NIST Technical Note 1925

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http://dx.doi.org/10.6028/NIST.TN.1925

National Institute of Standards and Technology
U.S. Department of Commerce

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September 2016

U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie E. May, Under Secretary of Commerce for Standards and Technology and Director

National Institute of Standards and Technology Technical Note 1925
Natl. Inst. Stand. Technol. Tech. Note 1925, 49 pages (September 2016)
CODEN: NTNOEF

This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.TN.1925

ABSTRACT
The U.S. Consumer Product Safety Commission (CPSC) and others are concerned about the hazard of acute carbon monoxide (CO) exposures from portable gasoline powered generators that can result in death or serious adverse health effects in exposed individuals. As of May 15, 2015, the CPSC databases contain records of at least 702 deaths (involving 523 incidents) from CO poisoning in the U.S. caused by consumer use of a generator in the period of 2004 through 2014 (Hnatov 2015). There were an additional 49 CO poisoning deaths (involving 39 incidents) associated with consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 751 CO poisoning deaths (involving 562 incidents) associated with generators for the same 11-year period. The majority of these deaths occurred when consumers used a generator in an enclosed or partially enclosed space or outdoors near an open door, window or vent. While avoiding the operation of such generators in or near an enclosed space is expected to reduce indoor CO exposures significantly, it may not be realistic to expect such usage to be eliminated completely. Another means of reducing these exposures would be to decrease the rate at which CO is emitted from these devices. A computer simulation study was conducted to provide CPSC staff with information to support comparisons of modeled residential CO exposures reflecting operation of current designs of portable engine-driven electric generators, inside homes or in attached garages. These results were compared to simulated operation of reduced emission generators meeting a potential CO emission rate limit performance requirement being considered by CPSC staff under portable generator rulemaking activities. These simulations employed the multizone airflow and contaminant transport model CONTAM, which was applied to a set of 40 buildings (consisting of 37 houses and 3 detached garages, considered broadly representative of fatal CO poisoning incidents reported in CPSC databases) that are primarily based on a collection of models representative of the U.S. housing stock. This report presents sample CO and carboxyhemoglobin (COHb) simulation results for three of the houses and one of the garages modeled. The results presented demonstrate that generators with the reduced CO emission rates result in peak CO concentrations that can be reduced by 40 % to more than 90 % depending on the specific case being analyzed. The reduced CO emission rates also result in significant reductions in COHb in many cases. Additionally, use of a thermal building model coupled with the airflow and IAQ model to properly account for thermal effects was shown to be important as the interaction of the generator's heat generation and the ambient weather conditions can significantly impact both air change rates and interzone airflow patterns in the buildings.

KEYWORDS: carbon monoxide; CONTAM; emergency generators; multizone airflow model; simulation

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1. INTRODUCTION

The U.S. Consumer Product Safety Commission (CPSC) and others are concerned about the hazard of acute carbon monoxide (CO) exposures from portable gasoline powered generators that can result in death or serious adverse health effects in exposed individuals. As of May 15, 2015, the CPSC databases contain records of at least 702 deaths (involving 523 incidents) from CO poisoning caused by consumer use of a generator in the period of 2004 through 2014 (Hnatov 2015). There were an additional 49 CO poisoning deaths (involving 39 incidents) associated with consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 751 CO poisoning deaths (involving 562 incidents) associated with generators for the same 11-year period. The majority of these deaths occurred when consumers used a generator in an enclosed or partially enclosed space or outdoors near an open door, window or vent. While avoiding the operation of such generators in or near an enclosed space is expected to reduce indoor CO exposures significantly, it may not be realistic to expect such usage to be eliminated completely.

Another means of reducing these exposures would be to decrease the rate at which CO is emitted from these devices. The magnitude of such reductions needed to reduce exposures to some specific level depends on the complex relationship between CO emissions from these generators and multiple factors influencing occupant exposure. Technically achievable levels of CO emissions reduction have been studied by NIST through an experimental investigation of CO emissions from generators in a shed and in a house. These investigations included measurements on prototype generators that were modified to reduce their CO emission rates (Emmerich et al. 2013). That study has provided a set of unique measurements of CO emission rates for both unmodified and modified generators.

The issue of how CO emission rates relate to occupant exposure and health impacts involves the interaction between generator operation, house characteristics, weather conditions, occupant activity, and health status. National Institute of Standards and Technology (NIST) Technical Note 1782 (Persily et al. 2013) described a computer simulation study conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate to support life-safety based analyses of potential CO emission limits. Those simulations employed the multizone airflow and contaminant transport model CONTAM (the most recent available version is described in detail by Dols and Polidoro 2015), which was applied to a collection of 83 single-family, detached dwellings and 4 manufactured homes that are representative of the U.S. housing stock for these housing types. All house heating, ventilating and air-conditioning (HVAC) systems were modeled as “off” in the simulations based on not having electric power during an outage. The project described in this report extended and modified the methods used in the previous work. This new work will support CPSC staff efforts to make, for a range of generator sizes, more accurate comparisons between likely CO exposures throughout homes resulting from operation of current portable engine-driven electric generators in residences and attached garages, as well as exposures from generators with low CO emissions that meet a technical feasibility-based performance requirement that CPSC staff is considering under its portable generator rulemaking activity.

Specific extensions and modification in this effort relative to the previous CO modeling study described in Technical Note 1782 include:

- accounting for temperature distributions within the simulated houses, accounting for ambient weather conditions and the heat released by the generator, using a version of the CONTAM model with heat transfer modeling capability;
- consideration of generator size-dependent CO emission rates;
- use of constant CO emission rates, independent of the source location O_2 level, for modeling generators meeting the potential performance requirements;
- use of generator size-dependent run times;
- calculation of percent carboxyhemoglobin (COHb) profiles for generic adult occupants in individual rooms using more refined, short term inhalation rates (respiratory minute volumes (RMV)) characteristic of indoor activities over 24 hours;
- modeling a subset of the 87 homes included in the previous study, including some modifications to the floorplans;
- modeling 3 additional buildings to represent various sizes and styles of detached garages; and
- reporting modeling results of all rooms, including unconditioned spaces such as basements and garages.

A total of over 45 thousand individual 24-hour simulations were conducted. This report presents detailed CO and COHb simulation results for three of the houses and one of the detached garages.

2. ANALYSIS METHOD

This simulation study was conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate in order to support cost-benefit analyses of potential CO emission limits for generators. These simulations employed the multizone airflow and contaminant transport model CONTAM, which was applied to 40 buildings including 37 versions of dwellings drawn from a collection that are representative of the U.S. housing stock (Persily et al. 2006) and three new garage buildings. These buildings were identified as broadly representative of fatal generator-related CO poisoning incidents reported in CPSC databases. A total of over 45 thousand individual 24-hour simulations were conducted that cover a range of house layouts and sizes, airtightness levels and weather conditions, as well as generator locations, CO source strengths and operating schedules. The locations include attached garages, crawlspaces and basements, in the houses that have such spaces, and two interior rooms in all of the houses considered. This section describes the approach used to perform the simulations, including the simulation program, the houses, the simulated generator locations and associated CO emission rates, and the manner in which the simulations were performed and the output analyzed.

2.1 Modeling approach

Using these homes (described below), indoor CO concentrations were calculated using the multizone airflow and contaminant transport model CONTAM (Dols and Polidoro 2015) over a range of source (generator) locations, CO emission rates, and weather conditions. As described below, these simulations yielded CO concentrations in the rooms of each house as a function of time during the 24-hour analysis interval, which included a scheduled period of CO emissions from generator operation followed by a period with no CO emissions. These concentrations were then used to calculate COHb values for an occupant spending the full 24 hours in each occupiable zone. This section describes the manner in which these simulations were conducted and the results analyzed.

CONTAM is a simulation tool for predicting airflows and contaminant concentrations in multizone building airflow systems. When using CONTAM, a building is represented as a series of interconnected zones (e.g. rooms), with the airflow paths (e.g., leakage sites, open doors) between the zones and the outdoors defined as mathematical relationships between the airflow through the path and the pressure difference across it. Outdoor weather conditions are also input into CONTAM, as they are key determinants of pressure differences across airflow paths in exterior walls. System airflow rates must also be defined to capture their effects on building and interzone pressure differences. These inputs are used to define mass balances of air into and out of each zone, which are solved simultaneously to determine the interzone pressure relationships and resulting airflow rates between each zone, including the outdoors. These airflow rates can be calculated over time as weather conditions and system airflow rates change. Once the airflows are established, CONTAM can then calculate contaminant concentrations over time in each building zone based on contaminant source characteristics and contaminant removal information, such as that associated with filtration. CONTAM has been used for several decades, and a range of validation studies have demonstrated its ability to reliably predict building air change rates and contaminant levels (Emmerich 2001, Emmerich et al. 2004, Poppendieck et al. 2016). Emmerich and Dols (2015) report a validation study that specifically evaluated the model's capability to predict CO concentrations in a test house from portable generator operation in an attached garage.

2. 2 Baseline house models

2.2.1 Description of homes

The house models used in the simulations are based on a collection of dwellings that were previously defined by Persily et al. (2006), which includes just over 200 dwellings that together represented 80 % of the U.S. housing stock. Those dwellings are grouped into four categories: detached (83 homes), attached (53 homes), manufactured (4 homes) and apartments (69). The definition of that set of dwellings was based on the following variables using the US Census Bureau's American Housing Survey (AHS) (HUD 1999) and the US Department of Energy's (DOE) Residential Energy Consumption Survey (RECS) (DOE 2005): housing type, number of stories, heated floor area, year built, foundation type, presence of a garage, type of heating equipment, number of bedrooms, number of bathrooms, and number of other rooms. Appendix A summarizes the characteristics of these dwellings and identifies the corresponding CONTAM project file name and associated floor plan. In addition to defining the dwellings, multizone representations were created in the airflow and contaminant transport model CONTAM to support their use in analyzing a range of ventilation and indoor air quality issues. The project files and floor plans can be downloaded at the CONTAM website www.bfrl.nist.gov/IAQanalysis under Case Studies. However, as discussed below, these files were modified for the purposes of this analysis.

Based on the CPSC analysis of CO poisoning death incidents from 2004 through 2012 (Hnatov 2015), a subset of the NIST suite of homes collection described above (in some cases with modifications) were used for this analysis, and includes 31 detached house (DH) models, 4 attached house (AH) models, and 2 manufactured house (MH) models. The modifications made to the models are described in Appendix B. Additionally, 3 new detached garage (GAR) buildings were defined and modeled including 2 single-zone garage/sheds (1 car size and 2 car size) and 1 larger garage/shed with a separate work space inside. None of the apartment models were employed due to the challenge in accounting for airflow between units and the lack of air leakage data for the partitions between units.

<u>Air handling system operation</u>: While the homes in the NIST suite of homes collection include air handling systems for heating and cooling, this analysis was based on the assumption that the forced-air distribution systems were not operating due to a power outage. This is consistent with the CPSC analysis of the CO incident database, which does not include incidents where the generator was used to operate the central HVAC system. Similarly, all local exhaust fans (kitchen and bath) were also assumed to be off.

<u>Weather conditions and wind exposure</u>: Each house and generator source combination was analyzed for 28 individual days. Each of the 28 simulations employed a different day of weather conditions, including outdoor temperature, wind speed and wind direction, that varied each day on

an hourly basis. These 28 days of weather (used in the previous study) correspond to two weeks of cold weather (due to the observed frequency of events during the winter season), one week of warm and one week of mild. The hourly weather data for these three conditions were a subset of typical weather files for the following three cities: Detroit MI (cold), Miami FL (warm) and Columbus OH (mild). Table 1 presents a summary of the weather conditions for the 28 days in the form of daily average, minimum and maximum outdoor temperatures and wind speeds.

Table 1 Summary of Hourly Weather Data Used in Simulations

Day	**Outdoor temperature, °C (°F)**			**Wind speed, m/s (mph)**		
	Average	Minimum	Maximum	Average	Minimum	Maximum
1-Jan	0.7 (33.3)	-1.7 (28.9)	5.6 (42.1)	3.2 (7.2)	0.0 (0.0)	5.7 (12.8)
2-Jan	6.1 (43.1)	0.0 (32.0)	12.2 (54.0)	3.9 (8.8)	2.1 (4.7)	5.7 (12.8)
3-Jan	2.5 (36.6)	1.1 (34.0)	4.4 (39.9)	3.1 (6.8)	2.1 (4.7)	4.1 (9.2)
4-Jan	0.9 (33.6)	0.0 (32.0)	1.7 (35.1)	2.9 (6.6)	0.0 (0.0)	4.6 (10.3)
5-Jan	-2.9 (26.8)	-5.0 (23.0)	0.0 (32.0)	5.8 (13.1)	4.1 (9.2)	8.2 (18.3)
6-Jan	-3.3 (26.1)	-5.0 (23.0)	-1.7 (28.9)	5.2 (11.6)	1.5 (3.4)	8.2 (18.3)
7-Jan	-3.8 (25.2)	-6.1 (21.0)	-2.2 (28.0)	3.2 (7.2)	0.0 (0.0)	5.2 (11.6)
8-Jan	-1.7 (28.9)	-3.3 (26.1)	0.0 (32.0)	2.4 (5.3)	0.0 (0.0)	5.2 (11.6)
9-Jan	-0.1 (31.8)	-1.7 (28.9)	1.1 (34.0)	3.5 (7.7)	1.5 (3.4)	6.2 (13.9)
10-Jan	1.8 (35.3)	1.0 (33.8)	2.8 (37.0)	3.5 (7.7)	0.0 (0.0)	6.7 (15.0)
11-Jan	0.6 (33.0)	-0.6 (30.9)	1.1 (34.0)	4.3 (9.5)	0.0 (0.0)	5.7 (12.8)
12-Jan	4.9 (40.7)	0.6 (33.1)	13.3 (55.9)	3.9 (8.7)	0.0 (0.0)	8.8 (19.7)
13-Jan	9.2 (48.5)	0.6 (33.1)	14.4 (57.9)	6.4 (14.3)	2.6 (5.8)	10.3 (23.0)
14-Jan	-5.5 (22.2)	-9.4 (15.1)	1.1 (34.0)	5.3 (11.9)	2.6 (5.8)	7.2 (16.1)
3-Apr	6.0 (42.7)	2.8 (37.0)	8.3 (46.9)	6.9 (15.5)	0.0 (0.0)	9.8 (21.9)
4-Apr	6.3 (43.3)	-0.6 (30.9)	13.3 (55.9)	2.1 (4.7)	0.0 (0.0)	5.7 (12.8)
5-Apr	9.0 (48.1)	1.1 (34.0)	15.6 (60.1)	1.8 (4.0)	0.0 (0.0)	3.6 (8.1)
6-Apr	11.9 (53.4)	5.0 (41.0)	18.9 (66.0)	3.7 (8.3)	2.1 (4.7)	6.2 (13.9)
7-Apr	16.2 (61.1)	11.1 (52.0)	22.8 (73.0)	5.4 (12.1)	0.0 (0.0)	12.4 (27.7)
8-Apr	11.0 (51.8)	7.0 (44.6)	13.9 (57.0)	6.0 (13.5)	0.0 (0.0)	9.8 (21.9)
9-Apr	8.5 (47.3)	3.9 (39.0)	13.3 (55.9)	5.5 (12.4)	0.0 (0.0)	8.2 (18.3)
25-Jul	28.5 (83.2)	25.6 (78.1)	33.3 (91.9)	2.5 (5.7)	1.0 (2.2)	5.2 (11.6)
26-Jul	29.3 (84.8)	25.0 (77.0)	35.0 (95.0)	3.4 (7.6)	1.5 (3.4)	7.2 (16.1)
27-Jul	29.5 (85.2)	25.0 (77.0)	35.0 (95.0)	2.5 (5.7)	1.5 (3.4)	6.2 (13.9)
28-Jul	30.0 (86.1)	25.6 (78.1)	35.6 (96.1)	3.0 (6.7)	1.0 (2.2)	5.2 (11.6)
29-Jul	28.5 (83.3)	25.6 (78.1)	33.9 (93.0)	3.3 (7.3)	1.0 (2.2)	11.3 (25.3)
30-Jul	29.2 (84.5)	26.1 (79.0)	33.3 (91.9)	3.0 (6.7)	1.0 (2.2)	6.2 (13.9)
31-Jul	29.0 (84.1)	27.8 (82.0)	31.7 (89.1)	4.3 (9.6)	0.0 (0.0)	8.2 (18.3)

A CONTAM model of a building is associated with a terrain shielding coefficient to account for the impacts of surrounding terrain, buildings and vegetation on surface-averaged, wind-induced pressures on the exterior façade of the building. CONTAM specifies three categories of terrain for flat exposed areas (e.g., airport), suburban, and dense urban centers, and a user can input coefficients to capture a range of terrain options in between the flat and urban extremes. These simulations employed the suburban category of terrain shielding, which corresponds to areas with obstructions of the size and spacing of single-family homes. The houses were oriented such that the predominant wind direction for the simulated weather conditions was directed toward the garage door for houses with garages or toward the front of the house for houses without garages.

Indoor air temperatures**:** In Persily et al. (2013), the indoor temperature was held constant at 23 °C (73.4 °F) in all interior zones during all of the simulations with the following exceptions. For cases with constant generator operation for 18 hours, the air temperature in zones containing the generators was assumed to increase linearly over two hours from 23 °C (73.4 °F) to 40 °C (104 °F). After the generator stopped operating, the temperature was assumed to decrease linearly over six hours back to 23 °C (73.4 °F). The air temperature in zones adjacent to the zone containing the generator was assumed to increase on the same schedule but only to 30 °C (54 °F). These indoor air temperature schedules in the source zone and adjacent zones are based on the results of a series of experimental studies of generator operation reported by Emmerich et al. (2013). The indoor air temperatures of unconditioned spaces (i.e., crawl spaces, unfinished basements, garages and attics), were held constant at 23 °C (73.4 °F). This assumption in Persily et al. (2013) does not capture temperature variations in such unconditioned spaces caused by the outdoor weather.

For this study, temperature distributions within the simulated buildings were calculated using a version of the CONTAM model with heat transfer modeling capability (Emmerich 2006, Wang et al. 2012). This model accounts for heat transfer conducted through the building envelopes due to ambient weather conditions and for the heat produced by the generator and thus results in more realistic spatial and temporal temperature variations in the buildings. The generator heat source varied depending on generator size and is reported in Table 2 along with the CO emission rates.

Door and window positions: Interior doors were assumed to be open 5 cm during the simulations and all exterior doors and windows closed with the following exceptions. Stairway doors between finished living space levels other than the first floor door were modeled with fully open doorways. Kitchen, dining, family and living room doors were modeled as fully open doorways. For cases in which the generator was located in an attached garage, the door from the garage to the house was assumed be open roughly 5 cm to accommodate an extension cord connecting the generator to appliances in the house.

