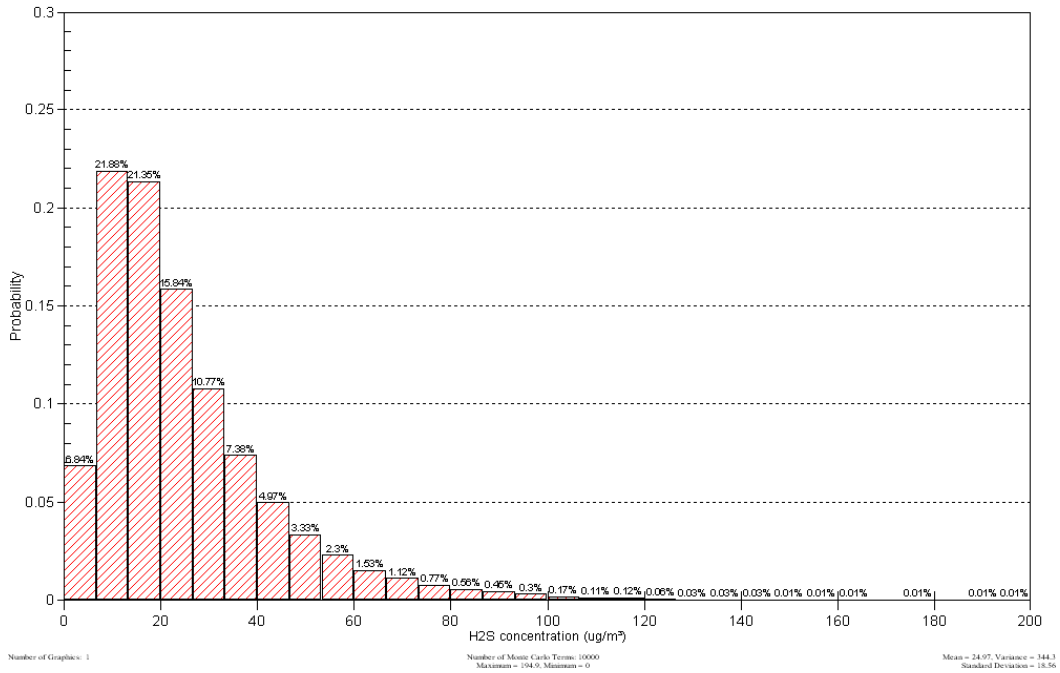


Figure 34. Monte Carlo results of H_2S concentration for drywall sample 9672 using LBNL 2010 data for Case A.

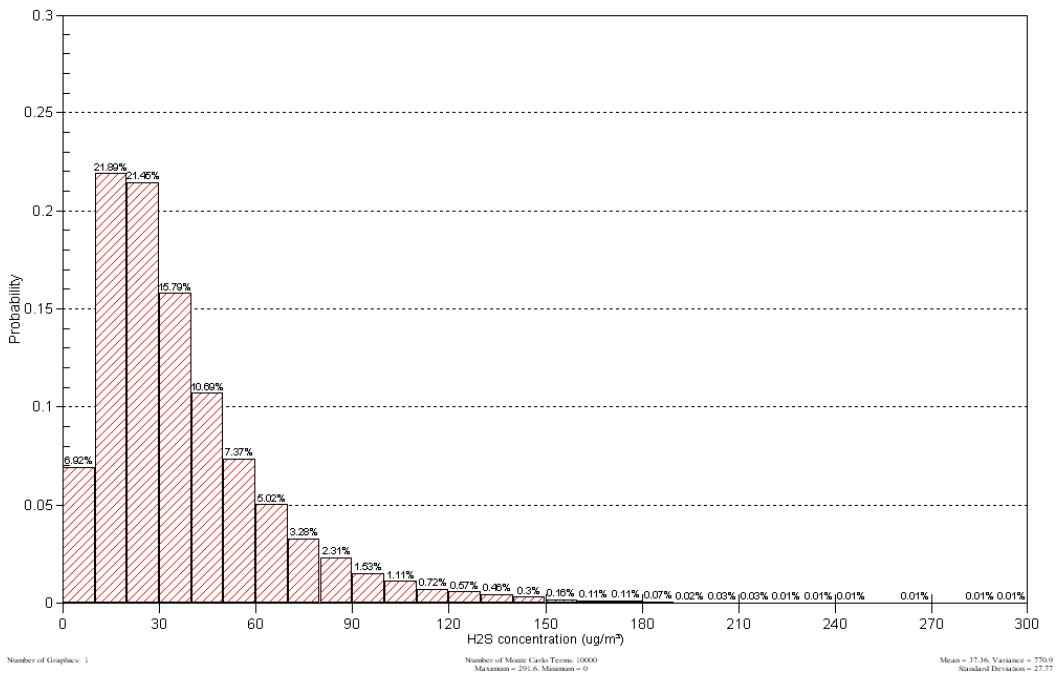


Figure 35. Monte Carlo results of H_2S concentration for drywall sample 9673 using LBNL 2010 data for Case A.

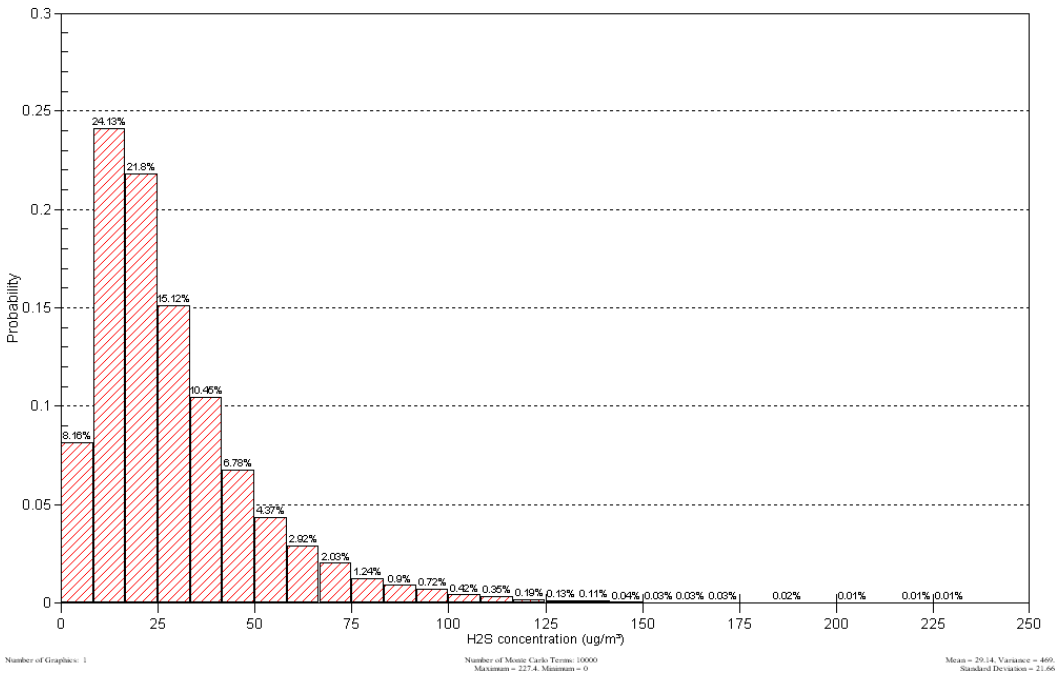


Figure 36. Monte Carlo results of H_2S concentration for modeled drywall using LBNL 2010 data for Case A.

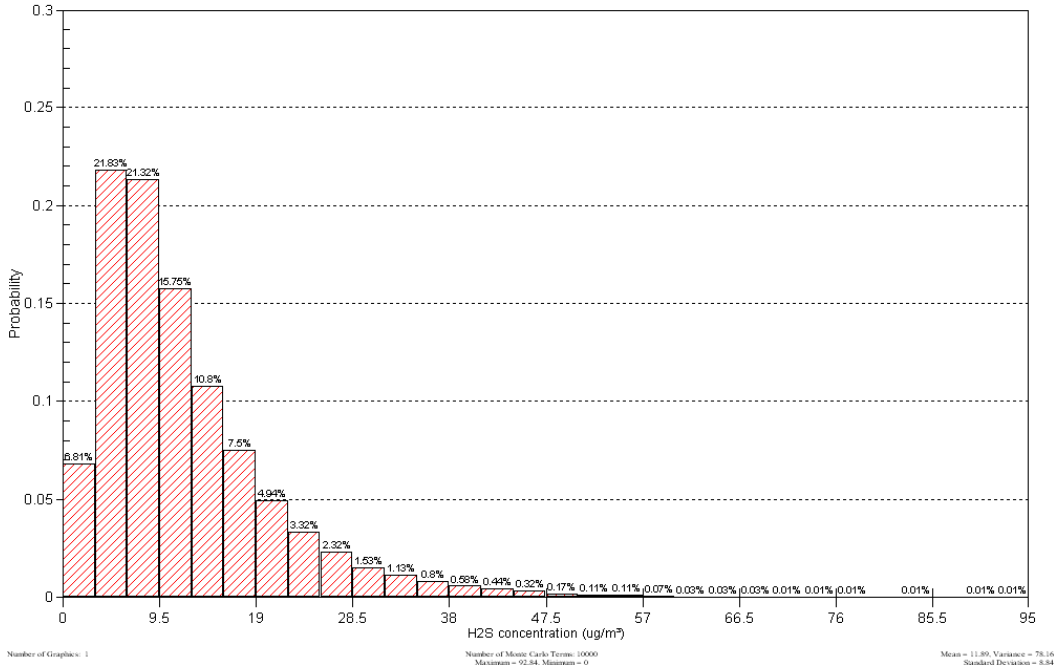


Figure 37. Monte Carlo results of H_2S concentration for drywall sample 8037 using LBNL 2010 data for Case A.