2.2.2 Source Locations and Emission Rates

For each building modeled, scenarios included up to three different source locations, a range of "constant" CO generation rates, and different durations of maintained source emissions. The specific source locations used for each simulated house are listed in Appendix B but in general the source locations included:

- Closed garage (if applicable to the model house)
- First floor room (kitchen or other most likely such room based on floor plan)

- An additional location in either the basement (if applicable to the model house, bedroom or den furthest away from master bedroom or in smallest bedroom or den if master bedroom is on 1st floor) if finished basement) OR crawlspace (if applicable) OR a second room on the first floor room if there is no basement (bedroom furthest away from master bedroom or other likely space)

The simulations require CO emission rates (g/h) and input values for source duration and source heat release rate. These were supplied by CPSC staff, derived from an analysis of currently marketed generators, and generator products/sizes identified in CPSC incident databases (Hnatov et al. 2016). Table 2 summarizes values for all of these modeled variables for four size ranges of generator products: HH (generators powered by spark-ignited (SI) handheld engines), C1 (generators powered by SI Class I non-handheld engines), C2 (generators powered by SI Class II non-handheld single cylinder engines) and C2 twin (generators powered by SI Class II non-handheld twin cylinder engines). For each generator size category, the baseline CO emission rate represents three times the EPA's 6-mode weighted ambient CO emission rates of carbureted engines used in multiple brands of popular generators (see Appendix C for more information on this factor). Table 2 also contains six potential rule-compliant reduced CO emission rates (to support the analysis of multiple options for cost-benefit analysis). The run-time represents the generators' advertised run time (determined by the CPSC market analysis to be representative of typical generators of that engine class, Hnatov et al. 2016), for one full tank of gasoline, when operated at half-load, which nominally represents the weighted load of the 6-mode profile. Two schedules were used for each generator size. The first was a full tank operation starting at 12 a.m. (called full schedule) and the second was a half tank operation starting at 8 a.m. (called half schedule).

Table 2 Baseline and reduced CO emission rates, run-times and heat rates for the generators

Generator size	**Baseline CO emission rate at reduced O_2 (g/h)**	**Reduced CO emission rates (g/h)**	**Run-time (h)**	**Heat release rate (kW)**	**Notes**
HH	900	50, 125, 250, 500	8	2	Only used in DH8 and MH1mod
C1	1800	50, 125, 250, 500, 1000	9	6	
C2 single	4700	50, 125, 250, 500, 1000, 2000	10	13	
C2 twin	9100	50, 125, 250, 500, 1000, 2000	9	25	Only used in GAR1 and GAR3

Notes: Baseline generators were simulated with a CO rate two-thirds of the table value for the first 2 hours of operation as the enclosed space starts at ambient oxygen level**.** Engine classifications are U.S. Environmental Protection Agency (EPA) definitions.

2.3 Simulation cases and output analysis

The simulations that were run are depicted in Figure 1, which shows the 40 buildings (37 houses and 3 detached garages), 3 source locations, up to 10 source strength levels, 28 days of weather and 2 schedule types. Note that not all combinations were simulated as not all buildings have garages, basements or crawlspaces and the HH and C2 twin sources were only used in 2 buildings.

Houses
- Detached (31)
- Manufactured (2)
-Attached (4)
-Garages (3)

Source locations
<u>Constant (for up to 10 hours)</u>
- closed garage (when applicable)
- basement/crawlspace (when applicable, first floor bedroom when there is no basement)
- kitchen

Up to 10 source strength levels for each of the source scenarios

Weather/schedule
- 14 days cold
- 7 days warm
- 7 days transition

Full and half schedule for each day

Figure 1 Schematic showing simulation cases

Each simulation corresponds to one house, one source location, one source strength, one schedule and one day of weather. The output of each simulation are the CO concentrations versus time in each zone of the house. Based on the simulation time step of 1 min, the output consists of 1440 concentrations values in each zone over each 24-h simulation. As noted earlier, the CO generation commenced either at the beginning of each 24-h period for the full schedule or at 8 a.m. for the half schedule. After the CO generation stopped, the indoor CO concentrations started decreasing back to ambient levels.

2.4 COHb time profile calculation

The COHb (%) level reflects the percentage share of the body's total hemoglobin pool occupied by CO. In acute, modeled exposure scenarios, it serves as a useful measure to compare expected poisoning severity in a reference individual. COHb levels were calculated for an occupant in each occupiable zone of the house and garage over the 24-h simulation period using the Coburn-Forster-Kane (CFK) non-linear differential equation (Peterson and Stewart 1975, Coburn et al. 1965) and input values determined in consultation with CPSC, specifically three RMV (respiratory minute volume) values of 10 L/min (representing a time-weighted average 24 hour value for males and females 16 to 80 years old, for expected residential indoor activity), 12 L/min (representing a time-weighted 75th percentile 24 hour value for adult males and females 16 to 80 years old for expected residential indoor activity), and 6 L/min (representing a baseline 75th percentile 24 hour value for adult males and females 16 to 80 years old for sleeping/sedentary activity levels, especially likely in bedrooms) and an initial COHb level of 0.00056 ml/ml.

3. RESULTS

This section presents a sample of the results of the simulations discussed in the previous section for four of the modeled buildings.

3.1 Sample results for a small manufactured house (MH1mod)

This section presents sample results for the building MH1mod, which was created for this project as a smaller version of the manufactured house MH-1 (also included in this study) from the NIST suite of homes discussed earlier. Figure 2 shows the floorplan of MH1mod as represented in the CONTAM Sketchpad. MH1mod has 82.5 m^2 of floor area with 2 bedrooms, 1 bathroom and a kitchen. MH1mod was modeled with generators located in the kitchen, bedroom 2 and the crawlspace.

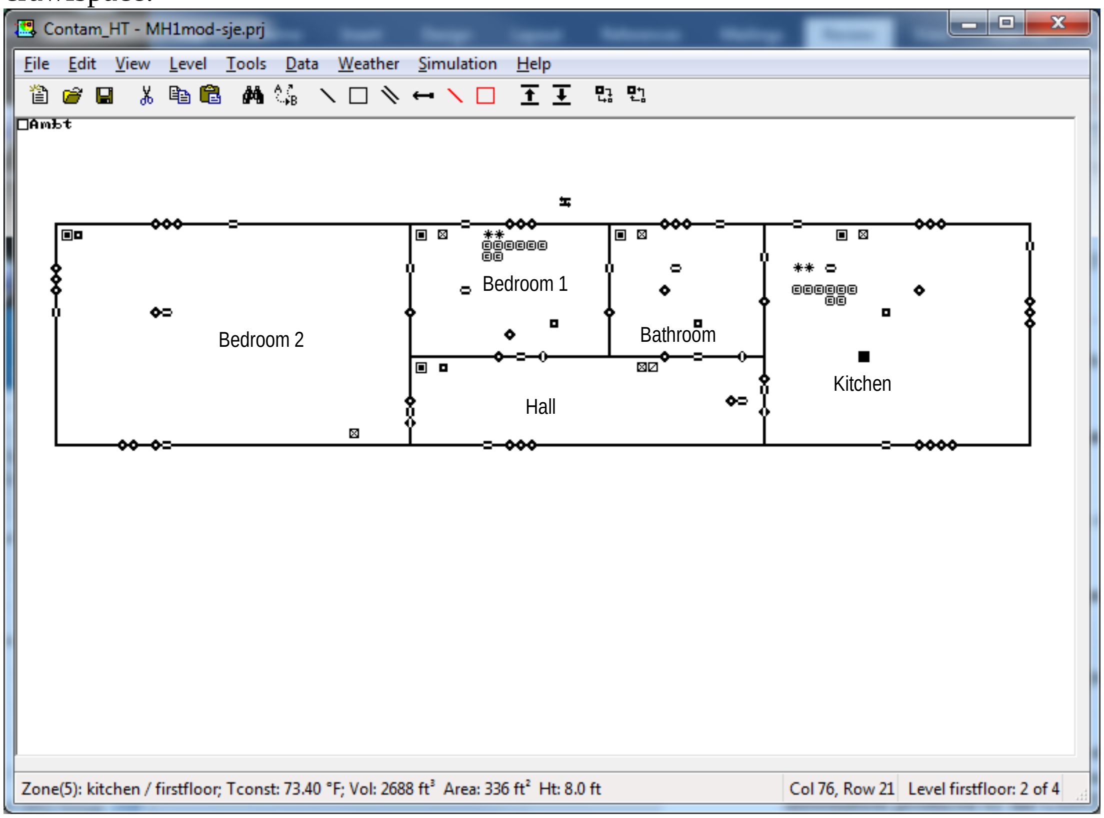

Figure 2 Floor plan of house MH1mod as represented in CONTAM

Figure 3 shows individual zone CO concentration results for the source located in bedroom 1 of house MH1mod on January 1st. Note that Figure 3 (and each of the following results plots) shows the results zone by zone for a single day along the x-axis. The concentration of CO in bedroom 1 reached a peak of over 8,000 µL/L (µL/L are equivalent to the commonly used unit for CO concentration of parts per million by volume or ppm_v) for the HH baseline source and peak concentrations ranged from around 1700 µL/L to 3000 µL/L in the other zones. Peak concentrations for the reduced rates of 50 g/h to 500 g/h were lower than the HH baseline source peaks by 40 % to more than 90 %.

Figure 4 shows individual zone COHb levels calculated with an RMV = 10 L/min for the same cases as Figure 3 (source in bedroom 1 on January 1st). Note that the calculation of COHb was cut off at 95 % for all cases because the calculated COHb levels are not meaningful at these high levels. Therefore, in some of the COHb figures the COHb is shown to artificially level off at 95 %. For reference, COHb levels of 70 % or greater are associated with death in less than 3 min, levels of 50 % are associated with headache, dizziness and nausea in 5 min to 10 min and death within 30 min, levels of 30 % with dizziness, nausea and convulsions within 45 min and becoming insensible within 2 h, and levels of 20 % with a slight headache in 2 h to 3 h and a loss of judgment (Goldstein 2008). In the absence of rescue, COHb levels that reach 60 % or more, typically end in acute lethal outcome (personal communication from S. Inkster of U.S. CPSC). The COHb quickly exceeded 40 % in all zones for both the HH and 500 g/h sources, but remained below 40 % in all zones for the 50 g/h source.

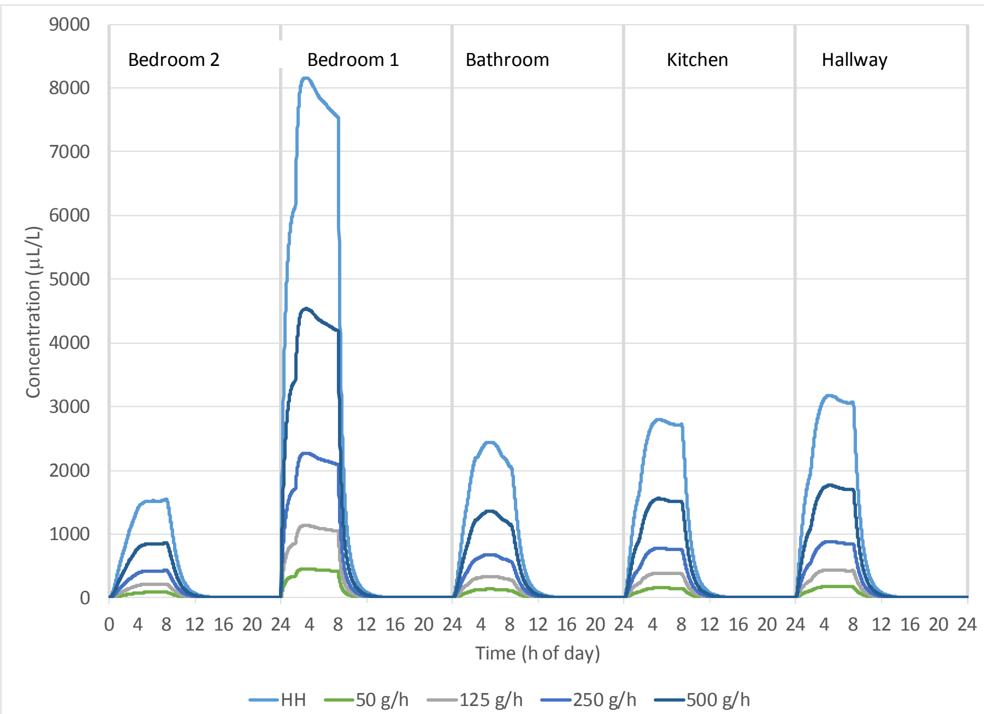

Figure 3 Individual zone transient CO results for the HH source in Bedroom 1 of MH1mod on January 1st

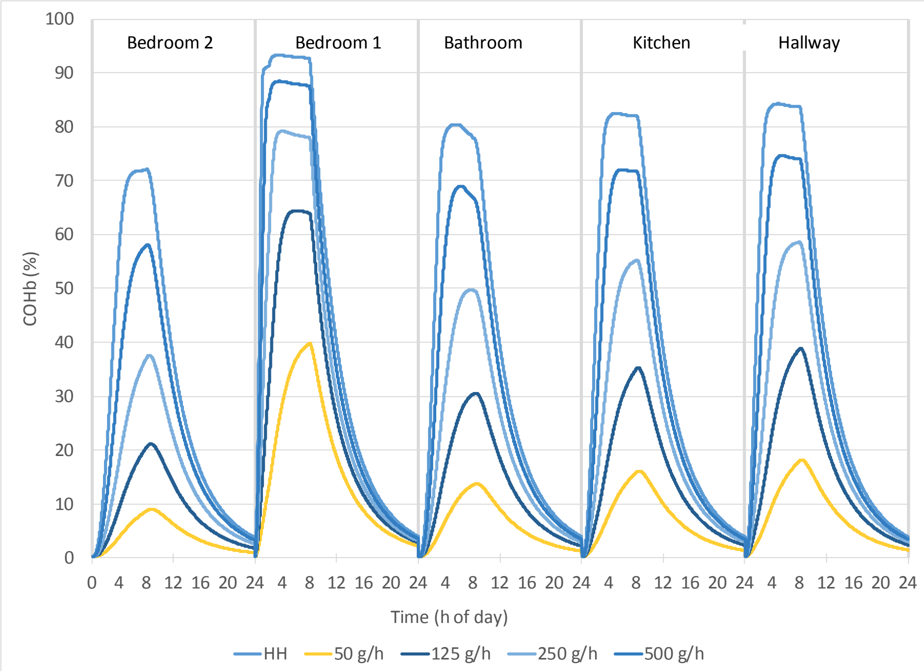

Figure 4 Individual zone transient COHb (RMV = 10 L/min) results for the HH source in Bedroom 1 of MH1mod on January 1st. Note that the calculation of COHb was cut off at 95 % for all cases.

Figure 5 shows individual zone CO concentration results for the source located in bedroom 1 of house MH1mod on July 25th. Due to the lower infiltration rate caused by the smaller indoor to outdoor temperature difference during the warmer weather, the concentration of CO in bedroom 1 reaches a much higher peak of over 16,000 μL/L for the HH baseline source (900 g/h), with peak concentrations ranging from around 7000 μL/L to 10,000 μL/L in the other zones. Reductions in peak concentrations for the reduced emission rates of 50 g/h to 500 g/h compared to the baseline HH source were similar to the January 1st reductions of 40 % to over 90 %.

Figure 6 shows zone COHb values calculated with an RMV = 10 L/min for the same cases as Figure 5 (source in bedroom 1 on July 25th). The COHb quickly exceeded 40 % in all zones for most of the source strengths. The COHb remained below or peaked at around 40 % in the non-source zones for the 50 g/h source.

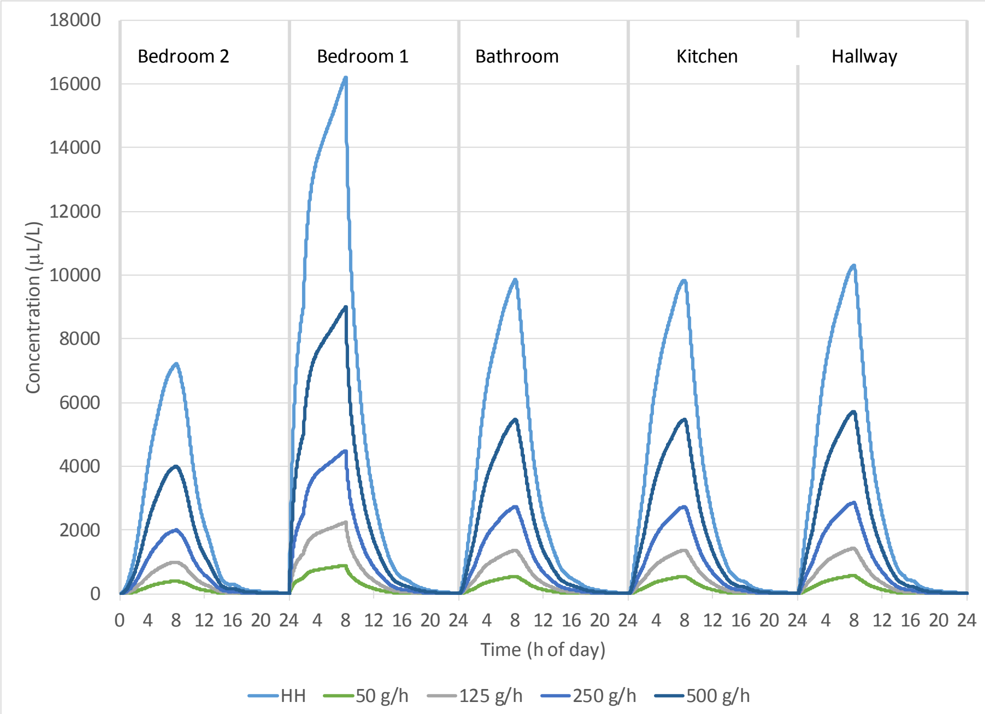

Figure 5 Individual zone transient CO results for the HH source in Bedroom 1 of MH1mod on July 25th

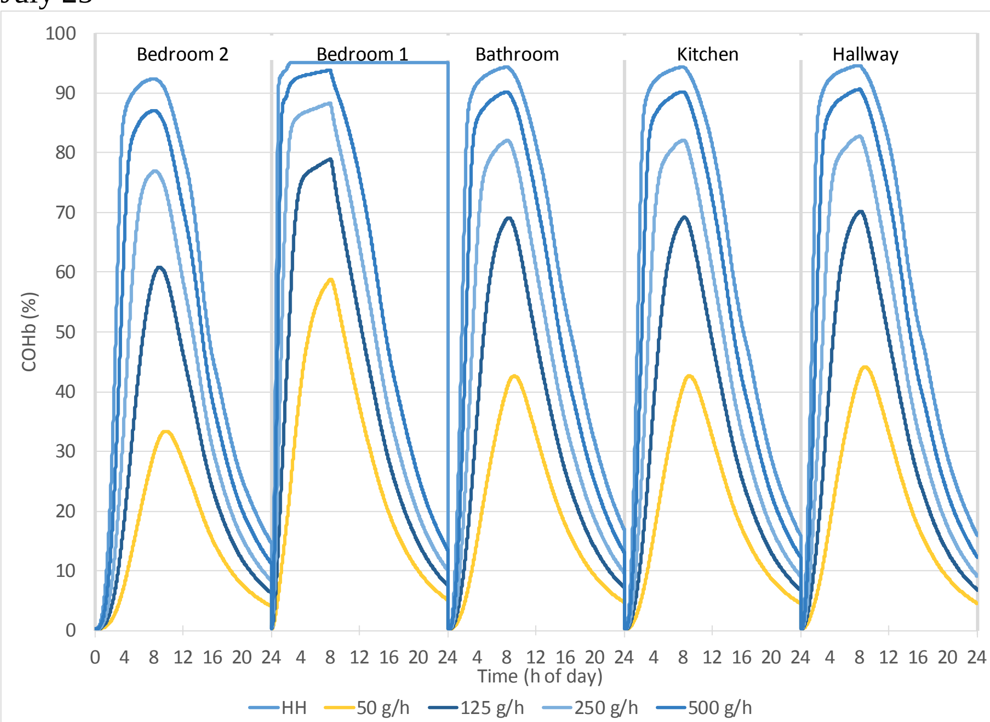

Figure 6 Individual zone transient COHb (with RMV = 10 L/min) results for the HH source in Bedroom 1 of MH1mod on July 25th

Figures 7 and 8 show individual zone CO concentration and COHb results, respectively, for the C1 source (1800 g/h, generators powered by SI class I non-handheld engines) and reduced rate sources located in bedroom 1 of house MH1mod on January 1st. Since the C1 source is twice as strong as the HH source, the CO concentrations for the baseline case reach much higher concentrations in Figure 7 compared to Figure 3. However, the increase is less than a full doubling, which is likely due primarily to air change rate differences since the C1 source has a higher heat release rate and thus results in higher zone temperatures. The higher zone temperatures mean the indoor-outdoor temperature difference that drives infiltration is larger. The higher air change rate with the C1 source also results in somewhat lower CO concentrations for the reduced rate sources in Figure 7 compared to Figure 3. Reductions in peak concentrations for the reduced emission rates of 50 g/h to 1000 g/h compared to the baseline C1 source peaks ranged from 40 % to over 90 %. The COHb results shown in Figure 8 were generally similar to those of Figure 4 with somewhat higher results for the larger C1 baseline case compared to the HH baseline as the COHb quickly exceeded 40 % in all zones for most of the source strengths. The COHb remained below 40 % in all zones for the 50 g/h source and in the non-source zones for the 125 g/h source.