Case B: Monte Carlo Analysis at mean ambient temperature *T* = 25.4 ^{o}C and mean relative humidity *RH* = 60%

In this case, we apply the procedure of Monte Carlo simulation shown in Figure 2 to obtain the statistical distribution of the steady-state concentrations in a room. For this case, the emission rates are obtained as a Monte Carlo outcome based on statistical distributions of the parameters of the empirical model used in the simulation of the *ER* earlier. The statistical distributions on room supply/exhaust air rate (*Q*) and room volume (*V*) are generated based on the specified parameters used in Monte Carlo simulation as listed in Table 5 and the resulting statistical distributions are shown in Figure 12. Using this procedure, we obtain the mean steady-state concentrations for all drywall samples as listed in Table 11. The resulting statistical distributions for H_2S concentrations are shown in Figures 38 and 43 for drywall samples as sample outcome.

Table 11. Mean steady-state concentrations for drywalls using the data developed in LBNL (2011) for Case B.

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**	39.83	13.59	31.15	3.54	0.64	0.16	2.30
	8357	42.91	12.55	58.44	5.02	1.66	0.17	0.99
	9672	34.00	14.65	35.08	3.67	0.71	0.23	0.47
	9673	35.69	10.93	24.37	4.31	0.88	0.25	0.52
	Modeled drywall	37.92	12.85	35.28	4.09	0.90	0.20	0.86
North Am.	**8037**	12.18	7.24	15.49	1.27	0.41	0.14	0.10

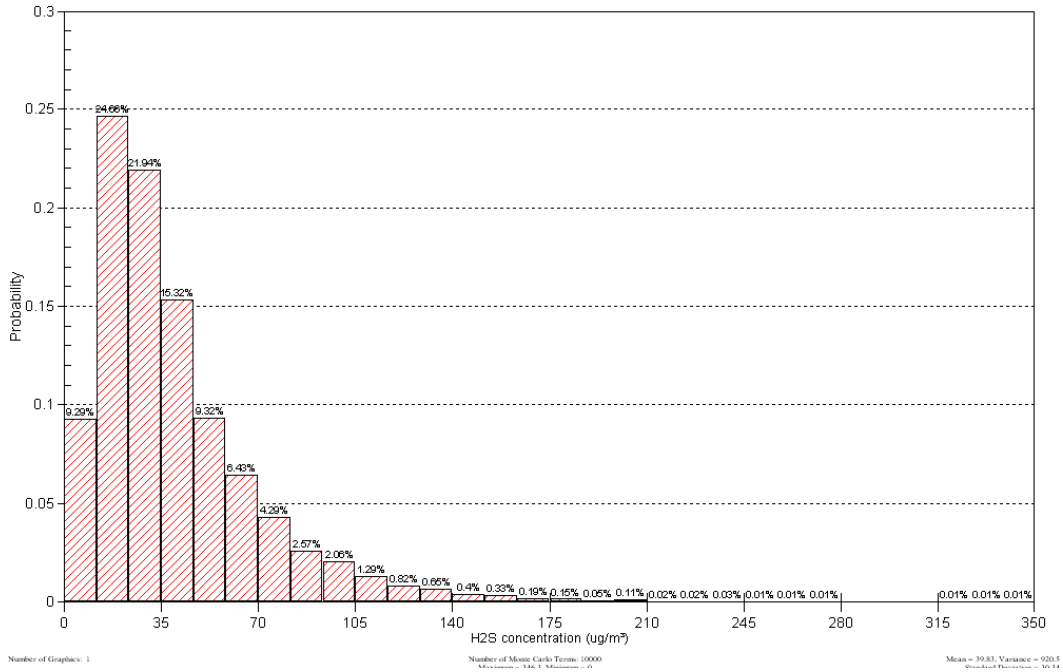


Figure 38. Monte Carlo results of H_2S concentration for drywall sample 7339 using LNBL 2010 data for Case B.

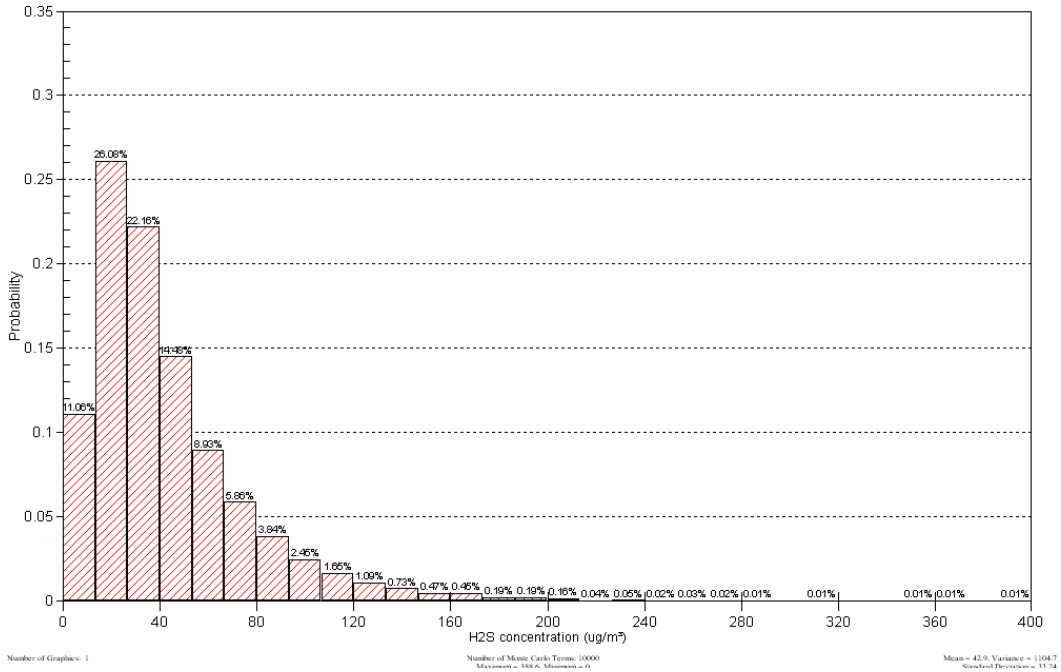


Figure 39. Monte Carlo results of H_2S concentration for drywall sample 8357 using LNBL 2010 data for Case B.

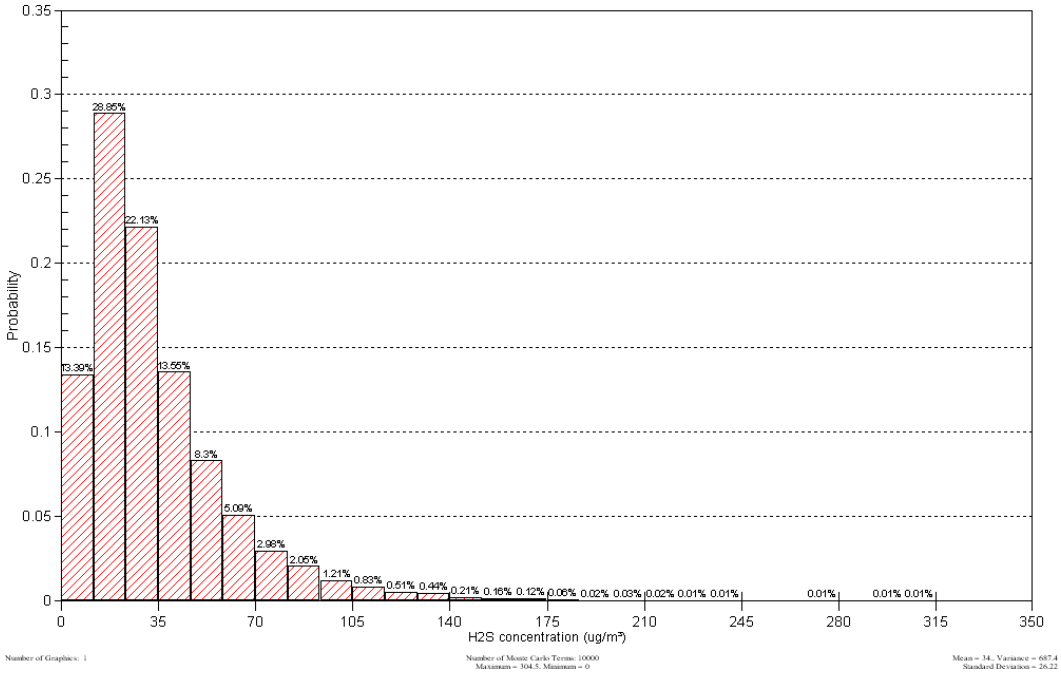


Figure 40. Monte Carlo results of H_2S concentration for drywall sample 9762 using LNBL 2010 data for Case B.