Figures 9 and 10 show individual zone CO concentration and COHb results, respectively, for the C1 source (1800 g/h) and reduced rate sources located in bedroom 1 of house MH1mod on July 25th. As with the January 1st results the stronger C1 source resulted in higher, but less than double, CO concentrations for the baseline case in Figure 9 compared to Figure 5. Reductions in peak concentrations for the reduced rates of 50 g/h to 1000 g/h compared to the baseline C1 source peaks again ranged from around 40 % to over 90 %. The COHb results shown in Figure 10 were generally similar to those of Figure 6 with somewhat higher results for the larger C1 baseline case compared to the HH baseline as the COHb quickly exceeded 40 % in all zones for most of the source strengths. The COHb remained below 40 % in non-source zones for the 50 g/h source only.

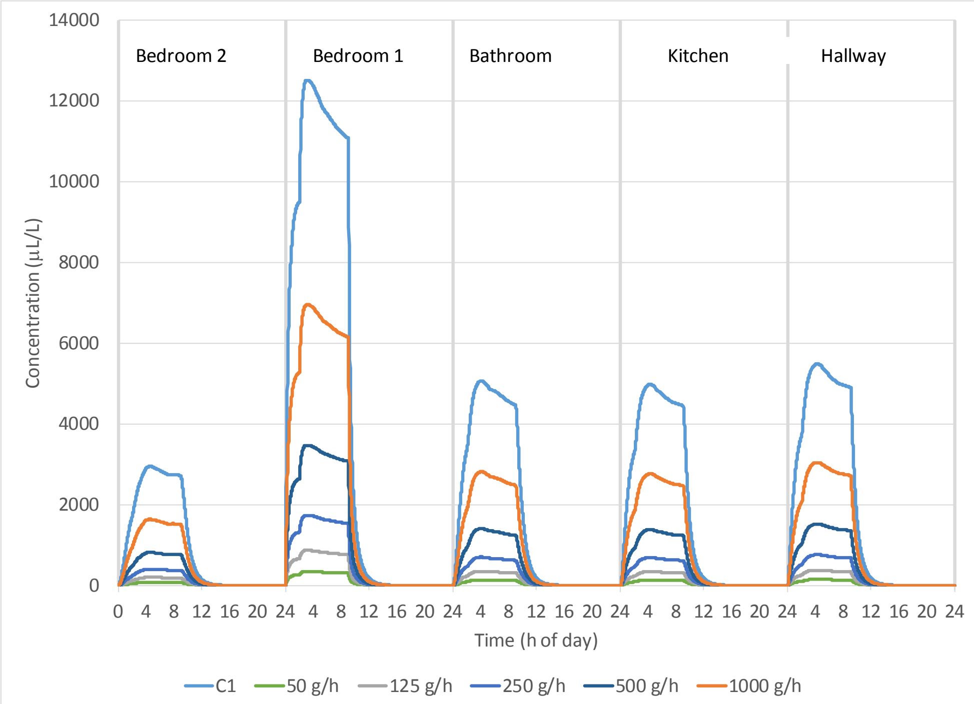

Figure 7 Individual zone transient CO results for the C1 source in Bedroom 1 of MH1mod on January 1st

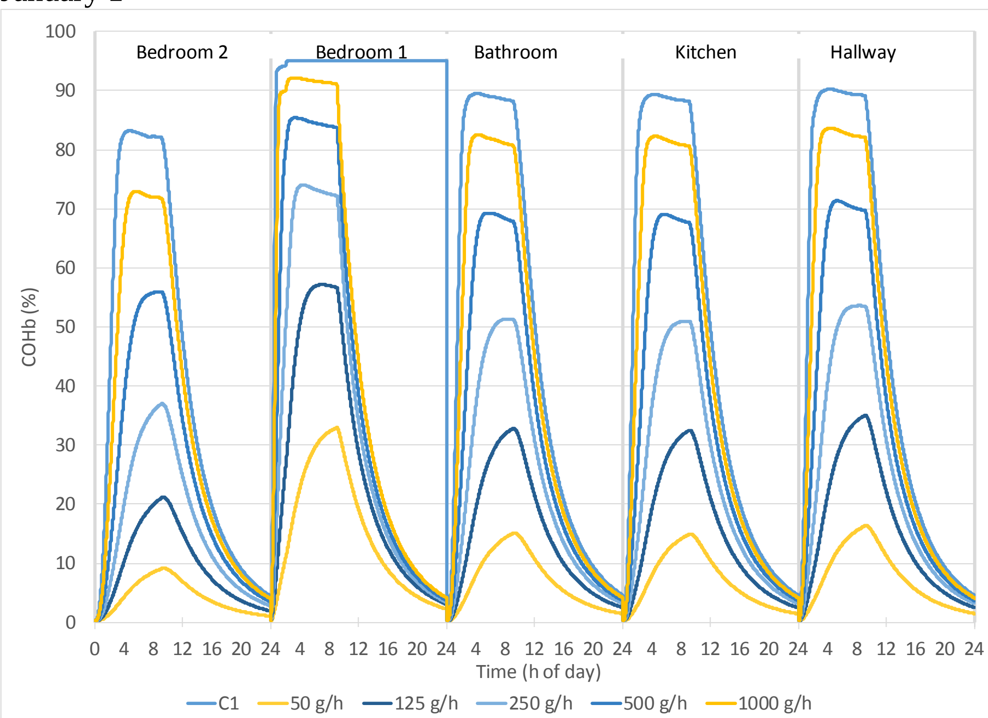

Figure 8 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Bedroom 1 of MH1mod on January 1st

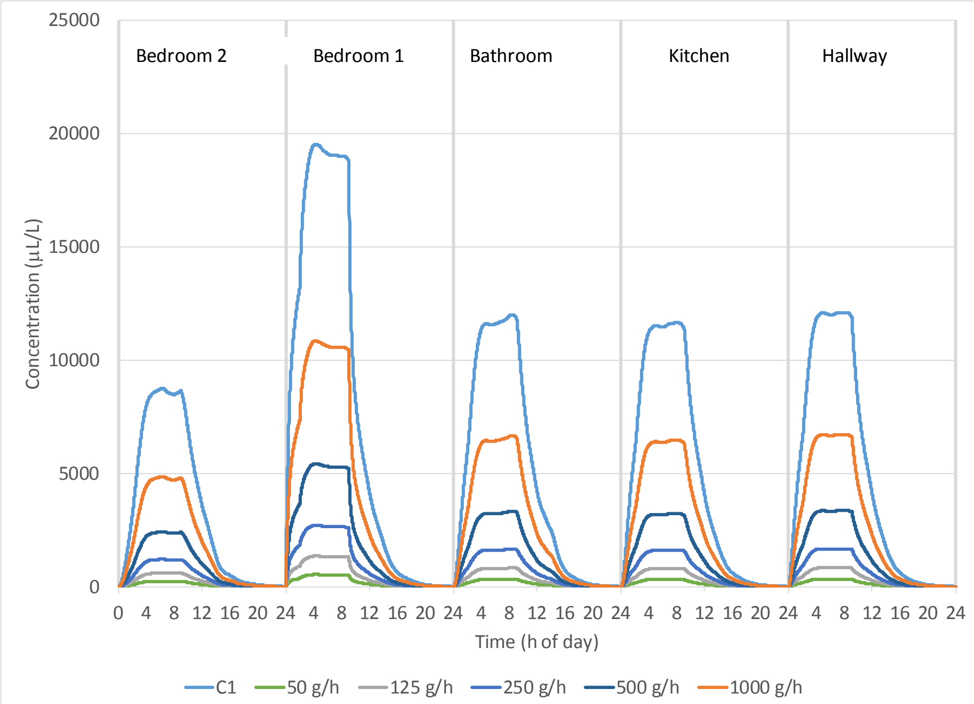

Figure 9 Individual zone transient CO results for the C1 source in Bedroom 1 of MH1mod on July 25th

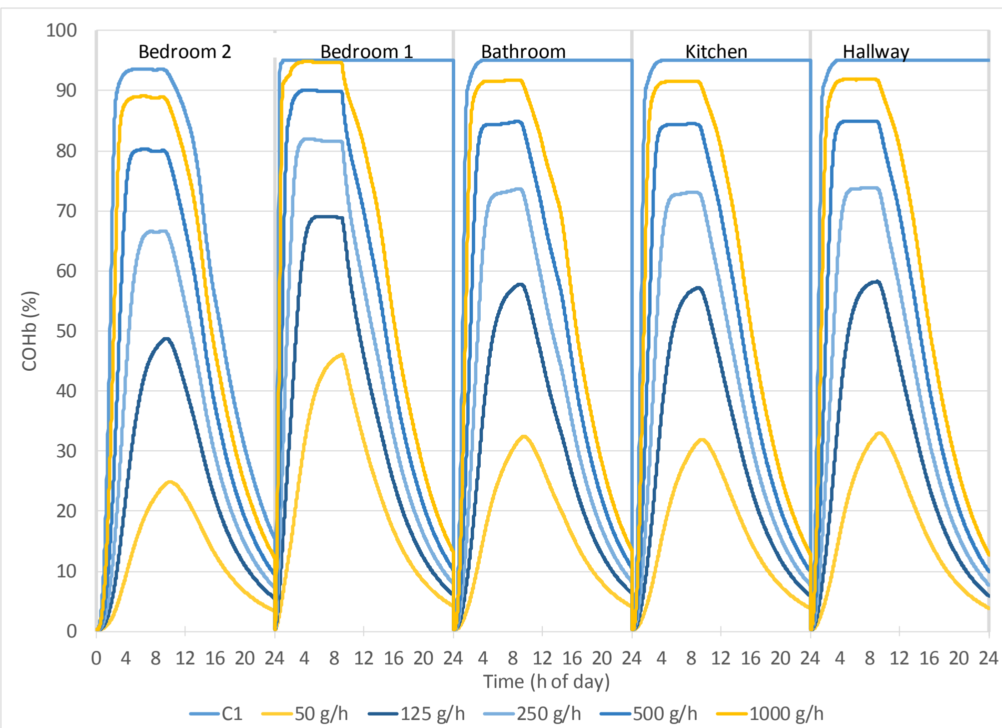

Figure 10 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Bedroom 1 of MH1mod on July 25th

The previous results in Figures through 9 were all for cases with the generator in the bedroom 1 zone. Figures 11 and 12 show individual zone CO concentration and COHb results, respectively, for the C1 source and reduced sources for the generator located in the kitchen of house MH1mod on January 1st. As discussed in Section 2.2.1, kitchens, including the kitchen zone of MH1mod, were connected to adjacent zones with fully open doorways rather than slightly ajar doors. As seen in Figure 11, this results in lower CO concentrations in the source zone (kitchen of Figure 11 compared to bedroom 1 of Figure 7) but higher CO concentrations in the non-source zones. However, reductions in peak concentrations for the reduced rates of 50 g/h to 1000 g/h compared to the baseline C1 source still ranged from around 40 % to over 90 %. The COHb results shown in Figure 12 were generally similar to those of Figure 8, with the COHb quickly exceeding 40 % in all zones for most of the source strengths but remaining near or below 40 % in all zones for the 50 g/h source and in the non-source zones for the 125 g/h source.

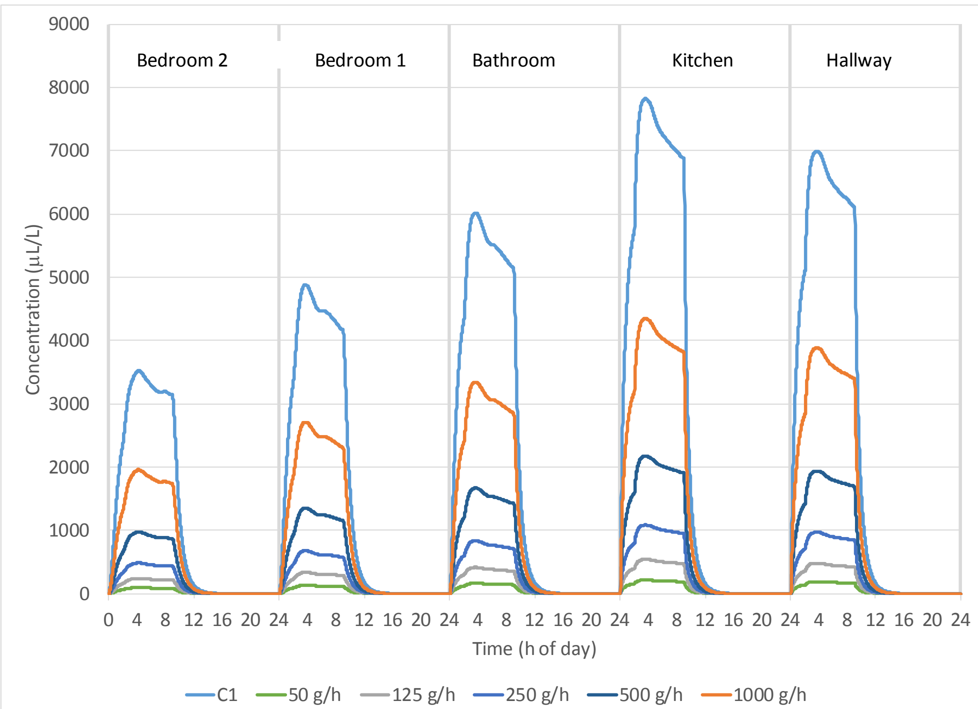

Figure 11 Individual zone transient CO results for the C1 source in Kitchen of MH1mod on January 1st

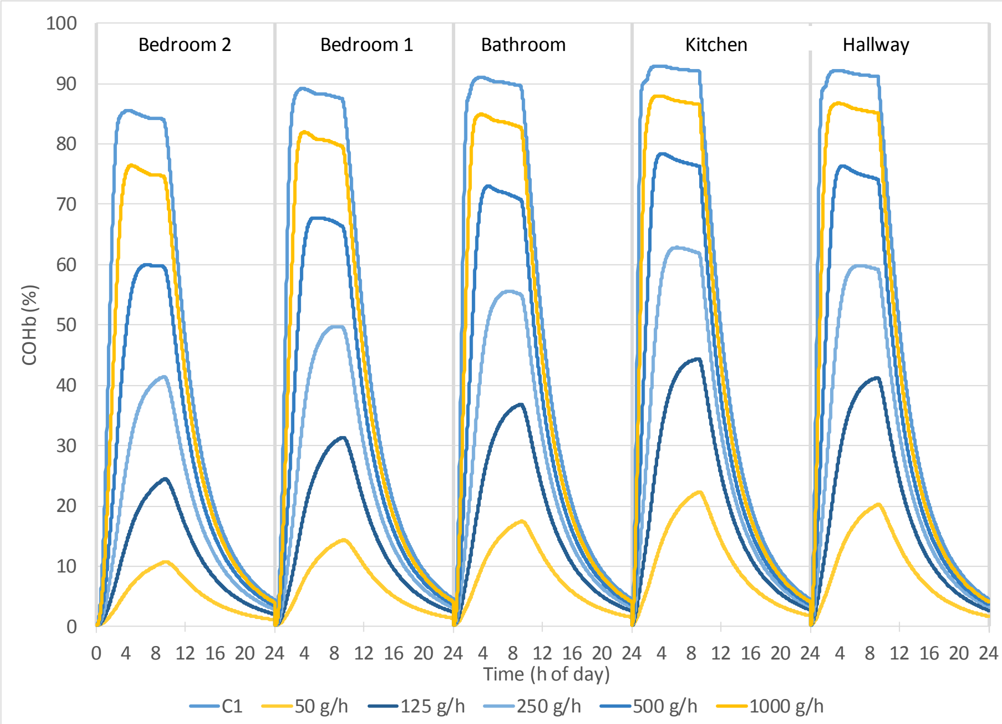

Figure 12 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Kitchen of MH1mod on January 1st

Figures 13 and 14 show individual zone CO concentration and COHb results, respectively, for the C1 source and reduced rate sources located in the kitchen of house MH1mod on July 25th. As with the bedroom 1 source location, the warmer temperatures (and lower air change rates) on July 25th result in higher CO concentrations and COHb compared to the January 1st results shown in Figures 11 and 12.