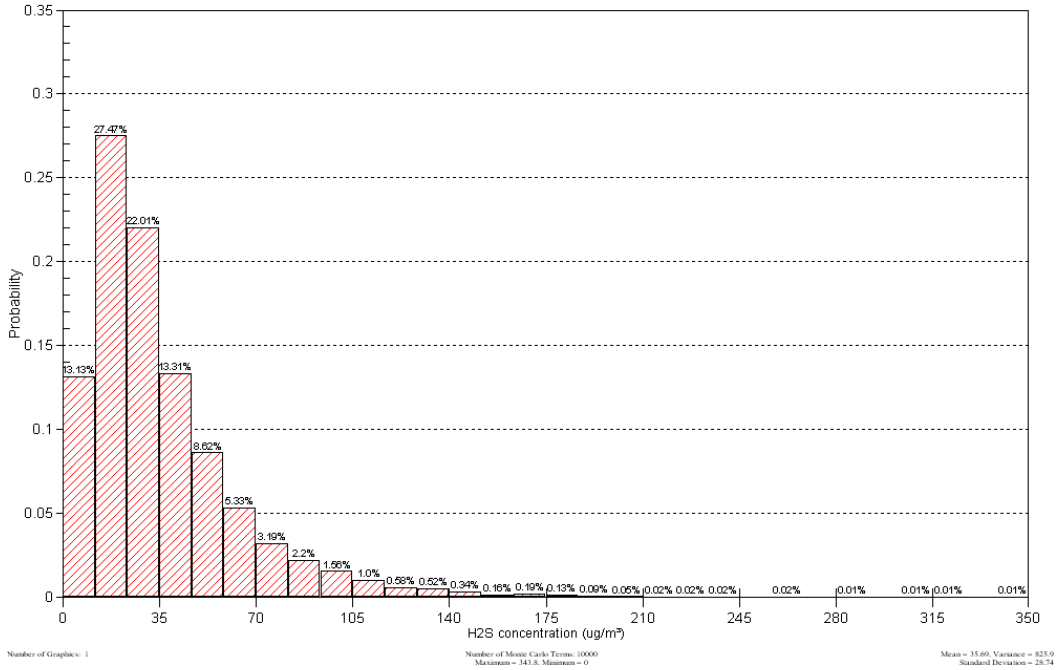


Figure 41. Monte Carlo results of H_2S concentration for drywall sample 9763 using LNBL 2010 data for Case B.

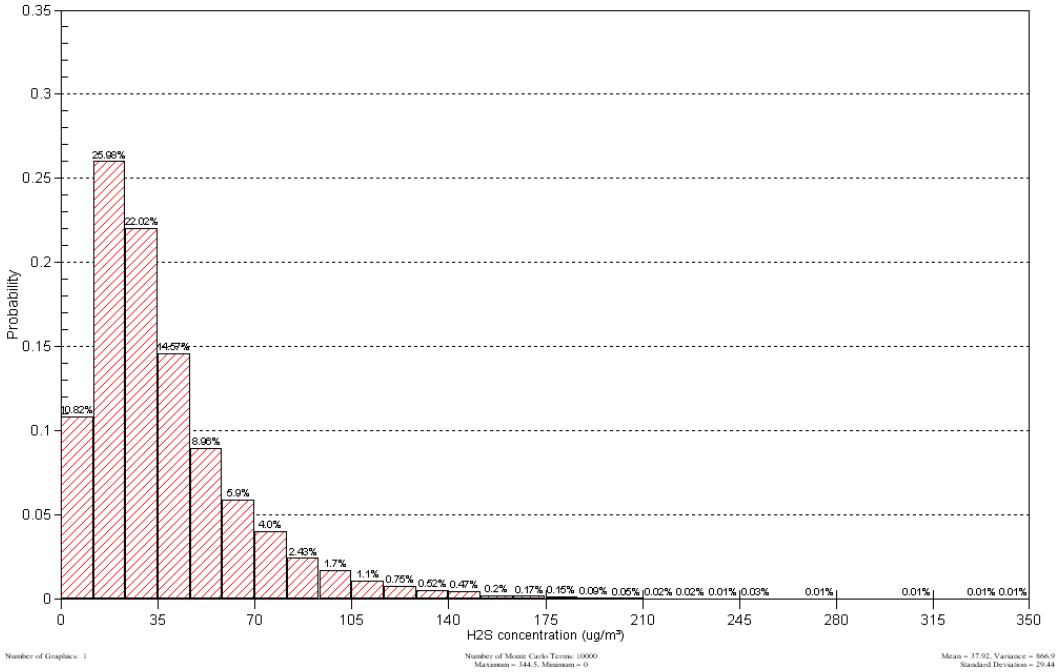


Figure 42. Monte Carlo results of H_2S concentration for modeled drywall using LNBL 2010 data for Case B.

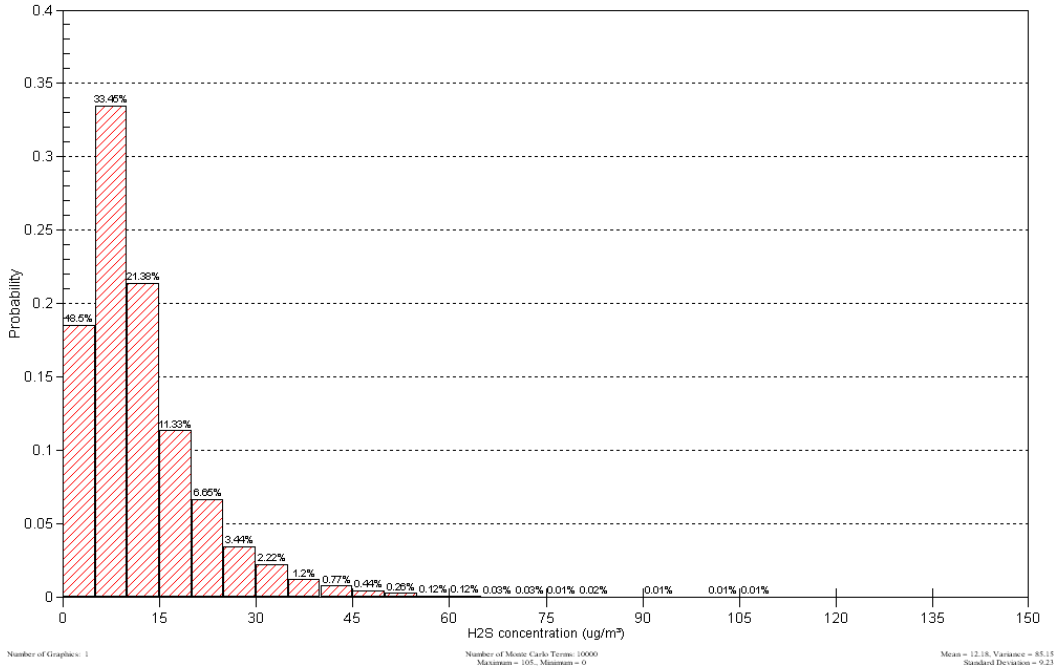


Figure 43. Monte Carlo results of H_2S concentration for drywall sample 8037 using LNBL 2010 data for Case B.

From the results of both cases, we may observe the following points:

i. The steady-state concentrations are likely to follow lognormal distributions. The concentrations distribute within relatively wide ranges, but most values are around the mean values.

ii. Among drywall samples, Sample 8357 seems to be the most contaminated one. Sample 8037 is the least contaminated one.

iii. When we compare the results in Tables 6, 10 and 11, contaminant concentrations for same samples largely drop from 2009 data to 2010 data.

4.6 Estimation of Confidence Intervals

In statistical inference, we would like to estimate population parameters using observed sample data. A confidence interval (CI) is a type of interval estimate for a population parameter and is used to reflect the reliability of an estimate. A confidence interval consists of a range of values (interval) that act as good estimates of the unknown population parameter. How frequently the confidence interval contains the true parameter is determined by the confidence level. The confidence level indicates the probability that the confidence interval captures this true population parameter given a distribution of samples. The confidence level corresponds to the level of significance (denoted as α). For example, the confidence level of 95% expresses that 95% of the confidence intervals will hold the true value of the parameter in a level of significance with 0.05 (α = 0.05).

Based on the results of the Monte Carlo simulation, the confidence intervals of concentrations in room can be estimated for a given level of significance α using statistical methods. If the statistical distribution of the concentration follows normal distribution, the confidence interval can be estimated by

$$\overline{C}(t) - t_{\alpha/2,n-1}\frac{s_i(t)}{\sqrt{n}} \le C(t) \le \overline{C}(t) + t_{\alpha/2,n-1}\frac{s_i(t)}{\sqrt{n}} \tag{3}$$

where n is the number of Monte Carlo simulation, $C(t)$ is the concentration at time t, $\overline{C}(t)$ is the corresponding mean value and is calculated by,

$$\overline{C}(t) = \frac{1}{n}\sum_{i=1}^{n} C_i(t) \tag{4}$$

s(t) is the standard deviation of concentrations at time t and is calculated by

$$s_i(t) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(C_i(t) - \overline{C}(t)\right)^2} \tag{5}$$

$C_i(t)$ is the concentration at time t in the ith Monte Carlo simulation, $t_{\alpha,n-1}$ is the t-distribution with (n – 1) degree of freedom.

In general, the statistical distribution of the concentration in room generated from drywalls does not follow normal distribution and these distributions are likely to follow lognormal distributions as shown earlier. We need to estimate the confidence intervals using histograms resulting from Monte Carlo simulation. Figure 44 illustrates the procedure used for this estimation.

i. For each time step, find the minimum and maximum values of the concentration and divide the range into n_h sub-intervals;

ii. Calculate the corresponding frequencies (f_i) for each sub-interval;

iii. For a given level of significance α, perform the summation calculation

$$p_1 = \sum_{i=1}^{l_1 \le n_h} f_i \text{ and } p_2 = \sum_{i=n_h}^{l_2 \ge 1} f_i \tag{6}$$

until $p_1 \ge \frac{\alpha}{2}$ *or* $p_2 \ge \frac{\alpha}{2}$, as shown in Figure 4. The corresponding concentration at interval l_1 is taken as lower bound of confidence interval, and at interval l_2 is taken as the upper bound of confidence interval. Where n_h is the number of sub-intervals, l_1 is the index of sub-interval in which $p_1 \ge \frac{\alpha}{2}$, l_2 is the index of sub-interval in which $p_2 \ge \frac{\alpha}{2}$. p_1 and p_2 are the cumulative probabilities in left side and right side.