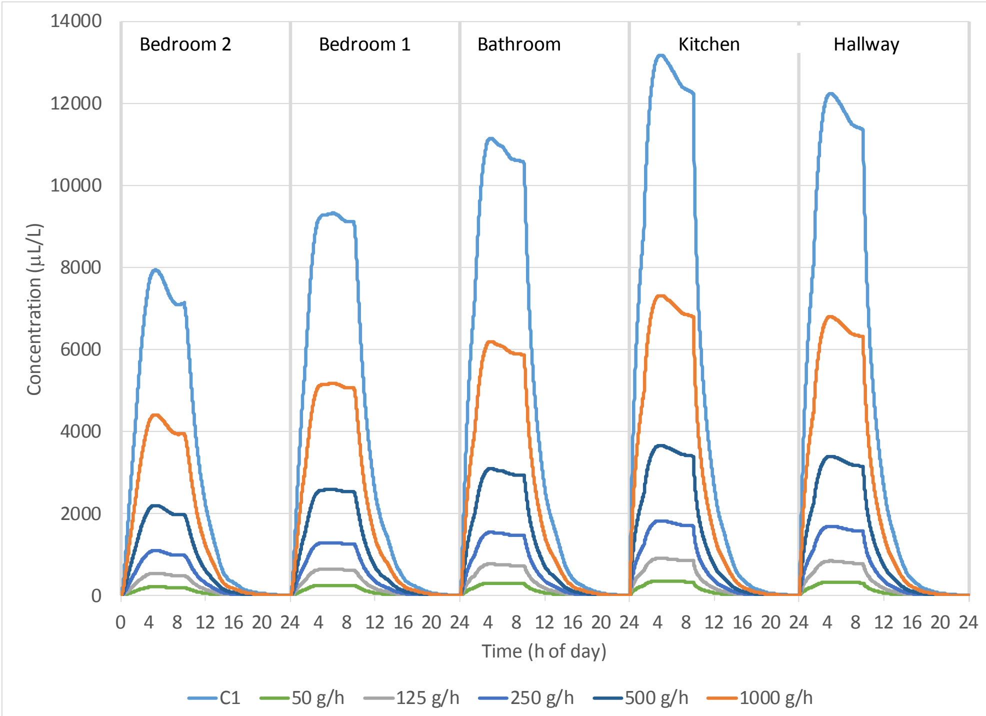

Figure 13 Individual zone transient CO results for the C1 source in Kitchen of MH1mod on July 25^{th}

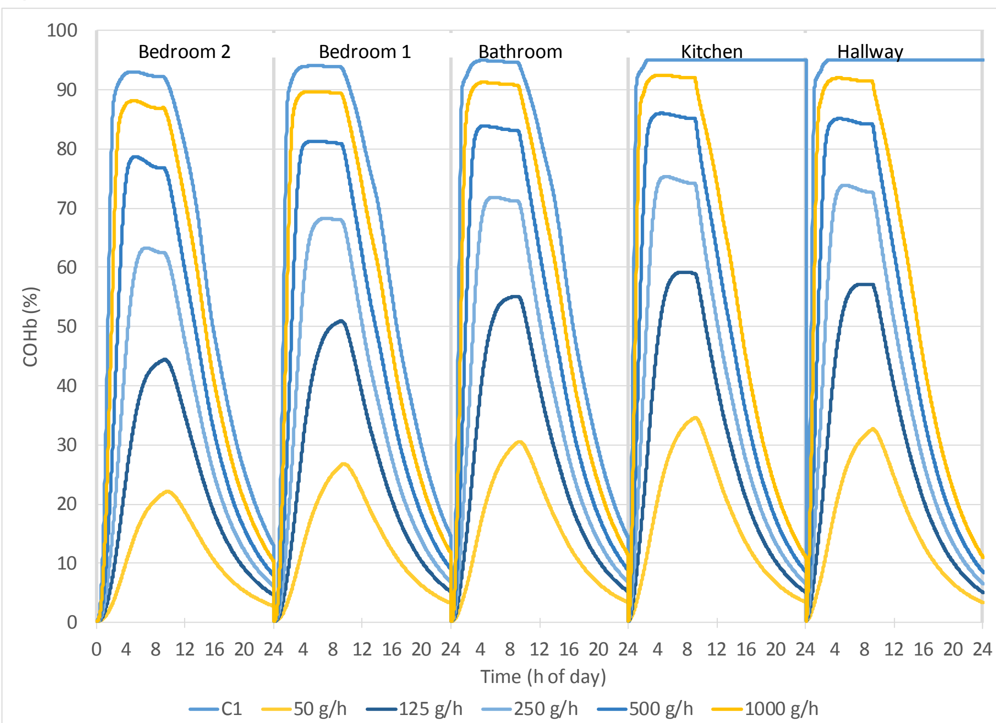

Figure 14 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Kitchen of MH1mod on July 25^{th}

3.2 Sample results for a mid-sized detached house with basement and integral garage (DH-45mod)

This section presents example results for building DH-45mod, which was created for this project based on the detached house DH-45 (also included in this study) from the NIST suite of homes. As described in Appendix B, two modifications were made to the DH-45 model. Part of the unfinished basement was converted to an integral garage and the air leakage was modified based on year built and floor area to represent the newest category of construction (1990 and newer) in the suite of homes analysis. Figure 15 shows the floorplan of DH-45mod as represented in the CONTAM Sketchpad. DH-45mod has 180 m^2 of floor area with a kitchen, dining room, living room, two bathrooms and one bedroom on the first floor and three bedrooms, a bathroom and a den on the second floor. DH-45mod was modeled with generators located in the kitchen, the unfinished basement and the garage.

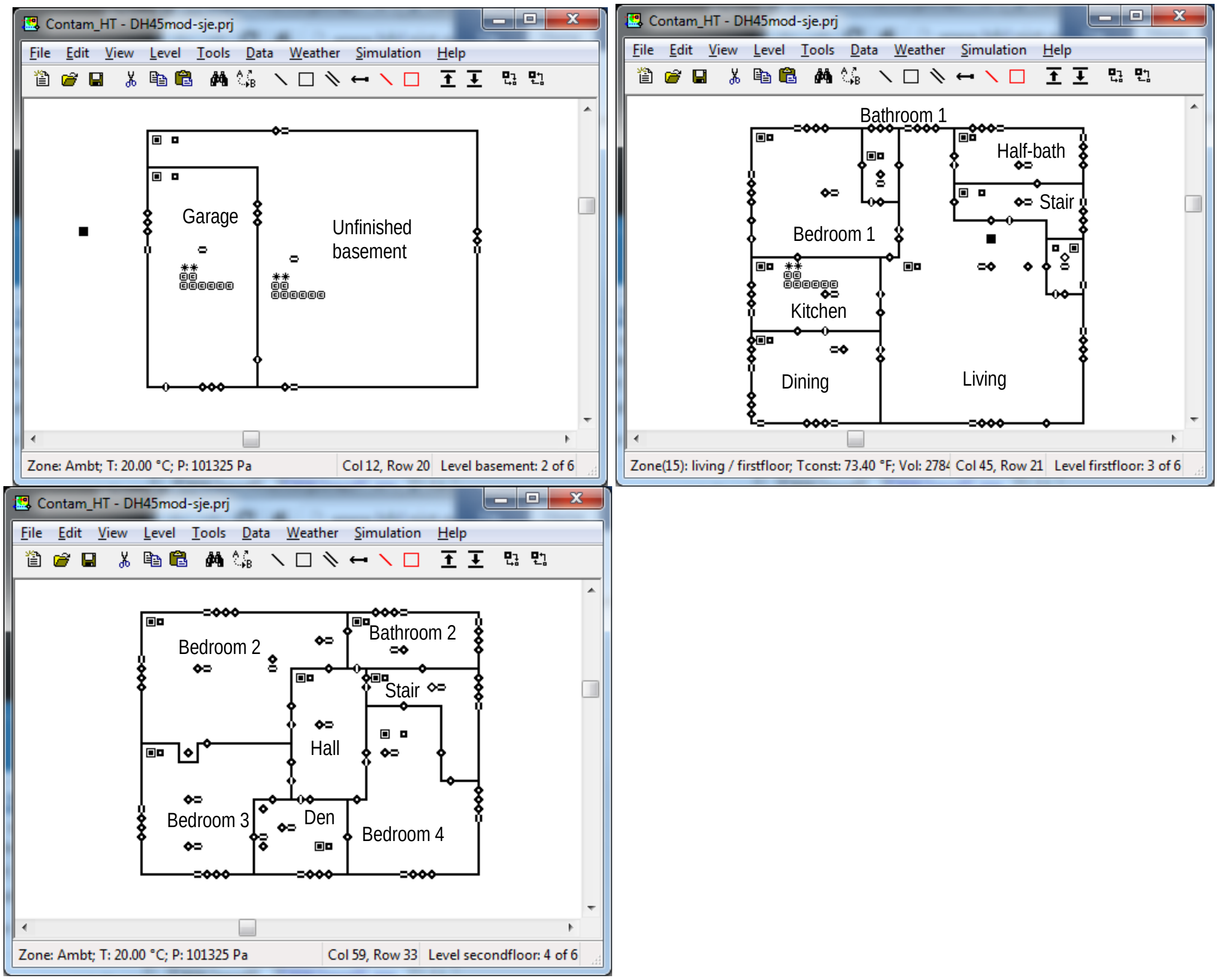

Figure 15 Floor plan of house DH-45mod as represented in CONTAM

Figures 16 and 17 show individual zone CO concentration and COHb results, respectively, for the C1 source and reduced rate sources located in the garage of house DH-45mod on January 1st. The peak CO concentrations resulting from the C1 baseline source reached around 17,000 μL/L in the source zone, over 14,000 μL/L in the adjacent unfinished basement zone and from around 8,000 μL/L to 10,000 μL/L in the remaining non-source zones. Reductions in peak concentrations for the reduced rates of 50 g/h to 1000 g/h, compared to the baseline C1 source peaks, were similar to those seen for the MH1mod cases and ranged from over 40 % to well over 90 %. As with many of the MH1mod cases, the COHb shown in Figure 17 exceeded 40 % in all zones for most of the source strengths, but remained below 40 % in all non-source zones for just the 50 g/h source. However, COHb generally increased more gradually in the 1st and 2nd floor zones since the source was in the garage on the basement level.

Figures 18 and 19 show individual zone CO concentration and COHb results, respectively, for the C1 source and reduced rate sources located in the garage of house DH45-mod on July 25th. As with the MH1mod cases, the warmer temperatures on July 25th result in significantly higher CO concentrations in the source zone than on January 1st (results in Figure 16). However, the results for the 1st and 2nd floor zones are much different on July 25th, as the 1st floor concentrations are somewhat lower and the 2nd floor concentrations are significantly lower compared to January 1st. The warmer outdoor air reduces the flow of air from the basement up to the 1st and 2nd floors due to a smaller indoor to outdoor temperature difference. However, the reductions in peak concentrations for the reduced sources are still in a range of over 40 % to over 90 % compared to the baseline C1 source. As seen in Figure 19, the COHb results were also quite different on July 25th compared to January 1st, with somewhat lower values for the 1st floor zones and significantly lower values for the 2nd floor zones, including a few zones that stayed below 40 % for all source strengths.

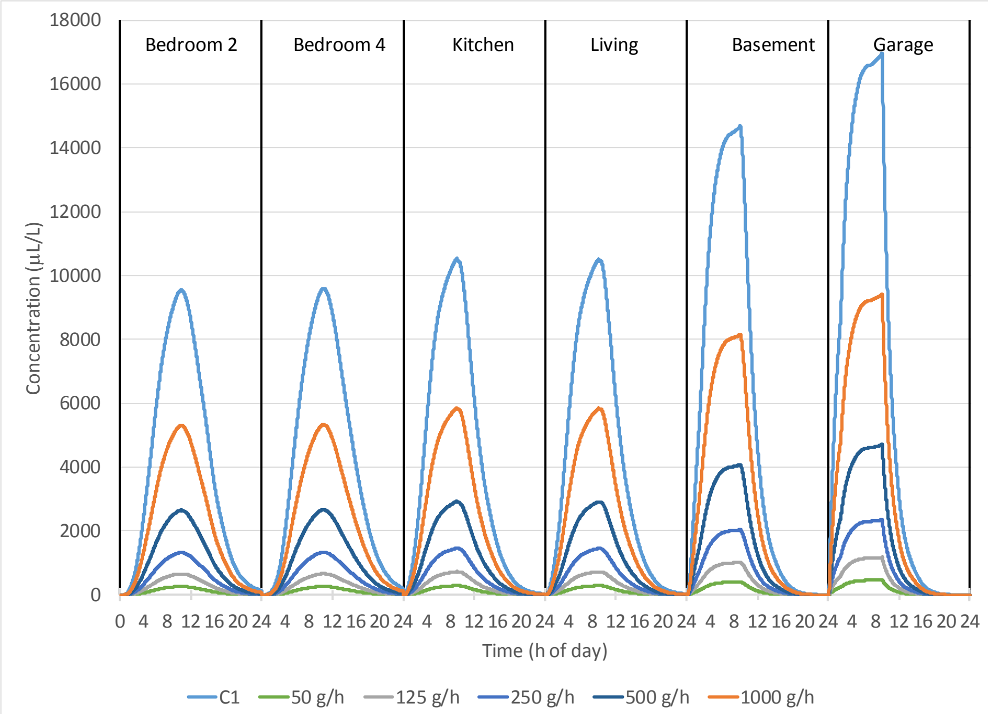

Figure 16 Individual zone transient CO results for the C1 source in Garage of DH-45mod on January 1st

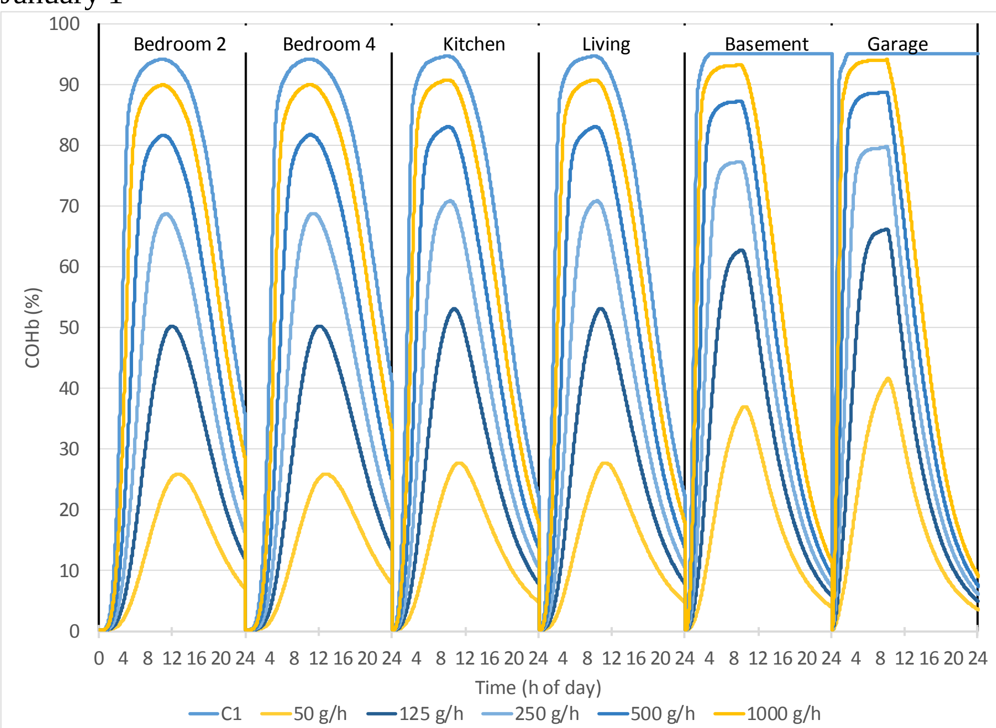

Figure 17 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Garage of DH-45mod on January 1st

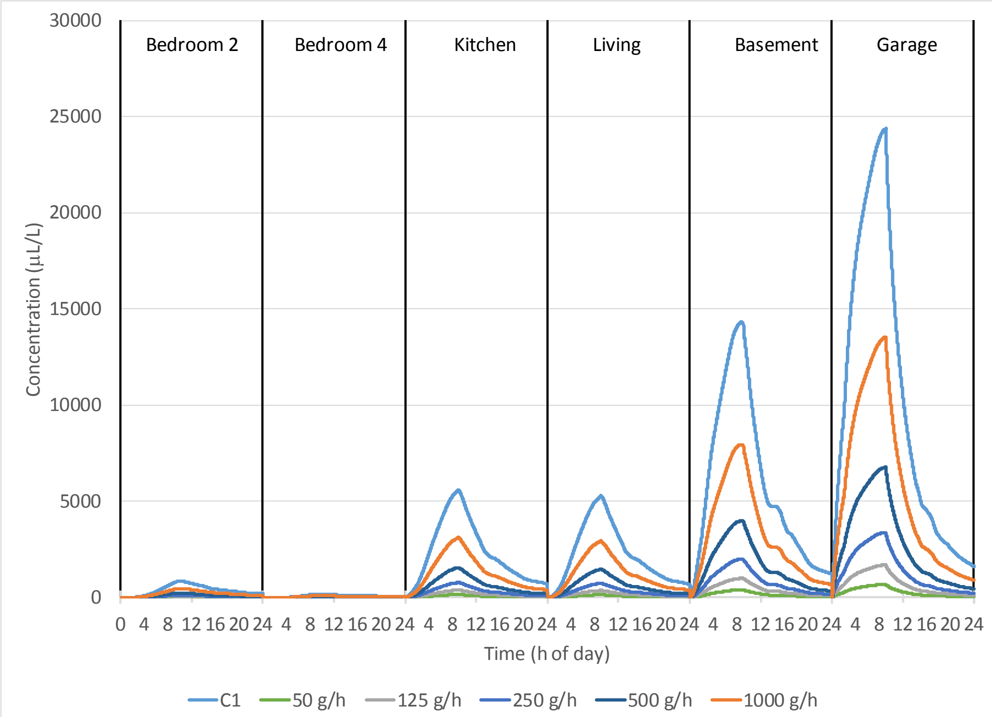

Figure 18 Individual zone transient CO results for the C1 source in Garage of DH-45mod on July 25th

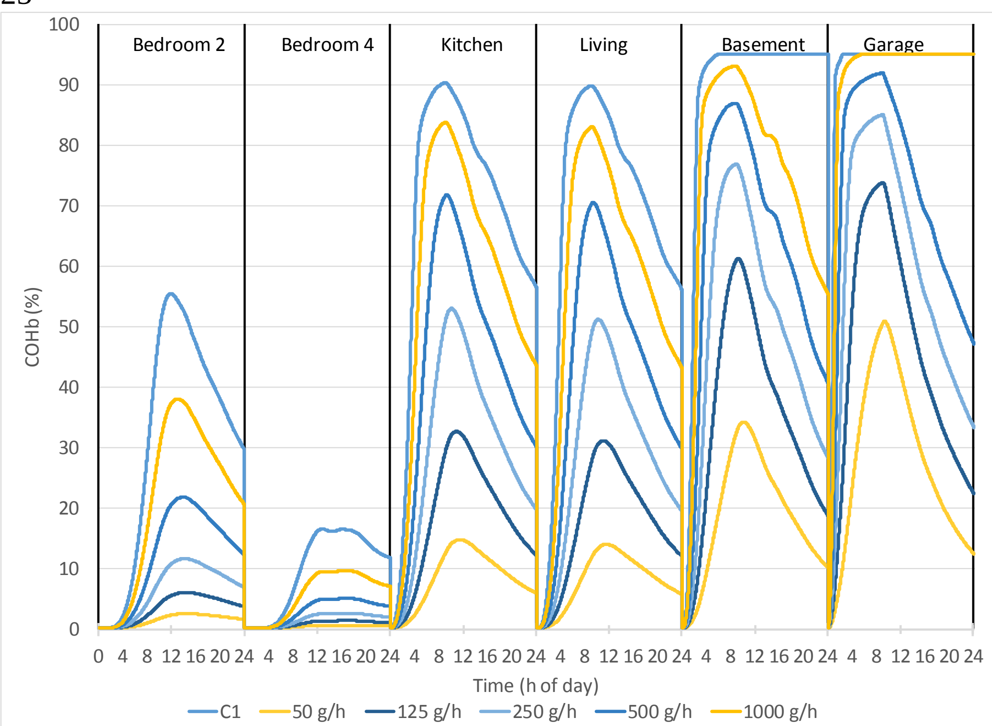

Figure 19 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in garage of DH-45mod on July 25th

Figures 20 and 21 show individual zone CO concentration and COHb results, respectively, for the C1 source (baseline 1800 g/h) and reduced rate sources located in the kitchen of house DH-45mod on January 1st. The peak CO concentrations resulting from the C1 baseline source reached around 11,000 μL/L in the source zone and around 10,000 μL/L in most of the 1st and 2nd floor non-source zones. Concentrations were near zero in the basement zones due to cold outdoor temperatures resulting in stack effect primarily causing flow upwards within the house. Reductions in peak concentrations for the reduced rates of 50 g/h to 1000 g/h, compared to the baseline C1 source peaks, were similar to those seen for other cases and ranged from over 40 % to well over 90 %. The COHb shown in Figure 21 exceeded 40 % in nearly all zones for most of the source strengths but remained below 40 % in all non-source zones for just the 50 g/h source. However, COHb stayed well below 10 % on the basement level.

Figures 22 and 23 show individual zone CO concentration and COHb results, respectively, for the C1 source and reduced rate sources located in the kitchen of house DH-45mod on July 25th. As with the garage source in Figure 18, the warm ambient temperatures on July 25th result in significant variations in CO concentrations, depending primarily on the floor of the house. The peak CO concentrations resulting from the C1 baseline source reached over 25,000 μL/L in the source zone and most other 1st floor zones (well-connected due to fully open doorways), between 15,000 μL/L and 20,000 μL/L in the 2nd floor zones, and at or below 5,000 μL/L in the basement zones. Once again, the reductions in peak concentrations for the reduced sources are in a range of over 40 % to over 90 % compared to the baseline C1 source. As seen in Figure 23, the COHb results were also quite different on July 25th compared to January 1st, with somewhat lower values and slower increases for the 2nd floor zones and significantly lower values and much slower increases for the basement zones.

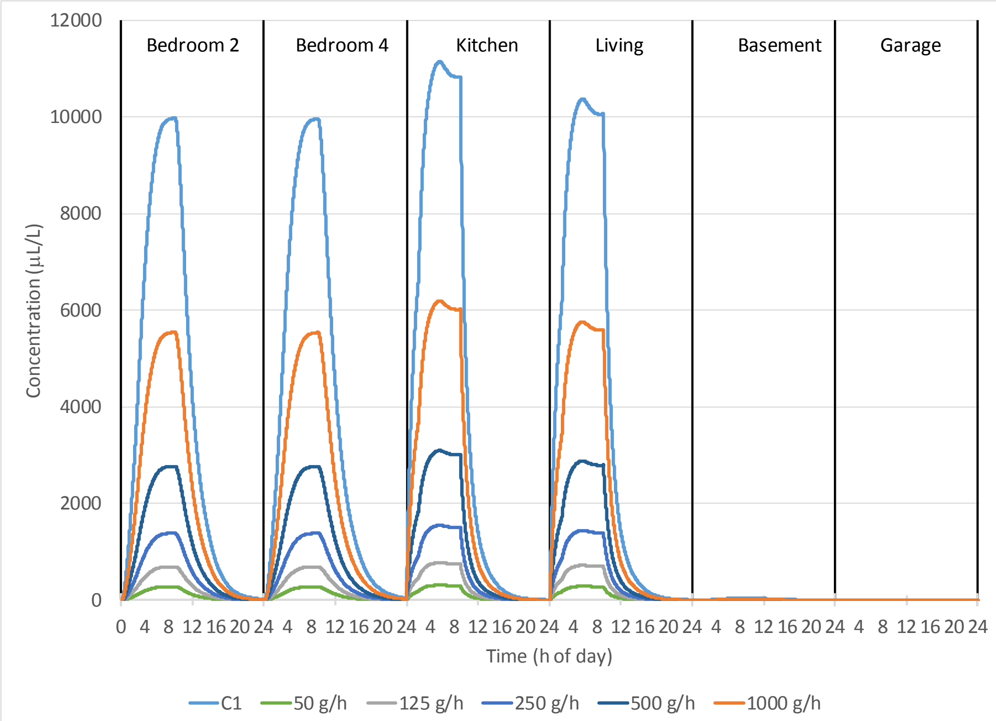

Figure 20 Individual zone transient CO results for the C1 source in Kitchen of DH-45mod on January 1st

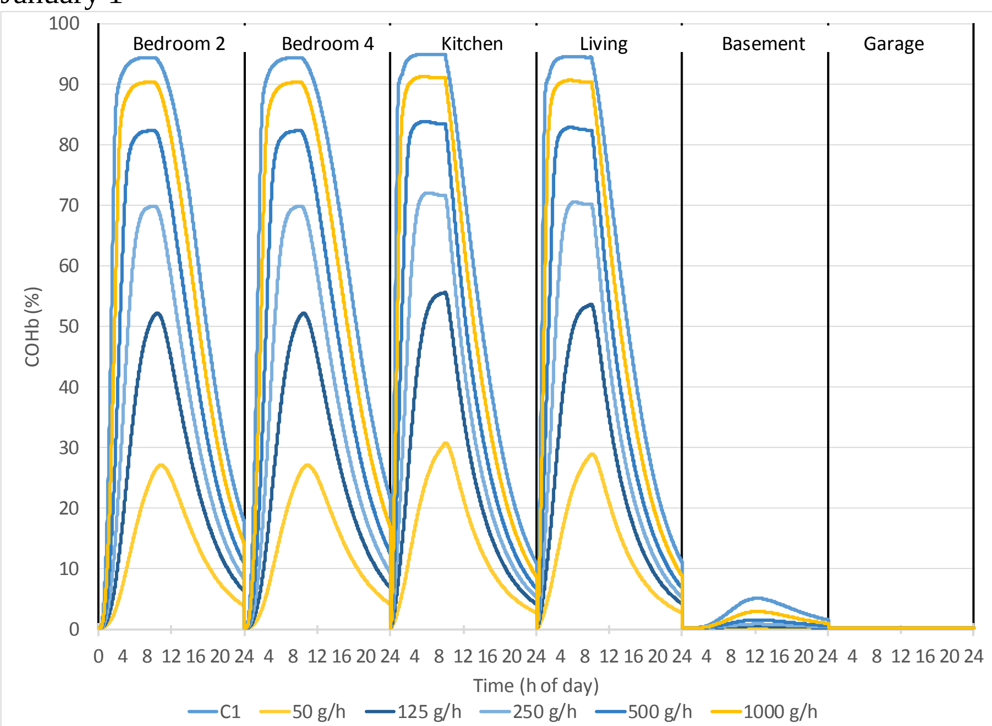

Figure 21 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Kitchen of DH-45mod on January 1st

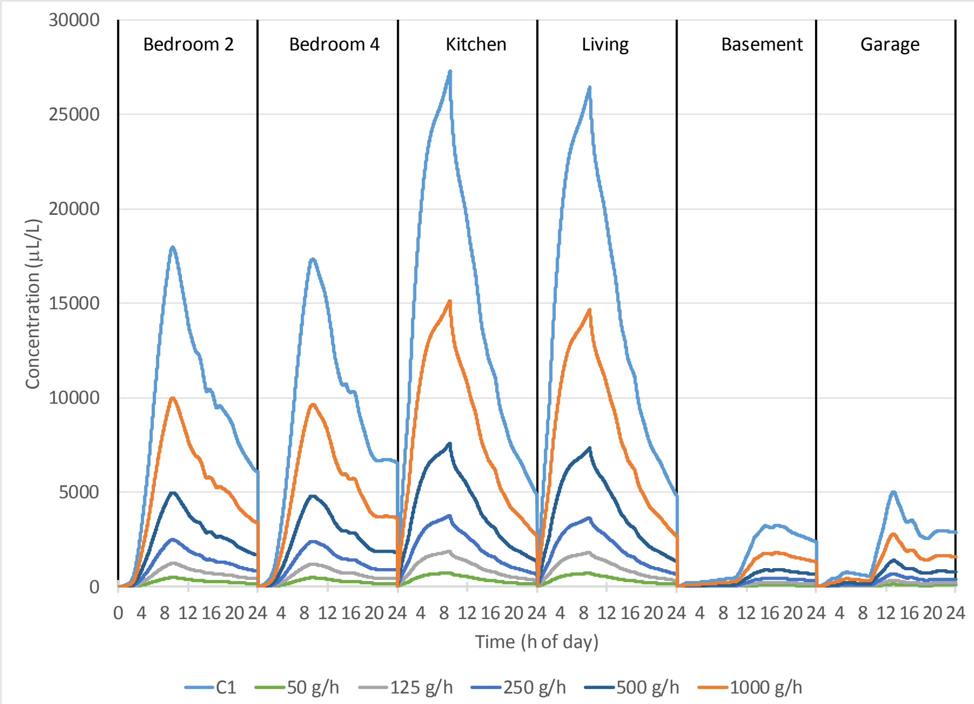

Figure 22 Individual zone transient CO results for the C1 source in Kitchen of DH-45mod on July 25th

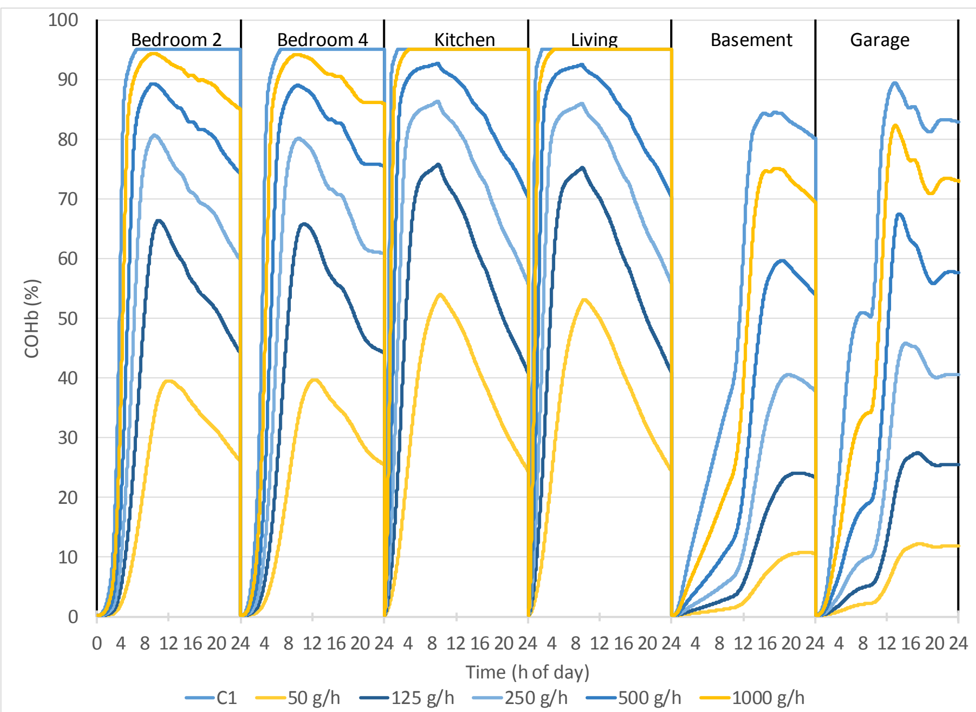

Figure 23 Individual zone transient COHb (with RMV = 10 L/min) results for the C1 source in Kitchen of DH-45mod on July 25th

3.3 Sample results for a large 2-story detached house with garage (DH-12)

This section presents simulation results for detached house DH-12 from the NIST suite of homes. Figure 24 shows the floorplan of DH-12 as represented in the CONTAM Sketchpad. DH-12 has 276 m^2 of floor area with a bedroom, den, family room and bathroom in the basement, a kitchen, dining room, living room, bathroom and attached garage on the first floor and three bedrooms and a bathroom on the second floor. DH-12 was modeled with generators located in the kitchen, bedroom 4 in the basement and the garage.

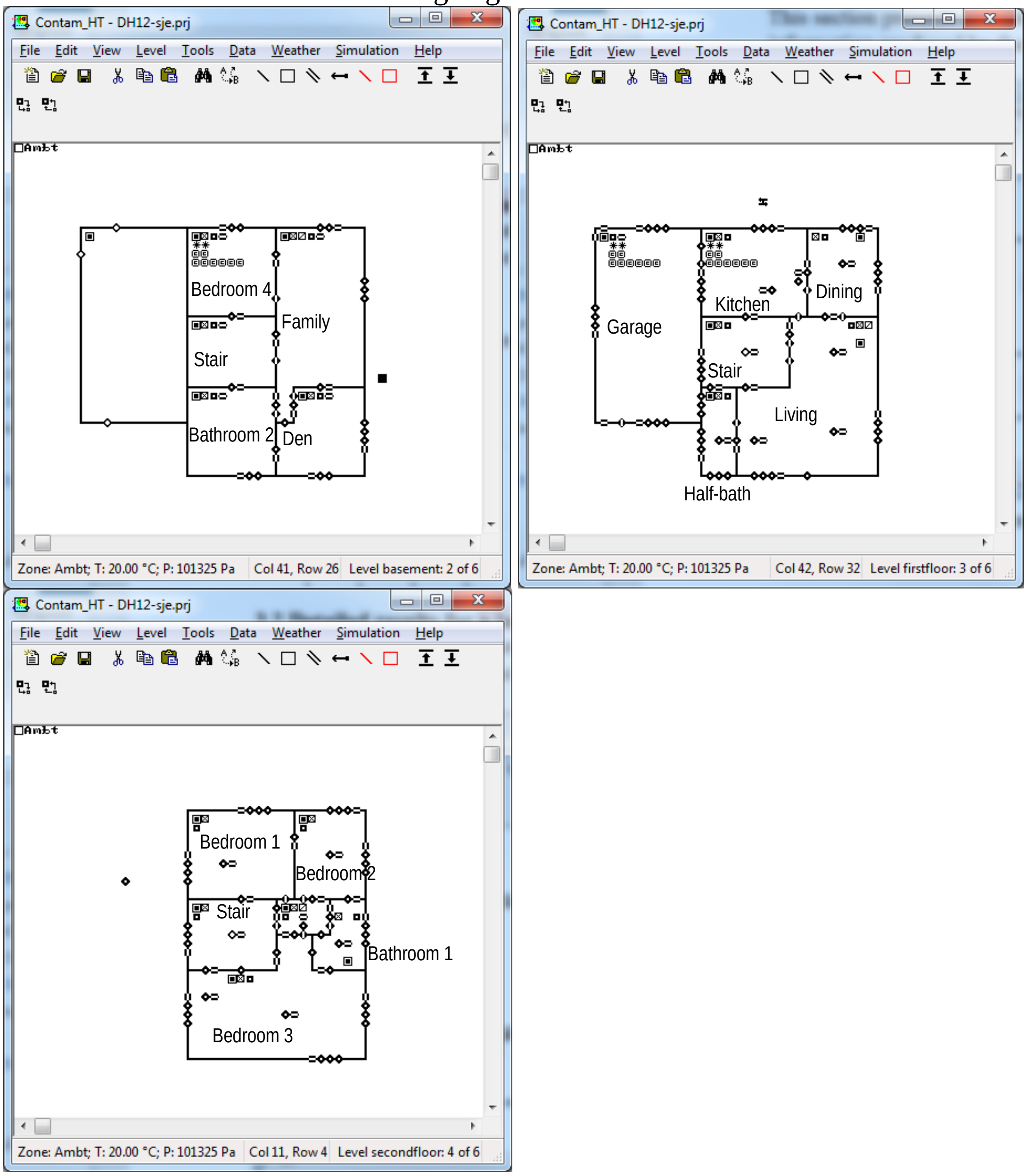

Figure 24 Floor plan of house DH-12 as represented in CONTAM

As with the DH-45mod results in Figures 16 through 23, the results for DH-12 shown in Figures 25 through 32 show significant variation by level of the house depending on the source location and weather. Figures 25 and 26 show individual zone CO concentration and COHb results, respectively, for the C2 single source (baseline 4700 g/h) and reduced rate sources located in the garage of house DH-12 on January 1st. The peak CO concentrations resulting from the C2 single baseline source reached around 20,000 μL/L in the source zone, around 3,000 μL/L to 6,000 μL/L in the non-source zones on the 1st and 2nd floors, and remained below 400 μL/L in the basement zones. Reductions in peak concentrations for the reduced rates of 50 g/h to 2000 g/h, compared to the baseline C2 single source peaks, were similar to those seen for the previous cases and ranged from over 50 % to well over 90 %. Unlike previous cases, the COHb shown in Figure 26 remained below 40 % in many non-source zones for reduced source strengths up to 500 g/h and below 40 % in the basement zones for all source strengths.

Figures 27 and 28 show individual zone CO concentration and COHb results, respectively, for the C2 single source and reduced rate sources located in the garage of house DH-12 on July 25th. For this case, the peak CO concentration reached around 23,000 μL/L in the garage but stayed below 2,000 μL/L in the other 1st floor zones, with little CO transport to the basement and none to the 2nd floor zones for this case. The reductions in peak concentrations for the reduced sources are still in a range of over 50 % to well over 90 % compared to the baseline C2 single source. As seen in Figure 28, the COHb remained below 40 % for all sources strengths up to 1000 g/h in all 1st floor non-source zones and below 20 % for all source strengths in the basement and 2nd floor zones.