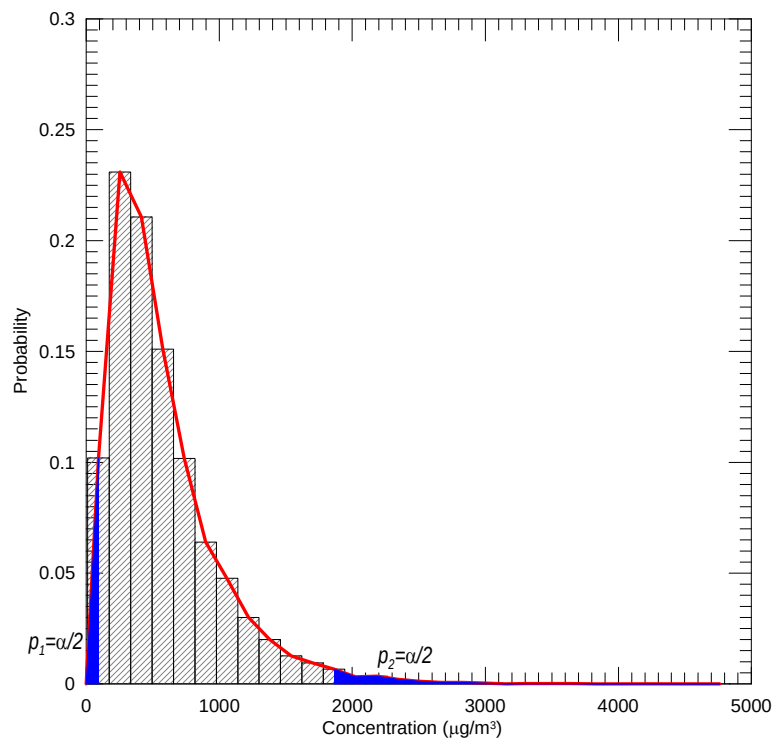


Figure 44. Estimation of confidence interval from histogram for a given α.

The estimation of confidence intervals below is based on Monte Carlo simulation described in Sections 4.2 to 4.5, i.e., the statistical distributions of uncertain parameters used in the estimation of confidence intervals, such as emission rates, room volume and supply/exhaust air rate, are the same as those used in Monte Carlo simulations for the corresponding scenarios. In the estimation of confidence interval, we first perform Monte Carlo simulation **for each time step**, and then use the statistical method described above to find the confidence interval **for each time step** which are connected to become a "confidence corridor".

In this study, we will apply the above procedure to estimate the confidence intervals of concentrations in room for LBNL 2009 and 2010 data respectively. The level of significance is given as 0.05, i.e., α = 0.05. In other words, we will estimate 95% confidence intervals of concentrations in room over time.

4.7 Estimation of Confidence Intervals Based on the LBNL 2009 Data (LBNL 2010)

Applying the above procedure to LBNL 2009 data, we obtain 95% confidence intervals of concentrations in room for all chemicals. Tables 12A – 12G list the confidence intervals and mean values of steady-state concentrations in a room. The confidence intervals of H_2S concentrations over time are shown in Figures 45 to 50. These figures will not be repeated for other chemicals. It is clearly seen that the confidence intervals are asymmetric due to the asymmetry of statistical distributions. Among drywall samples, Samples 9673 and 8357 have highest mean H_2S concentrations in a room, which are respectively 964.9 μg/m^3 and 890.1 μg/m^3, and they also contain highest mean SO_2 concentrations in a room, which are 461.3 μg/m^3 and 581.7 μg/m^3 respectively. The concentration for average for year 2009 is the lower than that for average for years 2005 and 2006.

Table 12A. 95% confidence intervals and mean values for H_2S steady-state concentration.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	**7339**	[174, 1938]	592.1
	8357	[262, 2913]	890.1
	9672	[95, 1056]	323.1
	9673	[284, 3158]	964.9
	Average for yrs. 2005 & 2006	[118., 1311]	400.5
	Average for yr. 2009	[13, 143]	43.6
North Am.	**8037**	NA	NA

Table 12B. 95% confidence intervals and mean values for SO_2 steady-state concentration.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	**7339**	[119, 1319]	403.1
	8357	[171, 1902]	581.7
	9672	[29, 328]	100.2
	9673	[136, 1508]	461.3
	Average for yrs. 2005 & 2006	[69., 765]	233.9
	Average for yr. 2009	[17, 188]	57.3
North Am.	**8037**	NA	NA

Table 12C. 95% confidence intervals and mean values for CS_2 steady-state concentration.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	7339	[4.27, 47.51]	14.52
	8357	[5.80, 64.47]	19.72
	9672	[0.36, 4.00]	1.22
	9673	[0.93, 10.35]	3.17
	Average for yrs. 2005 & 2006	[2.10, 23.39]	7.15
	Average for yr. 2009	[0.11, 1.18]	0.36
North Am.	8037	[1.09, 12.12]	3.71

Table 12D. 95% confidence intervals and mean values for MM steady-state concentration.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	7339	[2.66, 29.57]	9.05
	8357	[2.94, 32.68]	10.00
	9672	[0.79, 8.72]	2.67
	9673	[2.12, 23.5]	7.19
	Average for yrs. 2005 & 2006	[1.30., 14.49]	4.43
	Average for yr. 2009	[0.48, 5.33]	1.63
North Am.	8037	NA	NA

Table 12E. 95% confidence intervals and mean values for DMS steady-state concentration.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	7339	[1.13, 12.57]	3.84
	8357	[0.93, 10.35]	3.17
	9672	[0.05, 0.59]	0.18
	9673	[0.08, 0.89]	0.27
	Average for yrs. 2005 & 2006	[0.53, 5.92]	1.81
	Average for yr. 2009	[0.04, 0.44]	0.14
North Am.	8037	[0.47, 5.18]	1.58

Table 12F. 95% confidence intervals and mean values for OCS steady-state concentration.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	**7339**	NA	NA
	8357	[2.42, 26.91]	8.23
	9672	[5.23, 58.11]	17.78
	9673	[11.83, 131.45]	40.21
	Average for yrs. 2005 & 2006	[5.02., 55.75]	17.05
	Average for yr. 2009	[4.84, 53.82]	16.46
North Am.	**8037**	NA	NA

Table 12G. 95% confidence intervals and mean values for EM steady-state concentration.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	**7339**	NA	NA
	8357	NA	NA
	9672	NA	NA
	9673	[0.13, 1.48]	0.45
	Average for yrs. 2005 & 2006	[0.13, 1.48]	0.45
	Average for yr. 2009	[0.08, 0.89]	0.27
North Am.	**8037**	NA	NA

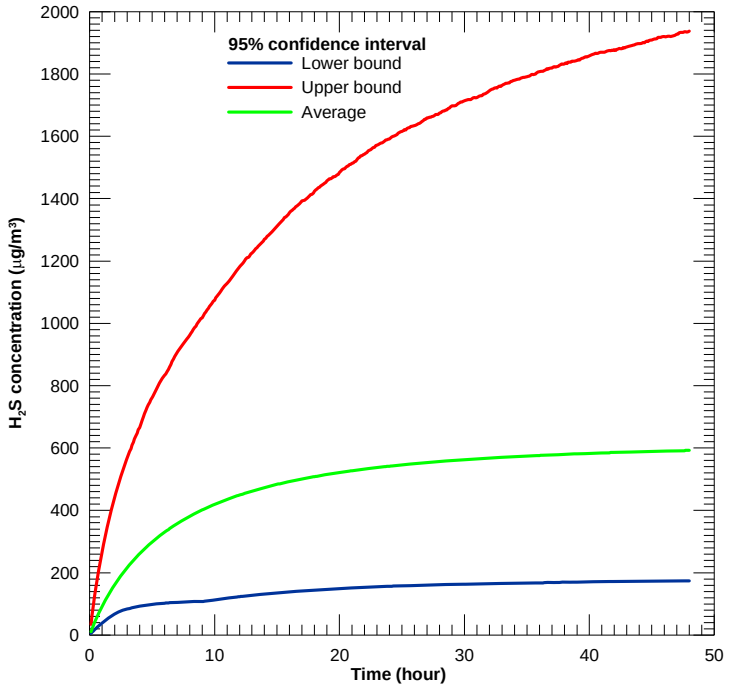


Figure 45. 95% confidence interval of H_2S concentration for drywall sample 7339.

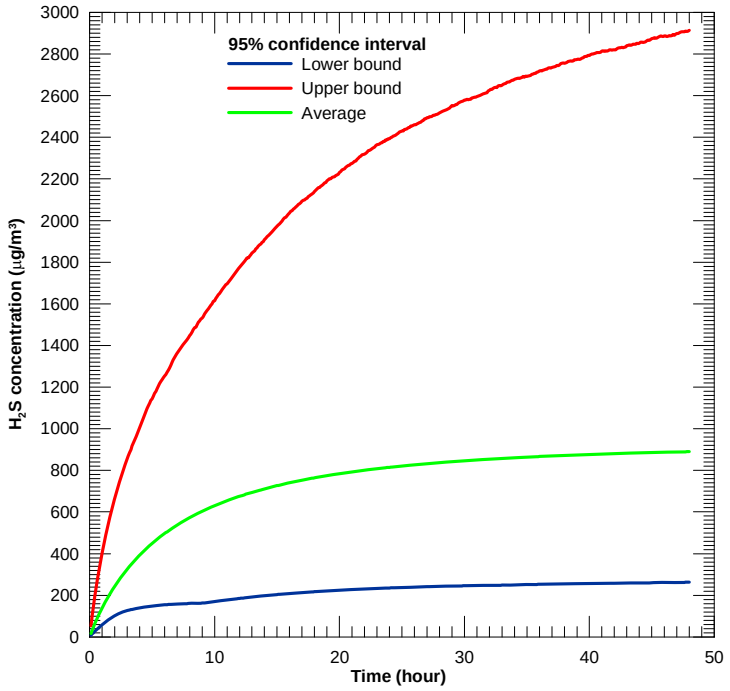


Figure 46. 95% confidence interval of H_2S concentration for drywall sample 8357.

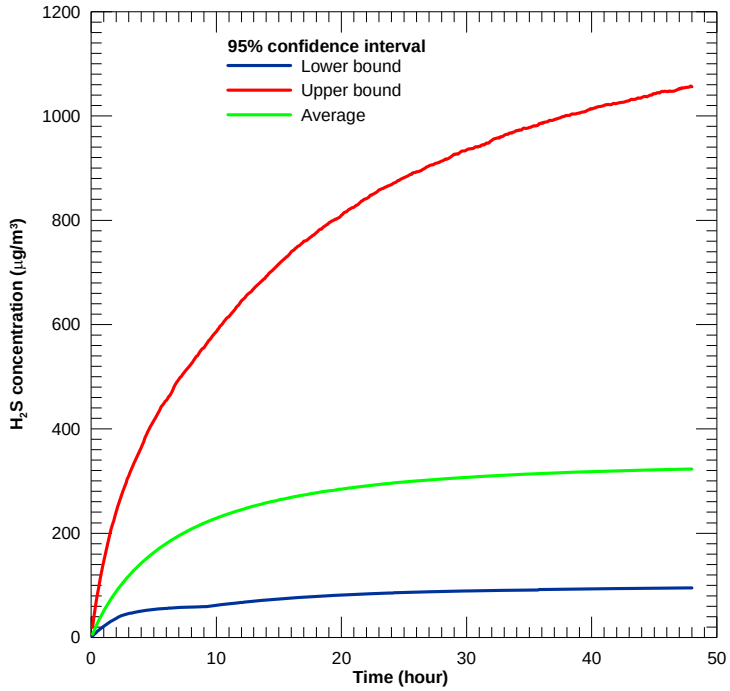


Figure 47. 95% confidence interval of H_2S concentration for drywall sample 9672.

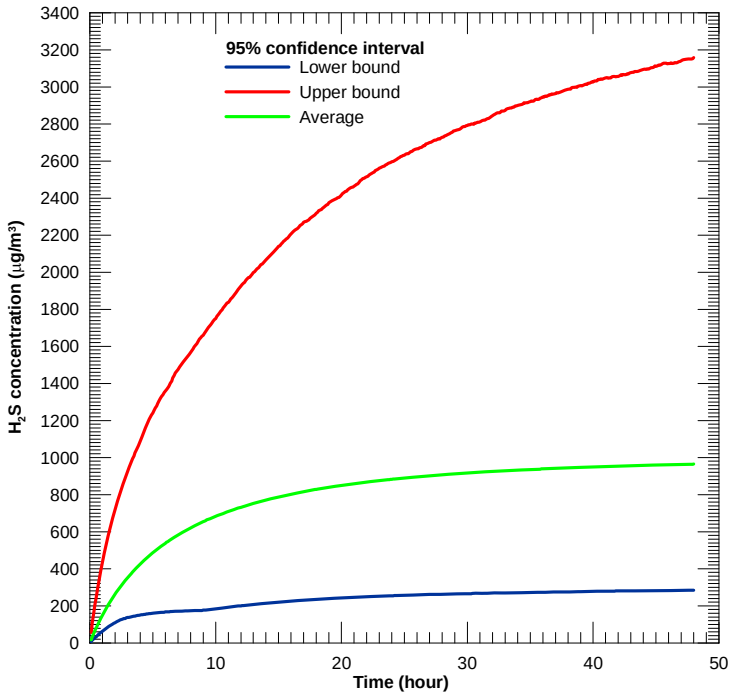


Figure 48. 95% confidence interval of H_2S concentration for drywall sample 9673.

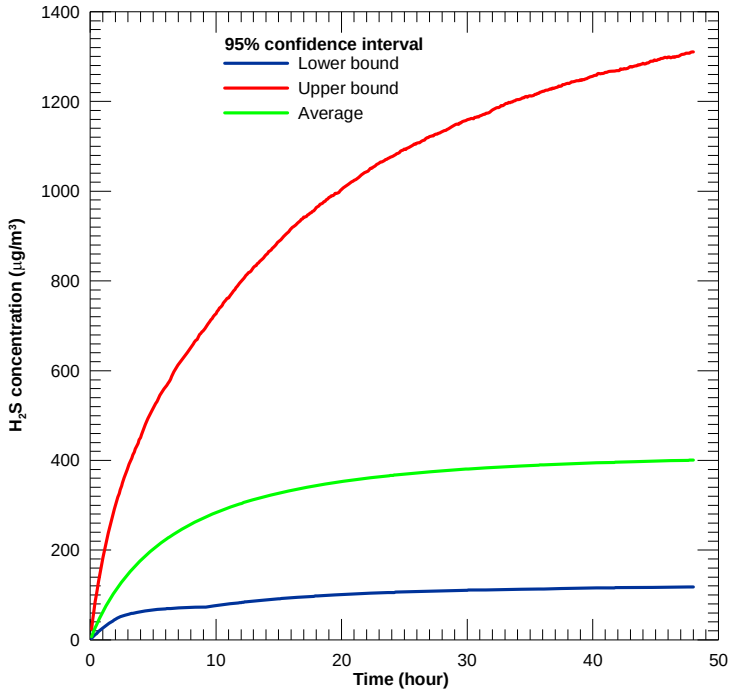


Figure 49. 95% confidence interval of H_2S concentration for average for yrs. 2005 & 2006.

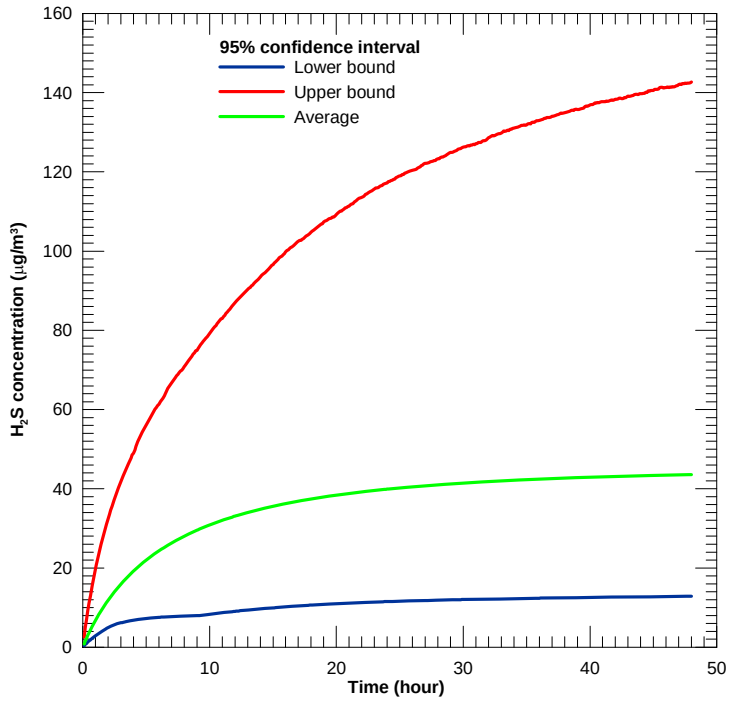


Figure 50. 95% confidence interval of H_2S concentration for average for yr. 2009.

4.8 Estimation of Confidence Intervals Based on the LBNL 2010 Data (LBNL 2011)

For the LBNL 2010 data (LBNL 2011), we apply the same procedure to estimate 95% confidence interval of chemical concentrations in room for all drywall samples for two cases: (A) for the mean ambient temperature (*T*) at 25 ^{o}C and mean relative humidity (*RH*) at 49%; and, (B) the mean ambient temperature (*T*) at 25.4 ^{o}C and mean relative humidity (*RH*) at 60%.

Case A: Monte Carlo Analysis at mean ambient temperature *T* = 25 ^{o}C and mean relative humidity *RH* = 49%

Applying the procedure described above to estimate confidence intervals of chemical concentrations in a room for all drywall samples for this case, the results are summarized in Tables 13A – 13G are obtained. The confidence intervals of H_2S concentrations over time are shown in Figures 51 to 56. Among drywall samples, Samples 7339 and 9673 have highest mean H_2S concentrations in a room, which are 37.6 µg/m^3 and 37.4 µg/m^3 respectively, while Samples 8357 and 9672 contain highest mean SO_2 concentrations in room, which are 87.3 µg/m^3 and 75.6 µg/m^3 respectively.