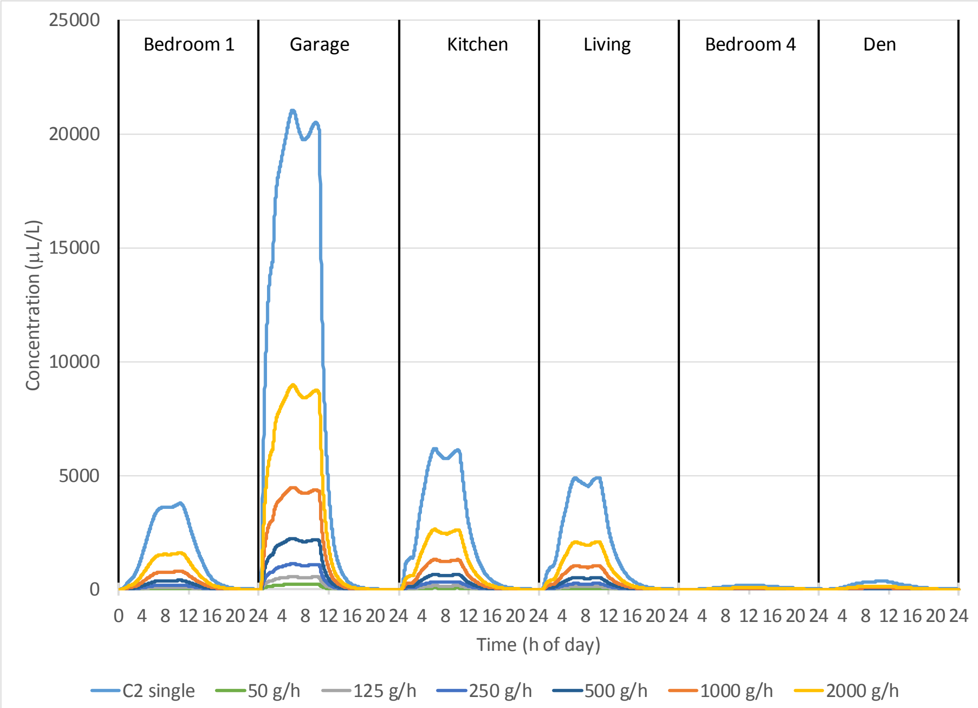

Figure 25 Individual zone transient CO results for the C2 single source in Garage of DH12 on January 1st

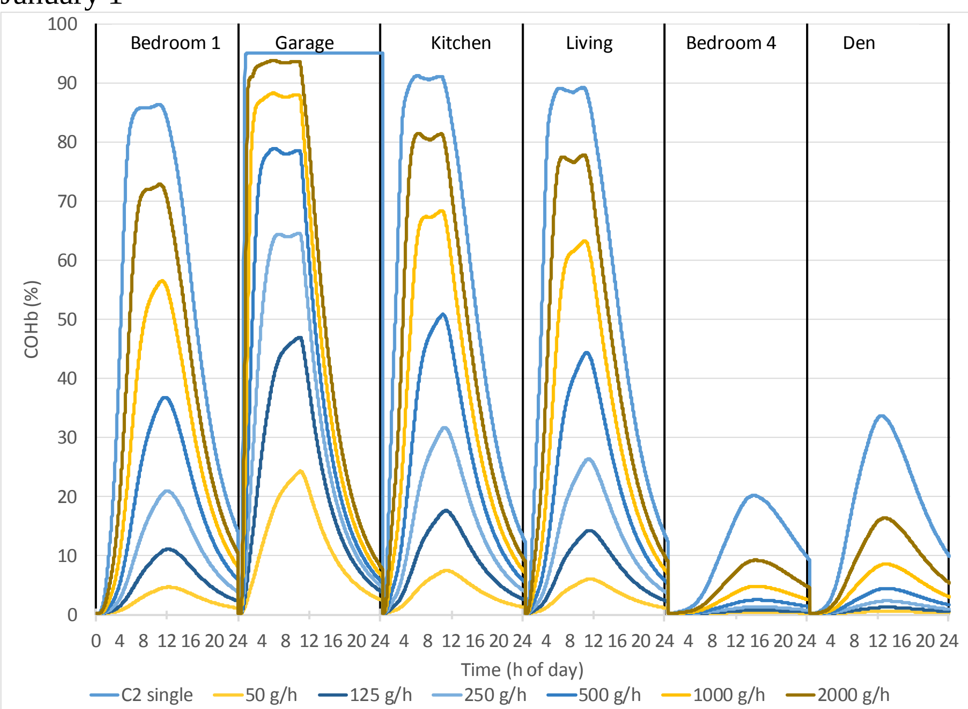

Figure 26 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 single source in Garage of DH12 on January 1st

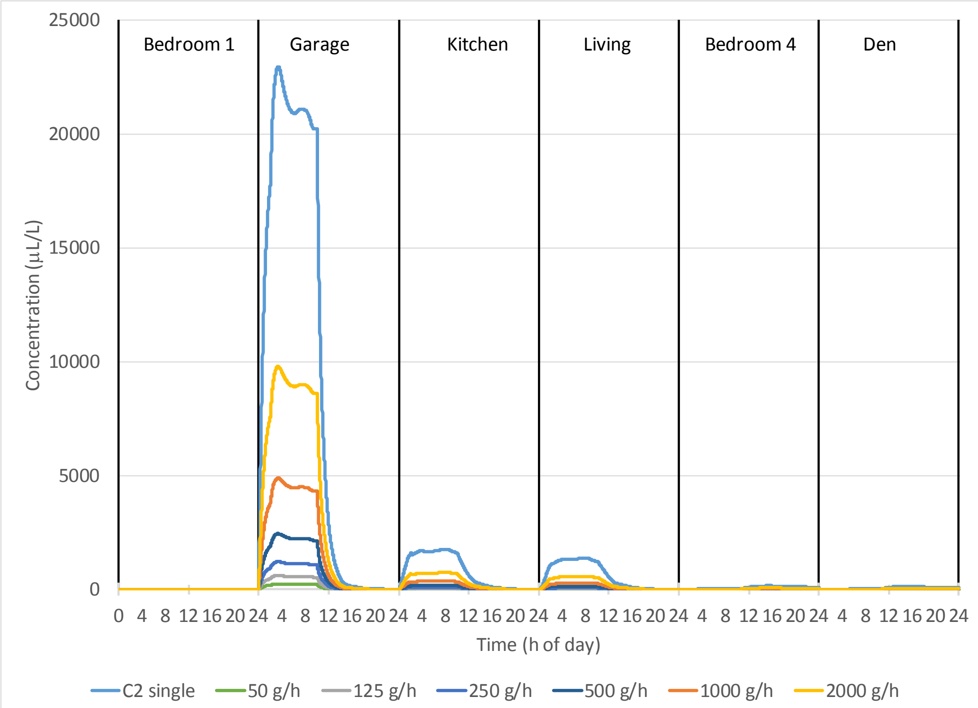

Figure 27 Individual zone transient CO results for the C2 single source in Garage of DH12 on July 25th

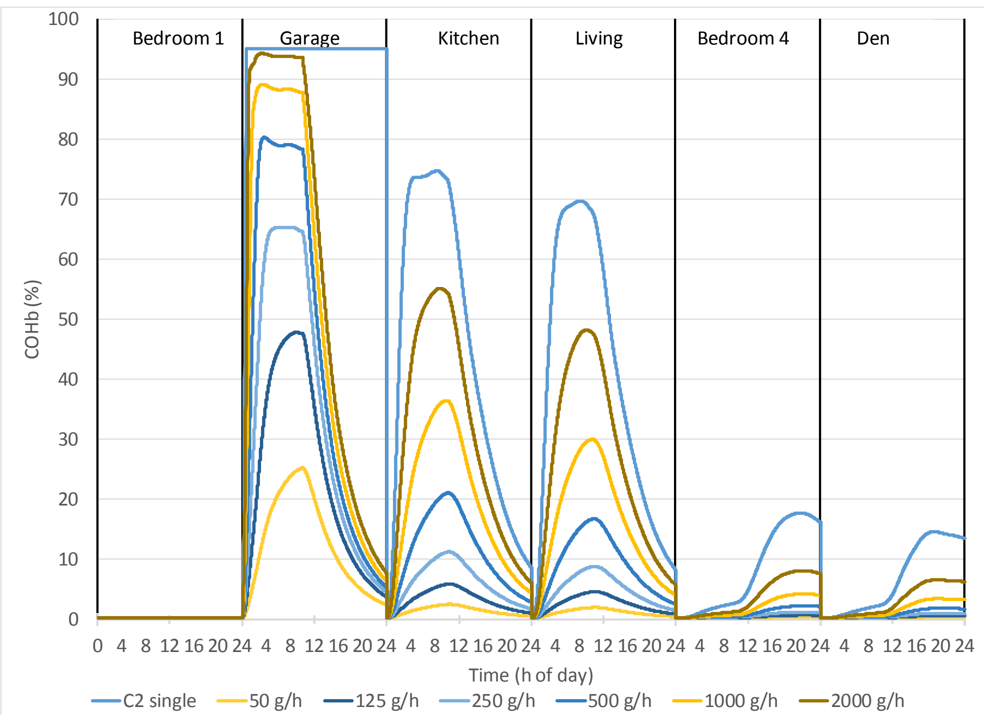

Figure 28 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 single source in Garage of DH12 on July 25th

Figures 29 and 30 show individual zone CO concentration and COHb results, respectively, for the C2 single baseline source and reduced rate sources located in bedroom 4 in the basement of house DH-12 on January 1st. Due to the relative lack of outdoor air infiltration into the basement, the peak CO concentrations resulting from the C2 single source reached 50,000 μL/L in the source zone, over 30,000 μL/L in the adjacent family room, and 15,000 μL/L to 20, 000 μL/L in most of the other zones (not including the garage). Reductions in peak concentrations for the reduced rates of 50 g/h to 2000 g/h compared to the baseline C2 single source peaks once again ranged from over 50 % to well over 90 %. The COHb shown in Figure 30 remained below 40 % in the non-source zones for only the 50 g/h source, but reached or exceeded 40 % in all house zones (not including the garage) for all other source strengths.

Figures 31 and 32 show individual zone CO concentration and COHb results, respectively, for the C2 single source and reduced rate sources located in bedroom 4 in the basement of house DH-12 on July 25th. For this case, the peak CO concentration for the C2 single source reached almost 100,000 μL/L in the garage, over 68,000 μL/L in the other basement zones and nearly 40,000 μL/L in the 1st floor zones. CO concentrations were much lower in the 2nd floor zones but still in the range of 1,000 μL/L to 5,000 μL/L. The reductions in peak concentrations for the reduced sources again range from over 50 % to well over 90 % compared to the baseline C2 single source. As seen in Figure 32, the COHb exceeded 40 % for all sources strengths in the basement zones, remained below 40 % for just the 50 g/h source in the 1st floor zones, and remained near or below 40 % for all sources up to 500 g/h in all 2nd floor zones.

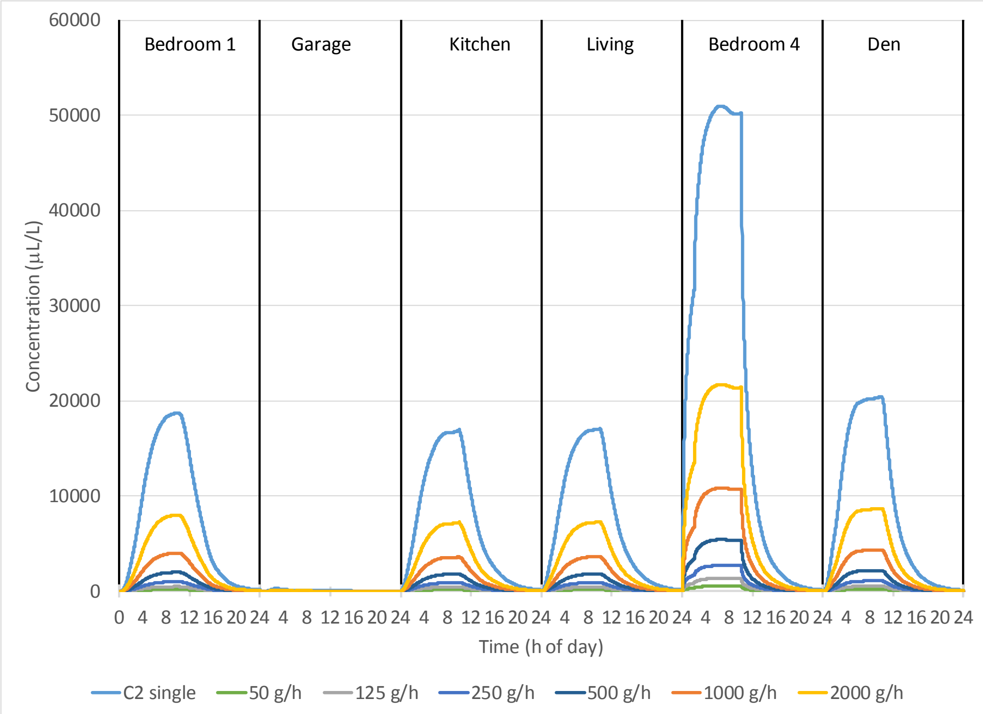

Figure 29 Individual zone transient CO results for the C2 single source in Bedroom 4 of DH12 on January 1st

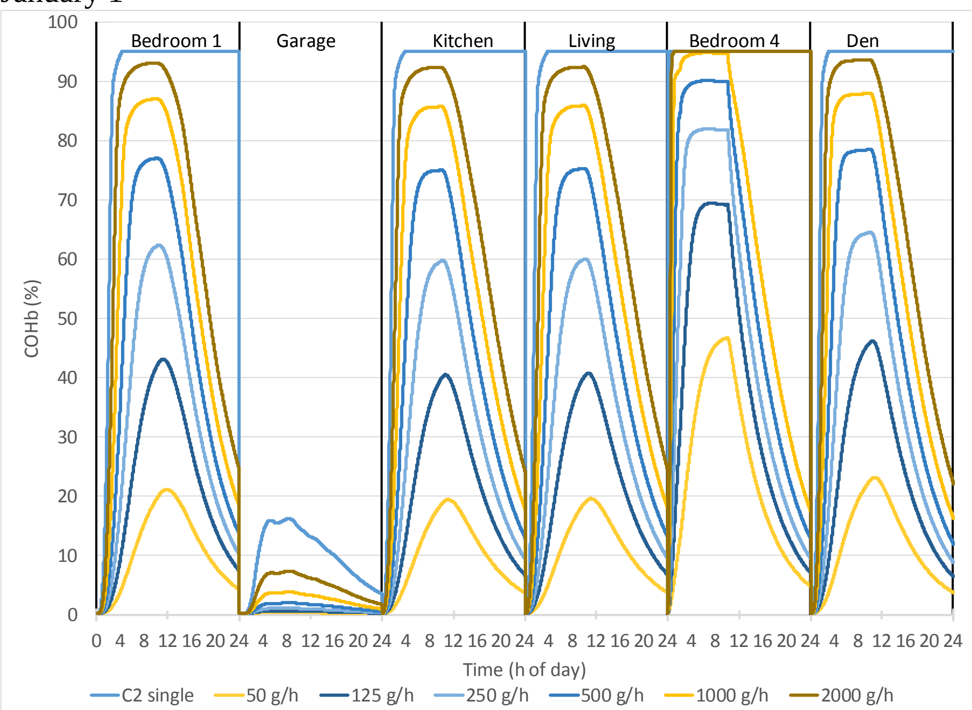

Figure 30 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 single source in Bedroom 4 of DH12 on January 1st

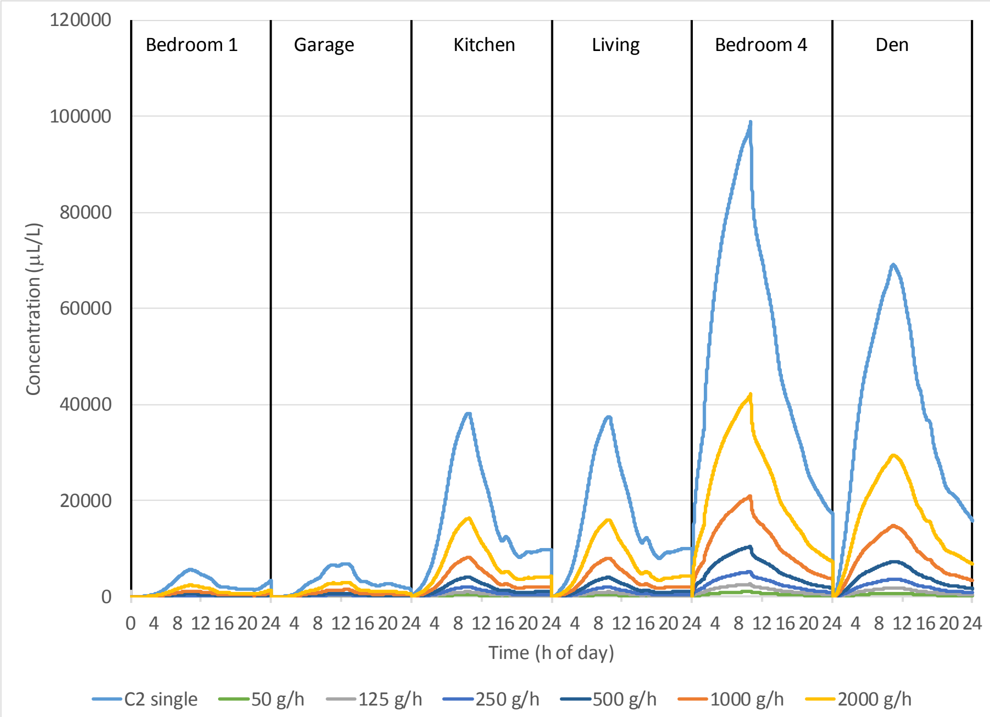

Figure 31 Individual zone transient CO results for the C2 single source in Bedroom 4 of DH12 on July 25th

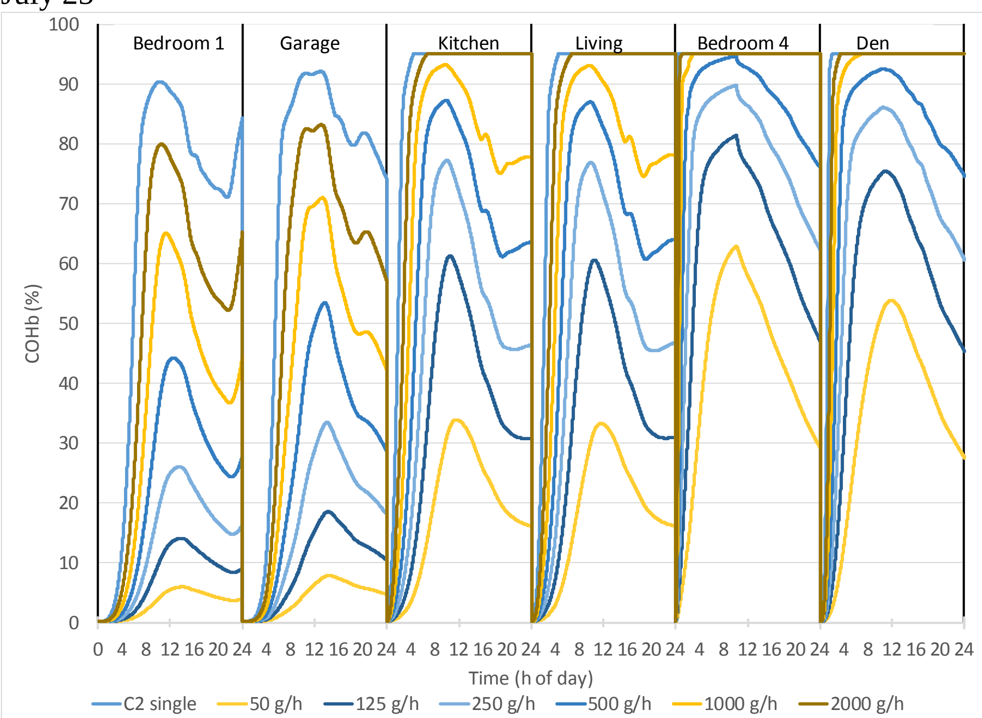

Figure 32 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 single source in Bedroom 4 of DH12 on July 25th

3.4 Sample results for large garage with workshop (GAR3)

This section presents sample results for the building GAR3, which was created for this project as a large two zone garage with 60.4 m^2 of floor area including a separate workshop zone.

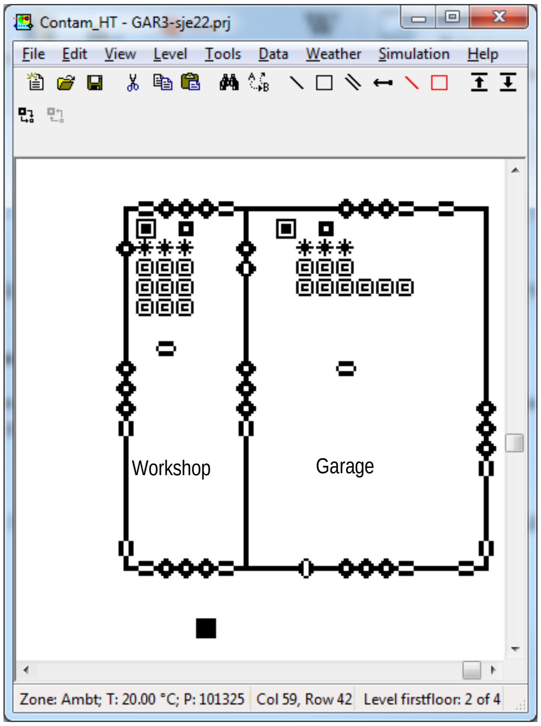

Figure 33 Floor plan of house GAR3 as represented in CONTAM

Figures 34 and 35 show individual zone CO concentration and COHb results, respectively, for the C2 twin baseline source (9100 g/h) and reduced rate sources located in the garage zone of GAR3 on January 1st. The peak CO concentrations resulting from the C2 twin source reached almost 35,000 μL/L in the garage and over 12,000 μL/L in the workshop. Reductions in peak concentrations for the reduced rates of 50 g/h to 2000 g/h, compared to the baseline C2 twin source, ranged from nearly 80 % to well over 90 %. The COHb shown in Figure 35 remained at or below 40 % in both zones for the 50 g/h and 125 g/h sources, but reached or exceeded 40 % in both zones for all source strengths over 500 g/h. However, Figure 35 also shows that the COHb increases more slowly in both zones as the source strength drops.

Figures 36 and 37 show individual zone CO concentration and COHb results, respectively, for the C2 twin source and reduced rate sources located in the garage zone of GAR3 on July 25th. The results for this case are quite similar to the January 1st results, with somewhat higher CO concentrations and COHb due to the lower air change rate during the warmer weather.

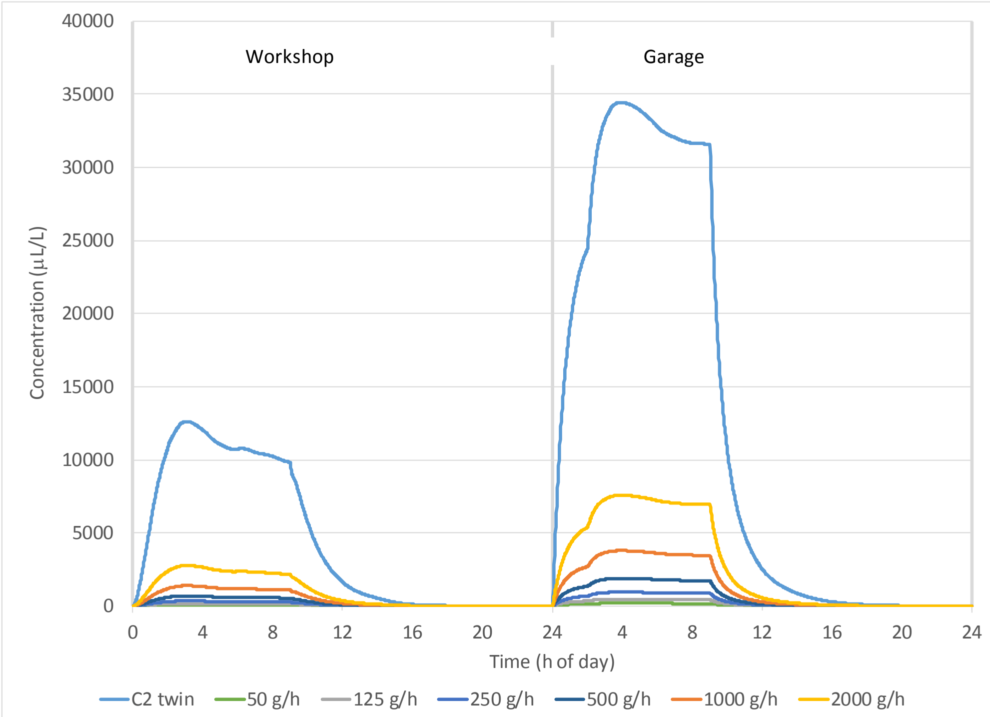

Figure 34 Individual zone transient CO results for the C2 twin source in the Garage zone of GAR3 on January 1st

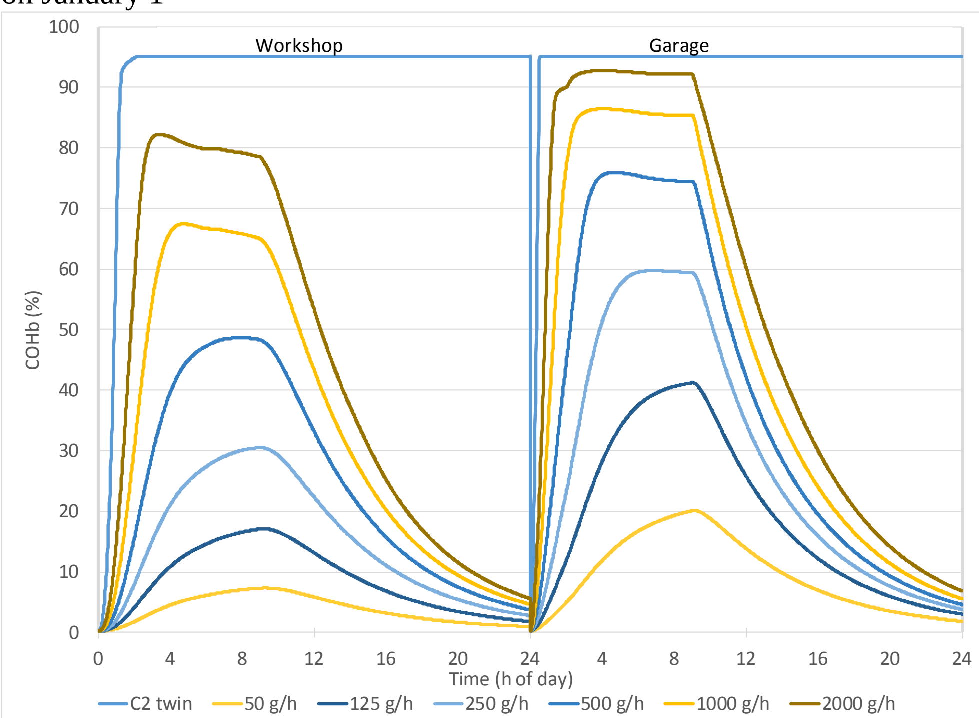

Figure 35 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 twin source in the Garage zone of GAR3 on January 1st

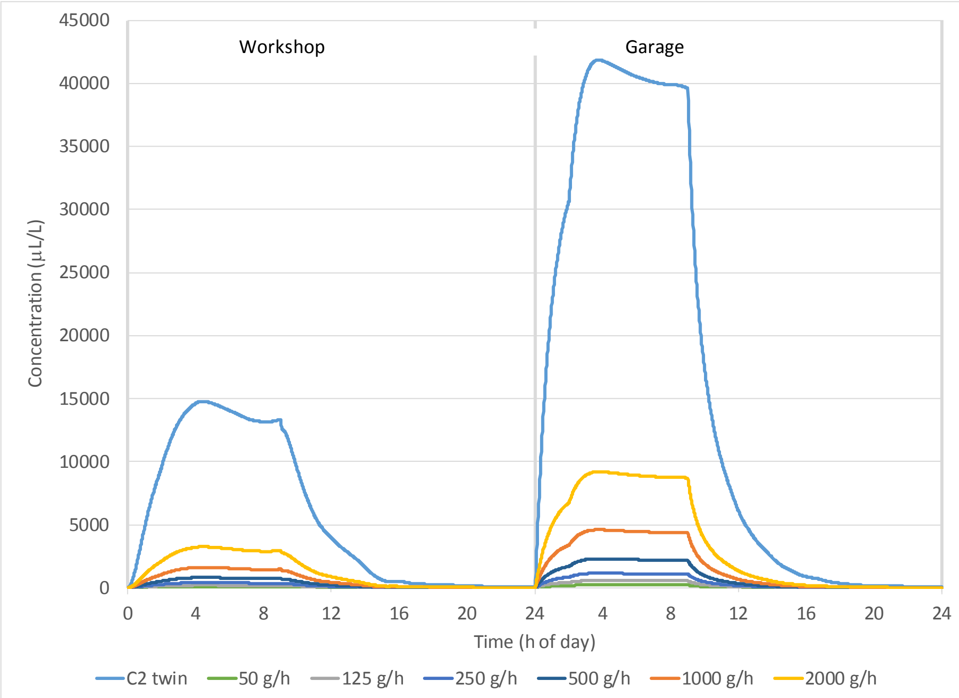

Figure 36 Individual zone transient CO results for the C2 twin source in the Garage zone of GAR3 on July 25th

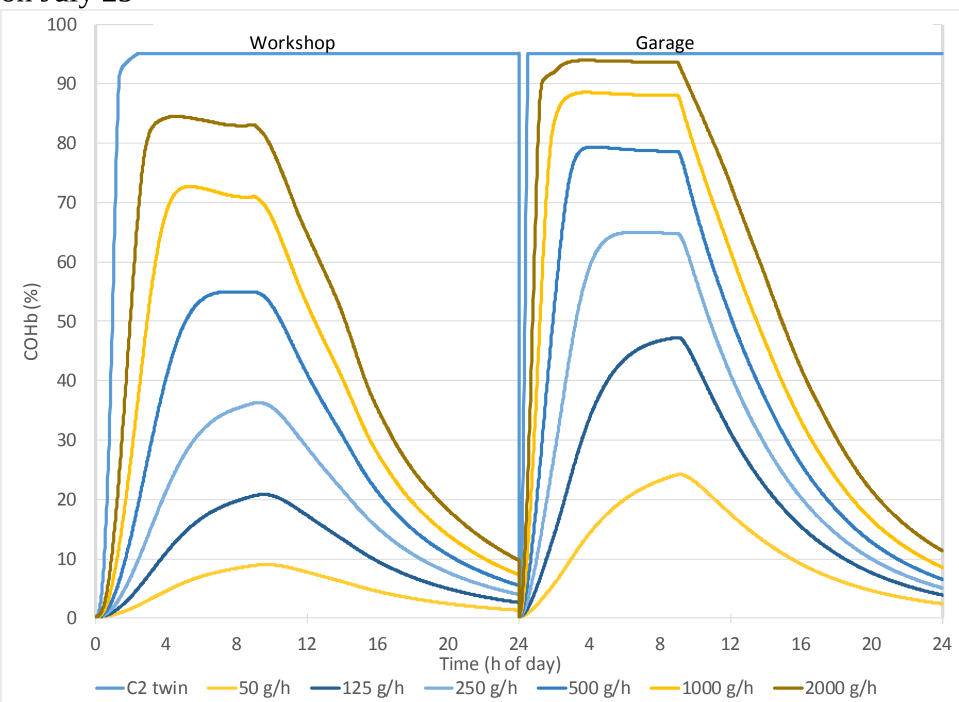

Figure 37 Individual zone transient COHb (with RMV = 10 L/min) results for the C2 twin source in the Garage zone of GAR3 on July 25th

4. SUMMARY AND DISCUSSION

This simulation study was conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate in order to support cost-benefit analyses of potential CO emission limits for generators. These simulations employed the multizone airflow and contaminant transport model CONTAM, which was applied to 40 residential buildings including 37 versions of dwellings drawn from a collection that are representative of the U.S. housing stock and 3 new detached garage buildings. A total of over 45 thousand individual 24-hour simulations were conducted that covered a range of house layouts and sizes, airtightness levels, weather conditions, generator locations, CO source strengths and operating schedules. The simulated generator locations include attached garages, crawlspaces and basements, in the houses that have such spaces, and two interior rooms in all of the houses considered. COHb levels were then calculated from the CO concentration results for an occupant in each occupiable zone of the buildings over the 24-h simulation period using 3 RMV values. This report presents sample simulation results of predicted CO concentration and COHb levels in individual zones for three of the modeled houses and one of the garages.

The results presented demonstrate that the reduced CO emission rates considered in this study result in peak CO concentrations that are reduced by 40 % to more than 90 % depending on the specific case being analyzed. The reduced CO emission rates also resulted in significant reductions in COHb in many cases. Additionally, use of a thermal model to more accurately account for thermal effects was shown to be important as the interaction of the generator heat source and the ambient weather conditions can significantly impact both air change rates and interzone airflow patterns in the buildings.

As observed previously by Persily et al. (2013), these simulation results demonstrate the complexity of multizone airflow and contaminant transport in buildings, which in turn supports the value in considering a wide range of homes and weather conditions in addressing the objective of this study. Variations in house layout, generator size (i.e., source strength and heat release), operating schedules, source location, and weather conditions can all have significant, and at times complex, impacts on airflow and CO transport. This inherent variability means that considering only one or a small number of buildings under a limited range of conditions would not be adequate to fully understand the levels of CO exposure in residences. Therefore, the results of individual cases, such as the ones presented in this report, should not be over-generalized but taken only as representative of the conditions for those cases.

5. ACKNOWLEDGEMENTS

This work was funded by the U.S. Consumer Products Safety Commission under interagency agreement No. CPSC-I-15-0024. The authors wish to express their appreciation for the support of Janet Buyer, Sandra Inkster, and Matthew Hnatov from CPSC in conducting this effort.

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APPENDIX A: House Characteristics

This appendix contains three tables that define the dwellings in the NIST Suite of Homes, with one table for each housing type: detached (A1), attached (A2) and manufactured home (A3). The dwelling definitions in the table are in terms of the variables discussed in detail in the report that defines these homes (Persily et al. 2006). Note that not all of these models were used in this simulation study and that some of the models were modified to better fit the houses in the CPSC CO incident database. See Appendix B for the details of which houses were used and what modifications were made to the models.