Table 13A. 95% confidence intervals and mean values for H_2S steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	7339	[11.1, 123.2]	37.6
	8357	[4.9, 54.3]	16.6
	9672	[7.4, 81.6]	25.0
	9673	[11.0, 122.3]	37.4
	Modeled drywall	[8.6, 95.4]	29.1
North Am.	8037	[3.5, 38.9]	11.9

Table 13B. 95% confidence intervals and mean values for SO_2 steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (µg/m^3)	Mean (µg/m^3)
Chinese drywall	7339	[17.8, 197.8]	60.4
	8357	[25.7, 285.2]	87.3
	9672	[22.3, 247.2]	75.6
	9673	[9.6, 107.2]	32.8
	Modeled drywall	[18.8, 209.3]	64.0
North Am.	8037	[2.1, 23.5]	7.2

Table 13C. 95% confidence intervals and mean values for CS_2 steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.21, 2.37]	0.72
	8357	[0.09, 1.04]	0.32
	9672	[0.07, 0.74]	0.23
	9673	[0.05, 0.59]	0.18
	Modeled drywall	[0.11, 1.18]	0.36
North Am.	8037	[0.01, 0.15]	0.05

Table 13D. 95% confidence intervals and mean values for MM steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.83, 9.18]	2.80
	8357	[0.51, 5.62]	1.72
	9672	[0.57, 6.36]	1.94
	9673	[0.83, 9.18]	2.80
	Modeled drywall	[0.68, 7.58]	2.32
North Am.	8037	[0.16, 1.77]	0.54

Table 13E. 95% confidence intervals and mean values for DMS steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.04, 0.44]	0.14
	8357	[0.03, 0.30]	0.09
	9672	[0.04, 0.44]	0.14
	9673	[0.05, 0.59]	0.18
	Modeled drywall	[0.04, 0.44]	0.14
North Am.	8037	[0.03, 0.30]	0.09

Table 13F. 95% confidence intervals and mean values for OCS steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[2.02, 22.48]	6.87
	8357	[1.98, 22.03]	6.74
	9672	[2.69, 29.87]	9.14
	9673	[1.88, 20.87]	6.38
	Modeled drywall	[2.14, 23.83]	7.28
North Am.	8037	[1.46, 16.28]	4.98

Table 13G. 95% confidence intervals and mean values for EM steady-state concentration for Case A.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.15, 1.63]	0.50
	8357	[0.24, 2.66]	0.81
	9672	[0.09, 1.04]	0.32
	9673	[0.16, 1.77]	0.54
	Modeled drywall	[0.16, 1.77]	0.54
North Am.	8037	[0.07, 0.74]	0.23

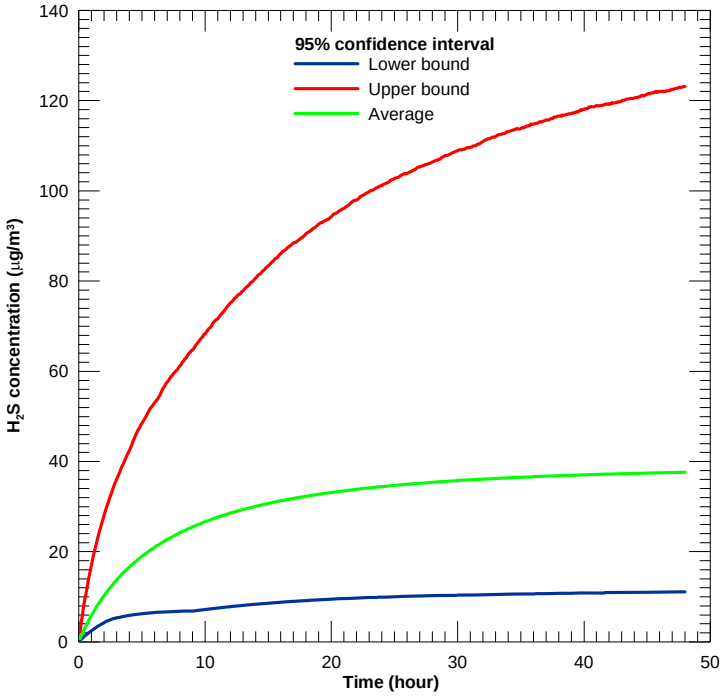


Figure 51. 95% confidence interval of H_2S concentration for drywall sample 7339 for Case A.

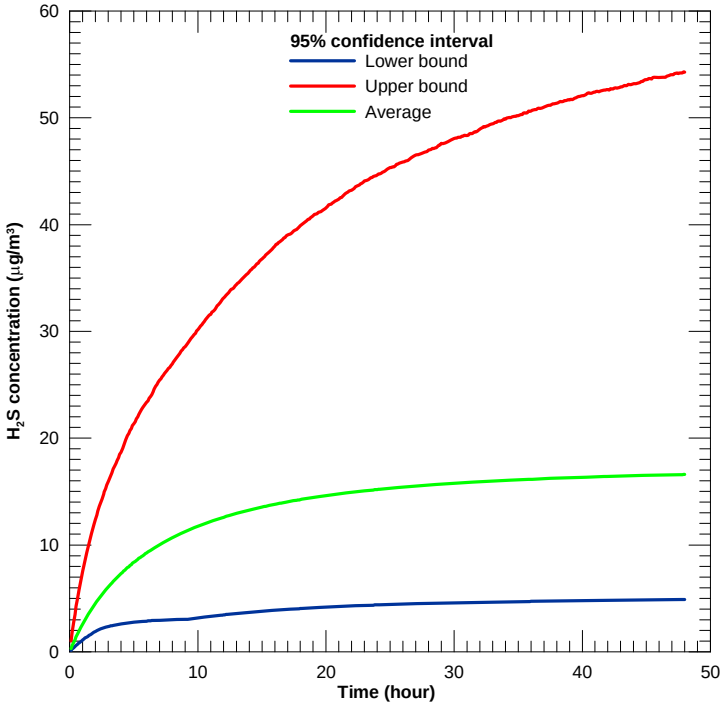


Figure 52. 95% confidence interval of H_2S concentration for drywall sample 8357 for Case A.

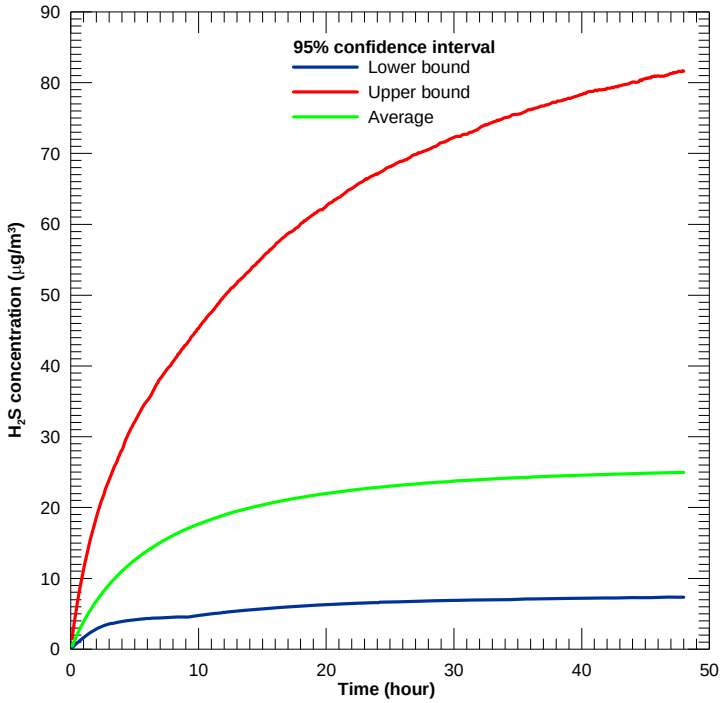


Figure 53. 95% confidence interval of H_2S concentration for drywall sample 9672 for Case A.

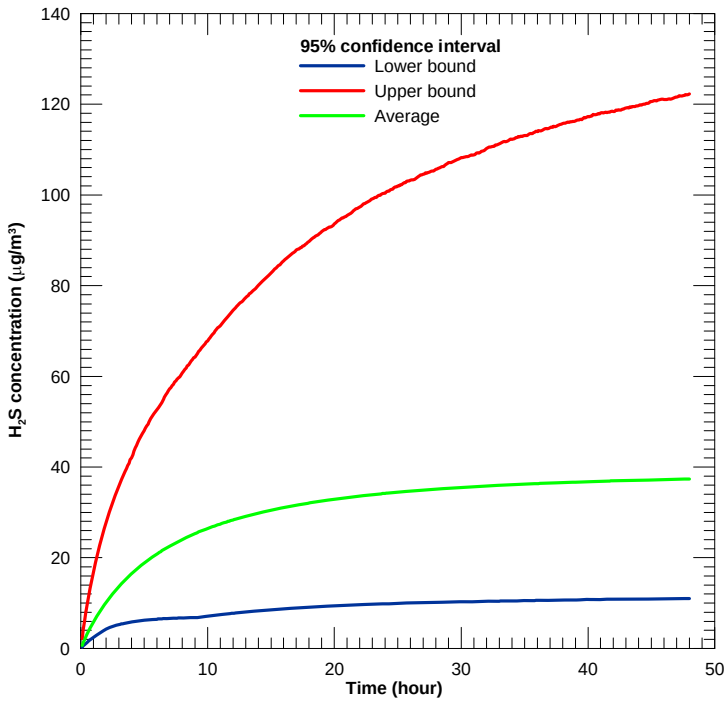


Figure 54. 95% confidence interval of H_2S concentration for drywall sample 9673 for Case A.

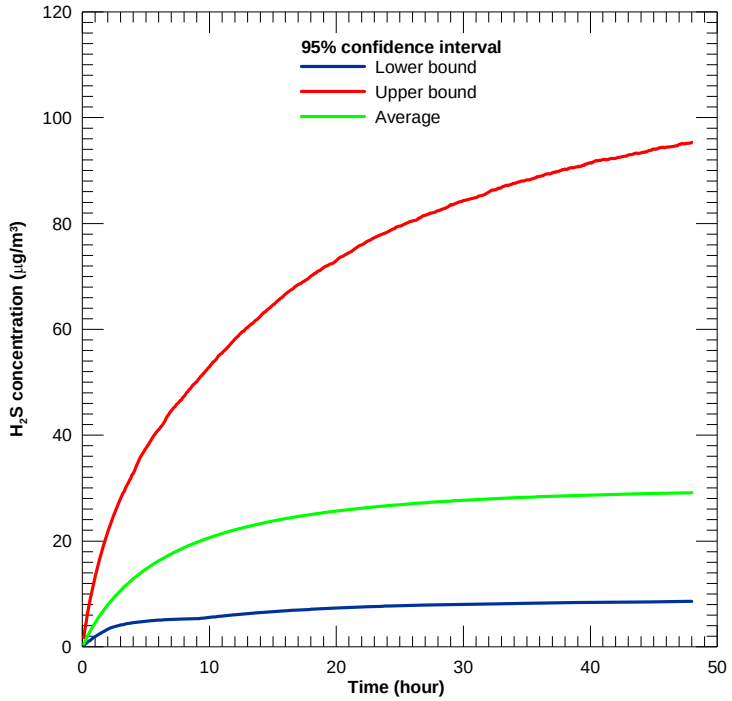


Figure 55. 95% confidence interval of H_2S concentration for modeled drywall for Case A.