Table A1. Detached Homes (83 total)

Key for Table A1:
# of floors: 1 = one story; 2 = two story
Floor area: 1 = less than 148.5 m^2 (1,599 ft^2); 2 = 148.6 m^2 to 222.9 m^2 (1,600 ft^2 to 2,399 ft^2); 3 = 223.0 m^2 (2,400 ft^2) or more
Year Built: 1 = before 1940; 2 = 1940-69; 3 = 1970-89; 4 = 1990 and newer
Foundation: 1 = concrete slab; 2 = crawl space; 3 = finished basement, 4 = unfinished basement
Garage: 1 = none; 2 = attached garage
Forced Air: 1 = other; 2 = central system present

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Foundation	Garage	Forced -air	Bedrooms	Full baths	Half baths	Other	
DH-1	1	2	3	1	2	2	3	2	0	3	DH-B(1)
DH-2	1	1	2	3	2	2	3	1	0	3	DH-A(8)
DH-3	1	1	2	2	1	1	2	1	0	2	DH-A(1)
DH-4	1	1	2	2	2	2	3	1	0	3	DH-A(7)
DH-5	1	1	3	1	2	2	3	2	0	3	DH-A(2)
DH-6	2	1	1	3	2	2	3	1	0	3	DH-D(3)
DH-7	1	2	2	3	2	2	3	2	0	4	DH-B(5)
DH-8	1	1	2	1	2	2	3	2	0	3	DH-A(2)
DH-9	2	1	2	3	2	2	3	1	0	3	DH-D(3)
DH-10	2	2	3	3	2	2	4	2	1	4	DH-E(8)

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Foundation	Garage	Forced -air	Bedrooms	Full baths	Half baths	Other	
DH-11	1	1	2	2	2	1	3	1	0	3	DH-A(7)
DH-12	2	3	3	3	2	2	4	2	1	5	DH-F(4)
DH-13	1	2	2	2	2	2	3	2	0	3	DH-B(1)
DH-14	2	2	1	3	2	2	3	1	1	4	DH-E(5)
DH-15	2	3	4	3	2	2	4	3	1	5	DH-F(5)
DH-16	1	1	2	2	1	2	3	1	0	3	DH-A(7)
DH-17	2	2	2	3	2	2	3	2	1	4	DH-E(6)
DH-18	2	1	1	3	1	2	3	1	0	3	DH-D(3)
DH-19	1	1	3	3	2	2	3	1	0	3	DH-A(8)
DH-20	2	2	1	3	2	1	4	1	0	4	DH-E(7)
DH-21	1	1	2	1	1	2	3	1	0	3	DH-A(7)
DH-22	2	3	3	1	2	2	4	3	1	5	DH-F(1)
DH-23	2	1	1	3	2	1	3	1	0	3	DH-D(3)
DH-24	2	2	3	1	2	2	4	2	1	4	DH-E(3)
DH-25	1	1	2	3	2	1	3	1	0	3	DH-A(8)
DH-26	1	1	2	1	1	1	2	1	0	2	DH-A(1)
DH-27	1	1	2	3	1	2	3	1	0	3	DH-A(8)
DH-28	2	3	4	1	2	2	4	3	1	4	DH-F(2)
DH-29	1	1	1	2	1	1	2	1	0	3	DH-A(3)
DH-30	1	2	3	2	2	2	3	2	0	3	DH-B(1)
DH-31	1	1	3	2	2	2	3	2	0	3	DH-A(2)
DH-32	1	1	4	1	2	2	3	2	0	2	DH-A(6)
DH-33	1	3	3	1	2	2	4	2	0	4	DH-C(1)
DH-34	1	1	3	1	1	2	3	1	0	3	DH-A(7)
DH-35	1	2	2	1	2	2	3	2	0	3	DH-B(1)
DH-36	2	2	4	1	2	2	4	2	1	4	DH-E(3)
DH-37	1	2	3	3	2	2	3	2	1	3	DH-B(4)
DH-38	1	1	3	2	1	2	3	1	0	3	DH-A(7)

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Foundation	Garage	Forced -air	Bedrooms	Full baths	Half baths	Other	
DH-39	1	2	2	2	1	2	3	2	0	3	DH-B(1)
DH-40	2	2	3	2	2	2	4	2	1	4	DH-E(3)
DH-41	2	2	1	3	1	2	3	1	0	4	DH-E(1)
DH-42	1	1	3	2	1	1	3	1	0	2	DH-A(4)
DH-43	2	2	2	3	2	1	4	2	0	4	DH-E(2)
DH-44	1	1	1	3	2	2	2	1	0	3	DH-A(9)
DH-45	2	2	3	4	2	1	4	2	1	4	DH-E(3)
DH-46	1	1	2	1	2	1	2	1	0	2	DH-A(1)
DH-47	1	1	3	2	2	1	3	1	0	3	DH-A(7)
DH-48	1	1	4	2	1	2	3	2	0	3	DH-A(2)
DH-49	1	1	2	3	1	1	3	1	0	3	DH-A(8)
DH-50	2	1	1	3	1	1	3	1	0	3	DH-D(3)
DH-51	2	3	3	2	2	2	4	2	1	4	DH-F(3)
DH-52	2	3	1	4	2	2	4	2	1	4	DH-F(3)
DH-53	1	2	3	1	1	2	3	2	0	3	DH-B(1)
DH-54	1	1	1	2	1	2	2	1	0	3	DH-A(3)
DH-55	1	1	4	2	2	2	3	2	0	2	DH-A(6)
DH-56	2	1	2	3	1	2	3	1	0	3	DH-D(3)
DH-57	1	2	2	2	2	1	3	2	0	4	DH-B(3)
DH-58	2	2	4	3	2	2	3	2	1	4	DH-E(6)
DH-59	2	3	2	3	2	1	4	2	1	5	DH-F(4)
DH-60	1	1	3	4	2	1	3	1	0	3	DH-A(7)
DH-61	1	1	1	4	1	2	2	1	0	2	DH-A(1)
DH-62	2	3	1	3	2	1	4	2	1	5	DH-F(4)
DH-63	2	1	2	4	2	1	3	1	1	3	DH-D(4)
DH-64	1	2	4	1	2	2	3	2	0	3	DH-B(1)
DH-65	1	1	1	4	1	1	2	1	0	3	DH-A(3)
DH-66	1	2	2	1	2	1	3	1	0	3	DH-B(2)

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Foundation	Garage	Forced -air	Bedrooms	Full baths	Half baths	Other	
DH-67	1	1	1	2	2	2	3	1	0	3	DH-A(7)
DH-68	2	1	2	3	1	1	3	1	0	3	DH-D(3)
DH-69	2	3	3	4	2	1	4	2	1	4	DH-F(3)
DH-70	1	1	3	1	1	1	2	1	0	2	DH-A(1)
DH-71	2	1	3	1	2	2	3	2	1	3	DH-D(1)
DH-72	1	2	1	4	2	2	3	2	0	4	DH-B(3)
DH-73	2	1	3	4	2	2	3	2	0	4	DH-D(2)
DH-74	1	3	3	4	2	2	3	2	1	5	DH-C(2)
DH-75	3	2	3	1	2	2	4	2	1	3	DH-G(1)
DH-76	1	1	4	4	2	2	3	2	1	3	DH-A(5)
DH-77	3	2	3	4	2	2	3	2	1	4	DH-G(2)
DH-78	1	1	3	1	2	1	3	1	0	3	DH-A(7)
DH-79	1	2	3	2	1	2	3	2	0	3	DH-B(1)
DH-80	1	2	2	4	1	2	3	2	0	4	DH-B(3)
DH-81	2	2	1	4	1	1	3	2	0	4	DH-E(4)
DH-82	1	2	2	4	2	1	3	2	0	3	DH-B(1)
DH-83	1	1	3	3	1	2	3	1	0	3	DH-A(8)

Table A2. Attached Homes (53 total)

Key for Table A2:
# of floors: 1 = one story; 2 = two story
Floor area: 1 = fewer than 148.5 m^2 (1,599 ft^2); 2 = 148.6 m^2 to 222.9 m^2 (1,600 ft^2 to 2,399 ft^2); 3 = 223.0 m^2 (2,400 ft^2) or more
Year Built: 1 = before 1940; 2 = 1940-69; 3 = 1970-89; 4 = 1990 and newer
Foundation: 1 = concrete slab; 2 = crawl space; 3 = finished basement, 4 = unfinished basement
Garage: 1 = none; 2 = attached garage
Forced Air: 1 = other; 2 = central system present

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Found -ation	Garage	Forced -air	Bed- rooms	Full baths	Half baths	Other	
AH-1	2	1	1	3	1	2	2	1	0	3	AH-C(11)
AH-2	2	1	3	1	1	2	2	2	1	3	AH-C(7)
AH-3	1	1	3	1	1	2	2	1	0	2	AH-A(2)
AH-4	1	1	3	1	2	2	2	1	0	3	AH-A(3)
AH-5	2	1	2	3	1	1	3	1	0	3	AH-C(15)
AH-6	2	1	3	1	2	2	2	2	1	3	AH-C(4)
AH-7	2	1	3	3	1	2	3	2	1	3	AH-C(16)
AH-8	1	1	2	1	1	1	2	1	0	2	AH-A(2)
AH-9	2	1	1	3	2	1	3	2	1	4	AH-C(17)
AH-10	2	1	1	3	1	1	2	1	0	3	AH-C(11)
AH-11	2	1	2	3	1	2	3	1	0	3	AH-C(15)
AH-12	1	1	4	1	2	2	2	1	0	2	AH-A(1)
AH-13	2	1	2	1	1	2	2	2	1	2	AH-C(6)
AH-14	1	1	2	1	1	2	2	1	0	2	AH-A(2)
AH-15	2	2	3	1	2	2	3	1	0	3	AH-D(1)
AH-16	2	1	1	2	1	1	2	1	0	2	AH-C(2)
AH-17	1	1	2	2	1	1	1	1	0	2	AH-A(5)
AH-18	2	1	3	1	1	1	2	1	0	2	AH-C(2)
AH-19	2	1	2	1	2	2	2	1	0	3	AH-C(3)

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Found -ation	Garage	Forced -air	Bed-rooms	Full baths	Half baths	Other	
AH-20	2	1	1	4	2	2	3	1	0	3	AH-C(12)
AH-21	2	2	1	4	2	2	3	1	0	3	AH-D(4)
AH-22	2	1	3	1	2	1	2	2	1	2	AH-C(1)
AH-23	2	1	3	4	2	2	3	2	1	3	AH-C(13)
AH-24	2	2	1	3	1	1	3	1	0	3	AH-D(5)
AH-25	1	1	2	1	2	1	2	1	0	2	AH-A(1)
AH-26	2	1	4	1	1	2	3	2	1	2	AH-C(5)
AH-27	2	2	1	4	2	1	3	1	0	5	AH-D(6)
AH-28	2	2	3	3	1	2	3	2	1	3	AH-D(7)
AH-29	2	2	4	1	2	2	2	1	0	3	AH-D(2)
AH-30	1	1	3	2	2	1	2	1	0	2	AH-A(1)
AH-31	1	1	2	3	1	2	1	1	0	3	AH-A(7)
AH-32	1	1	2	4	2	2	2	1	0	3	AH-A(4)
AH-33	1	1	1	3	1	2	1	1	0	2	AH-A(6)
AH-34	2	3	3	3	1	2	4	3	2	4	AH-E(1)
AH-35	2	1	2	1	1	1	2	1	0	2	AH-C(2)
AH-36	1	1	2	1	2	2	2	1	0	2	AH-A(1)
AH-37	1	1	2	2	2	1	2	1	0	2	AH-A(1)
AH-38	1	1	1	4	2	1	2	1	0	3	AH-A(4)
AH-39	1	1	4	1	1	2	2	1	0	2	AH-A(2)
AH-40	2	1	1	1	1	1	1	1	0	1	AH-C(8)
AH-41	2	2	2	3	1	2	3	2	1	4	AH-D(8)
AH-42	2	1	2	4	2	2	2	1	0	3	AH-C(10)
AH-43	1	2	3	1	2	2	3	1	0	3	AH-B(1)
AH-44	1	1	3	2	1	1	1	1	0	2	AH-A(5)
AH-45	1	1	2	2	1	2	2	1	0	2	AH-A(2)
AH-46	2	1	2	2	1	2	3	1	0	3	AH-C(9)
AH-47	1	1	3	4	2	2	3	2	1	3	AH-A(8)

House Number	# of Floors	House Variable					# of Rooms				Floor plan
		Floor area	Year Built	Found -ation	Garage	Forced -air	Bed-rooms	Full baths	Half baths	Other	
AH-48	2	1	3	2	1	2	2	2	1	2	AH-C(6)
AH-49	1	1	1	2	2	1	2	1	0	2	AH-A(1)
AH-50	2	1	3	2	2	2	2	2	1	3	AH-C(4)
AH-51	2	1	3	3	1	1	2	1	0	3	AH-C(11)
AH-52	2	2	3	1	1	2	3	2	1	4	AH-D(3)
AH-53	1	1	4	2	1	2	2	1	0	2	AH-A(2)

TABLE A3. Manufactured Homes

Key for Table A3:

Floor area: 1 = less than 148.5 m^2 (1,599 ft^2); 2 = 148.6 m^2 (1,600 ft^2) or more
Year Built: 1 = before 1940; 2 = 1940-69; 3 = 1970-89; 4 = 1990 and newer
Forced Air: 1 = other; 2 = central system present

House Number	Floor area	Year Built	Forced-air	# of Bedrooms	# of Baths	# of Half baths	# of Other rooms	Floor plan
MH-1	1	3	2	2	1	0	2	MH-B(1)
MH-2	1	4	2	3	2	0	2	MH-A(1)
MH-3	1	3	1	2	1	0	2	MH-B(1)
MH-4	1	2	2	2	1	0	2	MH-B(1)

Appendix B Source Locations and Model Modifications for Each Building

Table B1 lists the 40 buildings modeled in this simulation study and shows the locations of the generator simulated for each building. Based on CPSC analysis of CO poisoning death incidents from 2004 through 2012, a subset of the NIST suite of homes collection described above (in some cases with modifications to better represent the houses in the CPSC CO incident database) were used for this analysis including 31 detached house (DH) models, 4 attached house (AH) models, and 2 manufactured house (MH) models. Any modifications are listed in Table B1 and described in more detail below.

Three new building models were created to represent various forms of garages (GAR) modeled including 2 single-zone garage/sheds (1 car size and 2 car size) and 1 larger garage with a separate work space inside as described below.

Table B1. Source Locations and Model Modifications for Each Building

House number	PRJ file modified (yes/no)?	Floor plan	Source locations		
			Garage	**Basement/ crawlspace**	**Interior room(s)**
DH-1	N	DH-B(1)	GAR	n.a.	Kit, Bed3
DH-2	N	DH-A(8)	GAR	Bed1	Kit
DH-2	Add INT GAR	DH-A(8)	GAR	Bed2	Kit
DH-3	N	DH-A(1)	n.a.	CRAWL	Kit, Bed1
DH-5	N	DH-A(2)	GAR	n.a.	Kit, Bed3
DH-7	N	DH-B(5)	GAR	Bed3	Kit
DH-8	N	DH-A(2)	GAR	n.a.	Kit, Bed3
DH-10	N	DH-E(8)	GAR	Den	Kit
DH-12	N	DH-F(4)	GAR	Bed4	Kit
DH-19	Add INT GAR	DH-A(8)	GAR	bed2	kit
DH-21	N	DH-A(7)	n.a.	n.a.	Kit, Bed3
DH-21	Year Built	DH-A(7)	n.a.	n.a.	Kit, Bed3
DH-24	Year Built Delete GAR	DH-E(3)	n.a.	n.a.	Kit, Bed1
DH-27	N	DH-A(8)	n.a.	Bed1	Kit
DH-32	N	DH-A(6)	GAR	n.a.	Kit, Bed3
DH-33	Year built	DH-C(1)	GAR	NA	Kit, Bed2
DH-34	N	DH-A(7)	n.a.	n.a.	Kit, Bed3
DH-41	N	DH-E(1)	n.a.	Hall	kit
DH-44	N	DH-A(9)	GAR	Bed1	kit
DH-45	N	DH-E(3)	GAR	Basement	Kit
DH-45	Year built Add INT GAR	DH-E(3)	GAR	Basement	Kit,
DH-52	Year built	DH-F(3)	GAR	Basement	Kit
DH-56	N	DH-D(3)	n.a.	Bed2	Kitchen

House number	PRJ file modified (yes/no)?	Floor plan	Source locations		
			Garage	Basement/ crawlspace	Interior room(s)
DH-60	N	DH-A(7)	GAR	Basement	Kit
DH-60	Year Built Add INT GAR	DH-A(7)	GAR	Basement	Kit
DH-61	Year built	DH-A(1)	n.a.	Basement	Kit
DH-61	N	DH-A(1)	n.a.	Basement	Kit
DH-63	Year Built Delete GAR	DH-D(4)	n.a.	Basement	Kit
DH-63	Delete Gar	DH-D(4)	n.a.	Basement	Kit
DH-64	N	DH-B(1)	GAR	n.a.	Kit, Bed3
DH-81	N	DH-E(4)	n.a.	Basement	Kit
MH-1	N	MH-B(1)	n.a.	crawl	Kit, Bed1
MH-1	Size Year built	NA	n.a.	n.a.	Kit, Bed1
AH-3	N	AH-A(2)	n.a.	n.a.	Kit, Bed1
AH-10	N	AH- C(11)	n.a.	Den	Kit
AH-34	Add GAR	AH-E(1)	GAR	Bed3	Kit
AH-21	Add INT GAR	AH-D(4)	GAR	Basement	Kit
GAR-1	new	NA	GAR	NA	NA
GAR-2	new	NA	GAR	NA	NA
GAR-3	new	NA	GAR	NA	NA

The modifications are described further below:

DH-2: Bedroom 1 in the basement was converted to an integral garage.

DH-19: Bedroom 1 in the basement was converted to an integral garage.

DH-21: Air leakage was modified based on year built and floor area per Table 1 and Equation 1 of Persily et al. (2013) to represent the oldest category of construction (before 1940).

DH-24: Two modifications were made. The side attached garage was deleted and air leakage was modified based on year built and floor area to represent the oldest category of construction (before 1940).

DH33: Air leakage was modified based on year built and floor area to represent the newest category of construction (1990 and newer).

DH-45: Two modifications were made. Part of the unfinished basement was converted to an integral garage and air leakage was modified based on year built and floor area to represent the newest category of construction (1990 and newer).

DH-52: Air leakage was modified based on year built and floor area to represent the newest category of construction (1990 and newer).

DH-60: Two modifications were made. internal garage added and air leakage was modified based on year built and floor area to represent the second oldest category of construction (1940 to 1969).

DH-61: Air leakage was modified based on year built and floor area to represent the second oldest category of construction (1940 to 1969).

DH-63 (mod1): Two modifications were made. The side attached garage was deleted and air leakage was modified based on year built and floor area to represent the oldest category of construction (before 1940).

DH-63 (mod2): The side attached garage was deleted.

MH-1: MH1 was modified to be smaller with 78 m^2 (840 ft2) of floor area with 2 bedrooms, 1 bathroom and a kitchen. The air leakage was modified based on year built and floor area to represent the oldest category of construction (before 1940).

AH-34: The first floor living room was converted to an integral garage.

AH-21: The side attached garage was deleted and part of the unfinished basement was converted to an integral garage.

GAR-1 was created as a new model of a detached garage with a single 32.5 m^2 (350 ft^2) zone and envelope air leakage of 4.81 cm^2/m^2 based on the median garage envelope leakage in Table 2 of Emmerich et al. 2003.

GAR-2 was created as a new model of a detached garage with a single 60.4 m^2 (650 ft^2) zone and envelope air leakage of 4.81 cm^2/m^2 based on the median garage envelope leakage in Table 2 of Emmerich et al. 2003.

GAR-3 was created as a new model of a detached garage with two zones including a main 60.4 m^2 (650 ft^2) garage zone and a separate 32.5 m^2 (350 ft^2) workroom with envelope air leakage of 4.81 cm^2/m^2 based on the median garage envelope leakage in Table 2 of Emmerich et al. 2003.

Appendix C Analysis of Unmodified Generator X CO Emission Ratio at Reduced O_2 vs Ambient

The shed test data for unmodified Generator X from Figure 9 of NIST Technical Note 1781 (Emmerich et al. 2013) were used to assist in determining an appropriate ratio of the generator CO emission rate at reduced O_2 to the CO emission rate at ambient conditions. Table C1 shows the CO emission rate at ambient from the University of Alabama's testing of unmodified Generator X (Tab C of CPSC 2012) and average CO emission rate for all measured data below 18 % O_2 for the 6 loading modes. The calculated 6-mode weighted ratio for the generator was 3.0.

Table C1. Unmodified Generator X CO Emission Ratio at Reduced O_2

Mode	**Weighting**	**CO emission rate at ambient (g/h)**	**CO emission rate below 18 % O_2 (g/h)**	**Ratio**
1	0.09	1000.6	3652	3.6
2	0.2	671.16	3395	5.0
3	0.29	697.54	2487	3.6
4	0.3	1075.6	2100	1.9
5	0.07	971.04	1810	1.9
6	0.05	911.78	1623	1.8