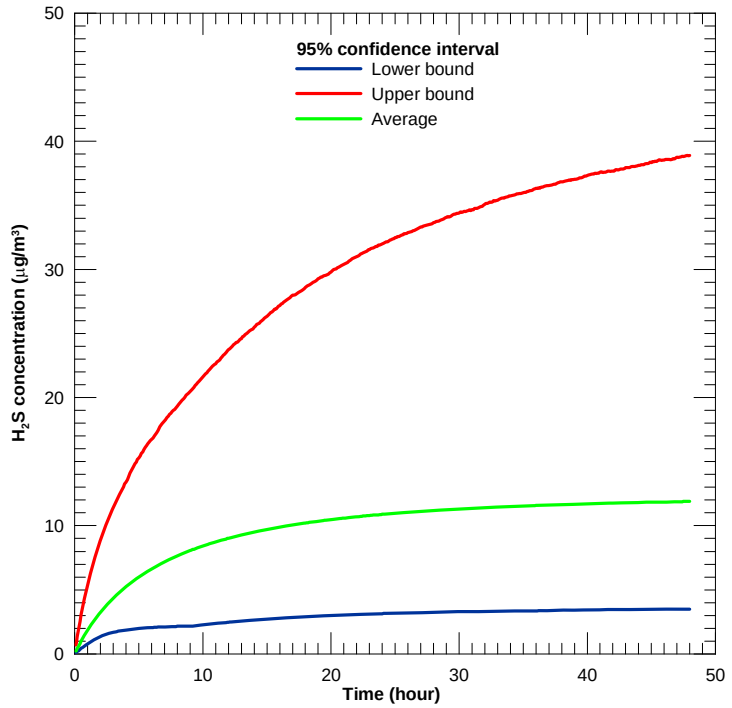


Figure 56. 95% confidence interval of H_2S concentration for drywall sample 8037 for Case A.

Case B: Monte Carlo Analysis at mean ambient temperature *T* = 25.4 °C and mean relative humidity *RH* = 60%

As stated earlier, the emission rates are estimated based on regression relations in this case, in which the input parameters of ambient temperature and relative humidity are given earlier. Similarly, applying the above procedure to estimate confidence intervals of chemical concentrations in room for all drywall samples for this case, the results are summarized in Tables 14A – 14G can be obtained. The confidence intervals of H_2S concentrations over time are shown in Figures 57 to 62. Among drywall samples, Samples 7339 and 8357 have highest mean H_2S concentrations in room, which are 39.8 μg/m^3 and 42.9 μg/m^{3}respectively, while Samples 8357 and 9672 contain highest mean SO_2 concentrations in room, which are 58.4 μg/m^3 and 35.1 μg/m^3 respectively.

Table 14A. 95% confidence intervals and mean values for H_2S steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[12.8, 133.2]	39.8
	8357	[14.3, 144.6]	42.9
	9672	[11.2, 114.9]	34.0
	9673	[12.5, 124.5]	35.7
	Modeled drywall	[12.6, 127.9]	37.9
North Am.	8037	[3.9, 40.6]	12.2

Table 14B. 95% confidence intervals and mean values for SO_2 steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[10.5, 106.5]	31.2
	8357	[20.4, 204.1]	58.4
	9672	[12.3, 123.7]	35.1
	9673	[9.0, 89.8]	24.4
	Modeled drywall	[12.4, 124.5]	35.3
North Am.	8037	[4.7, 50.9]	15.5

Table 14C. 95% confidence intervals and mean values for CS_2 steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.77, 7.79]	2.30
	8357	[0.34, 3.35]	0.99
	9672	[0.15, 1.57]	0.47
	9673	[0.18, 1.77]	0.52
	Modeled drywall	[0.29, 2.91]	0.86
North Am.	8037	[0.03, 0.34]	0.10

Table 14D. 95% confidence intervals and mean values for MM steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[1.15, 11.85]	3.54
	8357	[1.63, 16.86]	5.02
	9672	[1.22, 12.35]	3.67
	9673	[1.41, 14.45]	4.31
	Modeled drywall	[1.34, 13.73]	4.09
North Am.	8037	[0.41, 4.23]	1.27

Table 14E. 95% confidence intervals and mean values for DMS steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.05, 0.54]	0.16
	8357	[0.06, 0.57]	0.17
	9672	[0.08, 0.79]	0.23
	9673	[0.08, 0.82]	0.25
	Modeled drywall	[0.07, 0.67]	0.20
North Am.	8037	[0.04, 0.44]	0.13

Table 14F. 95% confidence intervals and mean values for OCS steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[4.16, 44.78]	13.59
	8357	[3.97, 41.68]	12.55
	9672	[4.54, 48.65]	14.65
	9673	[3.5, 36.45]	10.93
	Modeled drywall	[4.02, 42.67]	12.85
North Am.	8037	[2.29, 24.08]	7.24

Table 14G. 95% confidence intervals and mean values for EM steady-state concentration for Case B.

Drywall Type	Sample	95% confidence interval (μg/m^3)	Mean (μg/m^3)
Chinese drywall	7339	[0.20, 2.14]	0.64
	8357	[0.53, 5.52]	1.66
	9672	[0.21, 2.33]	0.71
	9673	[0.29, 2.96]	0.88
	Modeled drywall	[0.28, 2.99]	0.90
North Am.	8037	[0.12, 1.35]	0.41

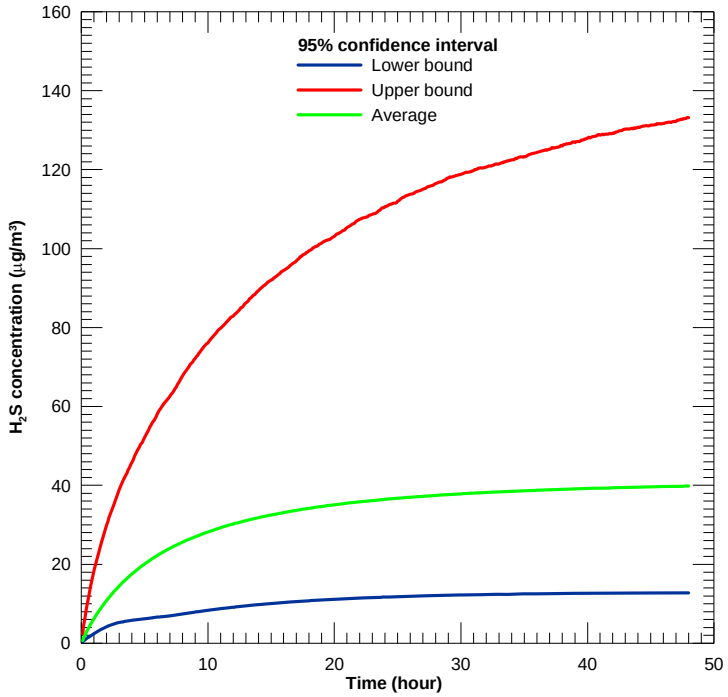


Figure 57. 95% confidence interval of H_2S concentration for drywall sample 7339 for Case B.

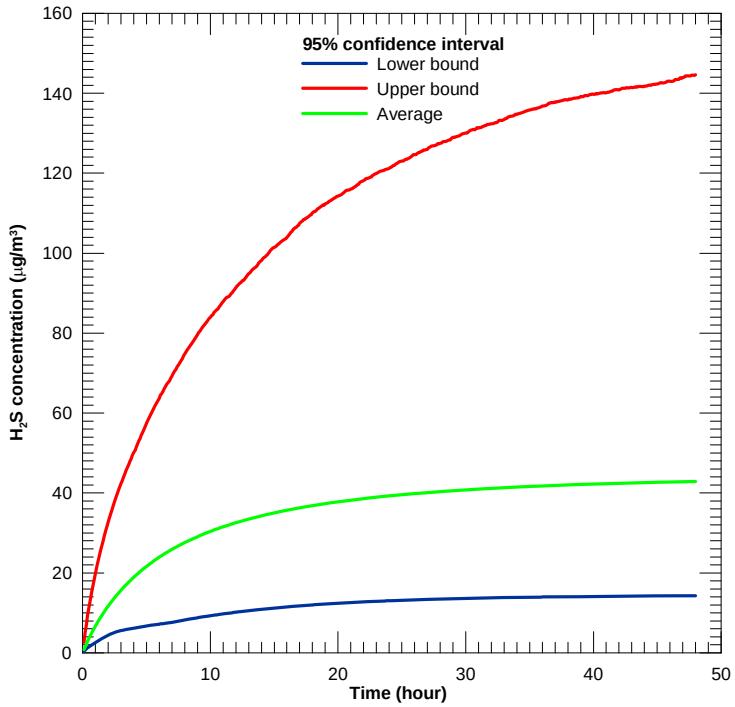


Figure 58. 95% confidence interval of H_2S concentration for drywall sample 8357 for Case B.

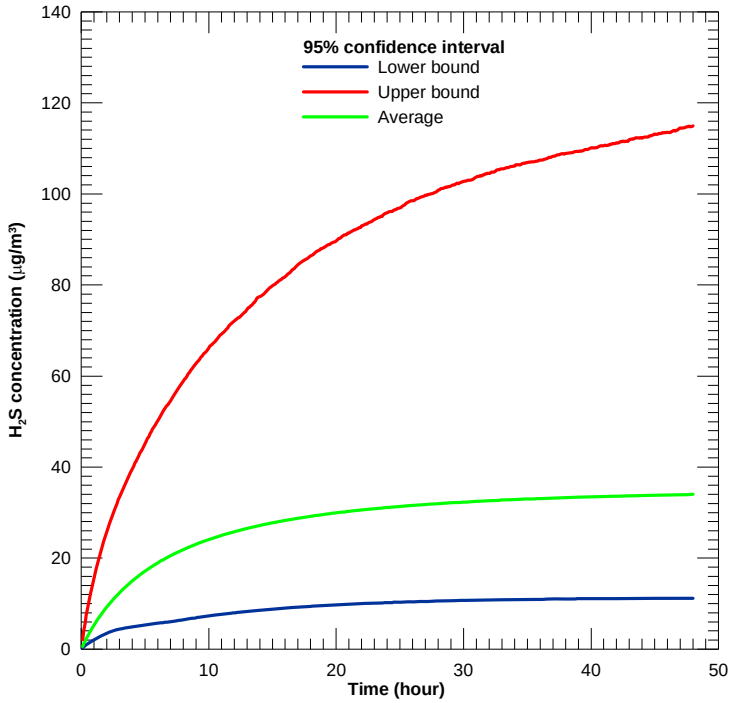


Figure 59. 95% confidence interval of H_2S concentration for drywall sample 9672 for Case B.

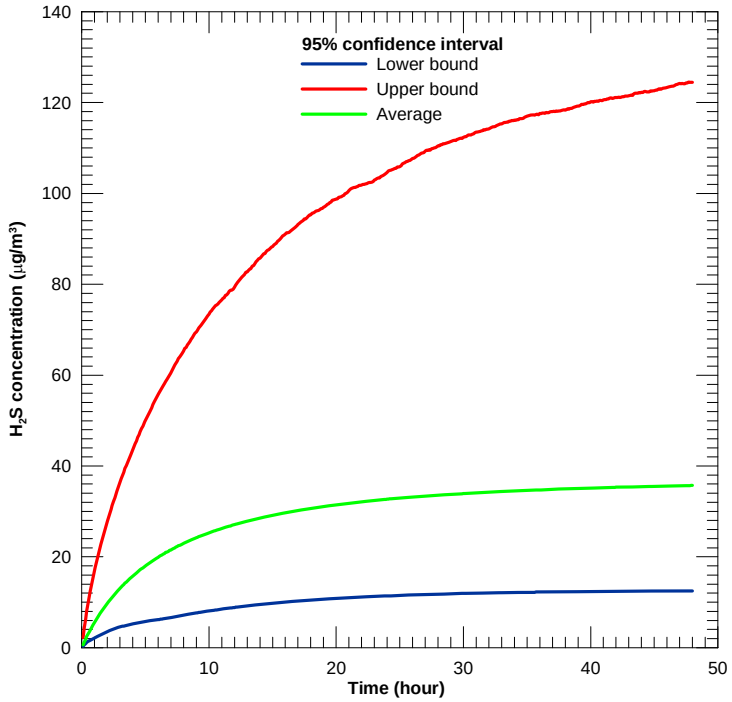


Figure 60. 95% confidence interval of H_2S concentration for drywall sample 9673 for Case B.

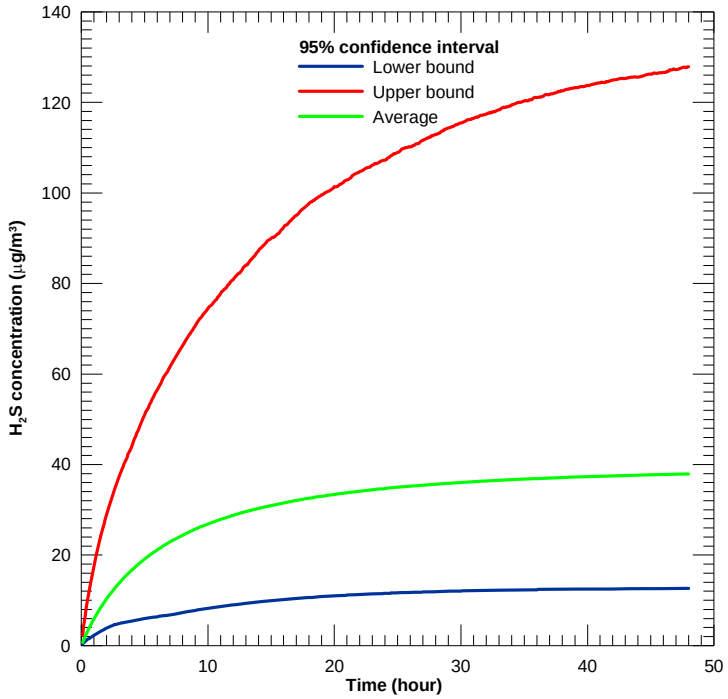


Figure 61. 95% confidence interval of H_2S concentration for modeled drywall for Case B.

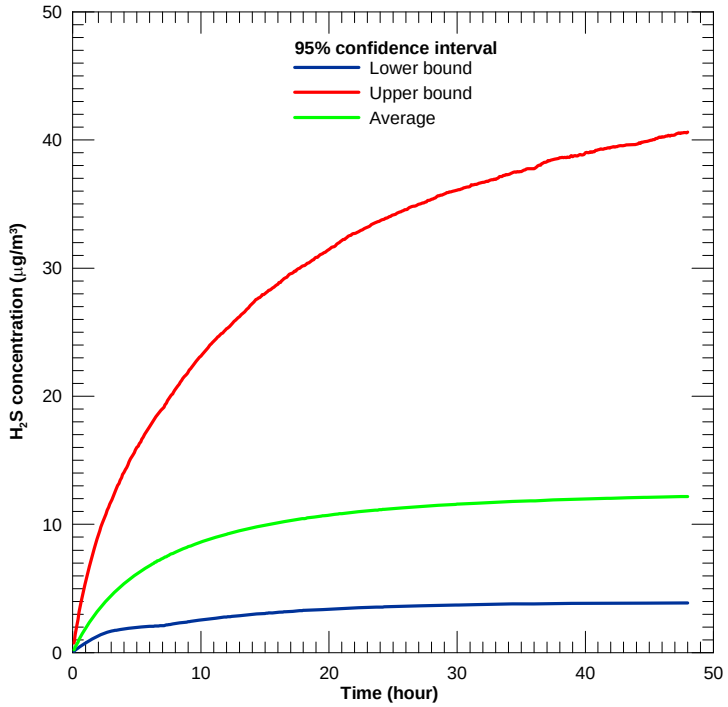


Figure 62. 95% confidence interval of H_2S concentration for drywall sample 8037 for Case B.

When compared to the steady-state contaminant concentrations obtained from the experimental data (LBNL 2010 and 2011), which are given in Phase I study report (Aral and Guan, 2013), we may observe the following two points:

i. Contaminant concentrations estimated from LBNL 2011 data are much lower than those estimated from LBNL 2010 data.

ii. Chemical concentrations for Chinese drywalls are much higher than those for North American drywall.

5. SUMMARY RESULTS FOR UNCERTAINTY ANALYSIS

Based on results of the uncertainty analysis presented above we have observed the following points:

i. Contaminant concentrations in Chinese drywalls, including Samples 7339, 8357, 9672 and 9673, are much higher than those in North American drywall (8037).

ii. Contaminant concentrations in drywalls in LBNL 2010 data are lower when compared with the LBNL 2009 data.

iii. Among drywall samples, Sample 8357 and 9673 seem to be more contaminated.

iv. Based on the given statistical characteristics of room supply/exhaust air rate, the room supply/exhaust air rate is a skewed distribution (lognormal), and the resulting concentrations in room also follow the lognormal distribution. This results in a wider confidence interval for the room concentrations for the upper bound; however, the concentrations around the mean value are with higher probabilities.

v. Compared with the emission rates estimated using mean input parameters in deterministic analyses with the mean emission rates estimated in uncertainty analyses, both values are almost identical. However, compared to the steady-state concentrations estimated using mean input parameters in deterministic analyses with the mean steady-state concentrations estimated in uncertainty analyses, we can clearly notice that the latter are higher than the former. The reason for this is the skewed distribution of the room supply/exhaust air rate. We regard such difference as the cost of uncertainty.

In uncertainty analysis, we have also observed the following points which should be paid close attention when health risk analysis is performed:

i. We use statistical characteristics such as mean, minimum, maximum values, variance and distribution to identify the Monte Carlo input parameters of a model. The different runs of Monte Carlo simulation for the given characteristics of input parameters may generate different outcomes for the model variable that is evaluated because Monte Carlo simulation is a random procedure. However, the statistical characteristics of the outcome, such as means and variances, will be basically unchanged or slightly changed. This is an important outcome of our expectations of the uncertainty analysis.

ii. Mean, minimum and maximum values of input variables may be obtained based on collected data or experiments, but variance selection has its own uncertainty if it is unknown. Generally, the larger the difference between minimum and maximum values, the larger the variance should be. An effective method to determine the variance is to perform a statistical calculation for the results of Monte Carlo simulation for a given variance and then analyze the statistical characteristics of the results. If the simulated average, minimum

and maximum values are close to the given values, the selected variance is a good guess; otherwise, one needs to adjust the value of the selected variance. For example, if the simulated minimum and maximum values are far from those given, one should increase the variance, and if the simulated mean is smaller than the given value, one should decrease the variance. This is very helpful to determine the variance of as stochastic variable if it is unknown as employed in this study.

iii. The most important consideration is the upper bounds of the estimated confidence intervals. Since the distributions obtained for concentrations are logarithmic the upper and lower bounds of the 95% confidence interval are asymmetric and the upper bounds tend to be larger than the estimated lower bounds in their range relative to the mean values of the interval. This may significantly influence the Health Consultation performed by ATSDR.

6. REFERENCES

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