NIST Technical Note 2200

Carbon Monoxide Concentrations and Carboxyhemoglobin Profiles from Commercially Available Portable Generators Equipped with a CO Hazard Mitigation System

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https://doi.org/10.6028/NIST.TN.2200

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

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January 2022

U.S. Department of Commerce
Gina M. Raimondo, Secretary

National Institute of Standards and Technology
James K. Olthoff, Performing the Non-Exclusive Functions and Duties of the Under Secretary of Commerce for Standards and Technology & Director, National Institute of Standards and Technology

National Institute of Standards and Technology Technical Note 2200
Natl. Inst. Stand. Technol. Tech. Note 2200, 92 pages (January 2022)
CODEN: NTNOEF

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2200

Abstract

The U.S. Consumer Product Safety Commission (CPSC) is focused on addressing the hazard of acute carbon monoxide (CO) poisoning of consumers from portable generators that can result in serious, long-term health effects or death in exposed individuals. Under an interagency agreement with CPSC (CPSC-I-17-0023), the National Institute of Standards and Technology (NIST) conducted a series of tests on four commercially available portable generators advertised as being certified to one of two voluntary standards requiring CO hazard mitigation systems for portable generators. These tests characterized the indoor CO concentrations and the resulting calculated carboxyhemoglobin (COHb) profiles on simulated occupants when the generators were operated in or near a test house under various operational and environmental conditions. This report presents the measured CO data and calculated COHb levels from those tests. In addition, model validation tests and simulations were performed for two cases (three tests for each) to supplement those already reported in NIST Technical Note 2049.

Keywords

Generator; carbon monoxide; carboxyhemoglobin; CONTAM; exposure; indoor air quality; health; measurements; multizone airflow model; simulation.

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Introduction

The U.S. Consumer Product Safety Commission (CPSC, Commission) is focused on addressing the hazard of acute carbon monoxide (CO) poisonings of consumers from portable generators that can result in serious, long-term health effects or death in exposed individuals. CPSC produces two annual reports which contain information on CO poisoning in regards to generator usage, a CO poisoning from Engine-Driven Tools (EDT) report (Hnatov 2021a) and a report that contains annual estimates of CO poisoning from consumer products (Hnatov 2021b).

The first report contains only the actual data as reported to CPSC through 2020 and should not be assumed to be annual estimates. It should also be noted that the latter years of the report should be considered incomplete as often new data becomes available to CPSC staff up to a few years after the incident occurred due to reporting delays. This report contains more detailed information on the specific incidents and the victims involved than does the estimates report. As of May 17, 2021, CPSC databases contain records of at least 753 consumer deaths (711 from generator use alone, 42 from generator use in conjunction with another CO-producing consumer product) from CO poisoning associated with non-work-related use of generators between 2010 and 2020. Typically, these deaths occur when consumers use a generator in an enclosed or partially enclosed space or outdoors near an open door, window or vent, and they often occur after severe weather events such as hurricanes and ice or snow storms.

The second report contains the annual estimates of generator CO fatalities and indicates the magnitude of generator-related CO poisoning deaths in relation to all consumer product-related CO poisoning deaths. The estimated percentage of CO poisoning deaths specifically associated with generators, excluding the estimates that involved a generator and another CO-producing consumer product, for five most recent years of data are 33 % (2014), 49 % (2015), 38 % (2016), 51 % (2017) and 42% (2018). Per the Hnatov 2021 report, the estimated CO fatalities from all consumer products under CPSC's jurisdiction has risen for the sixth straight year. Part of this increase in the estimated CO fatalities is due to an increase in the number of CO fatalities associated with EDTs. In the eleven years covered by this report, portable generators are responsible for over 81% of all EDT-related CO deaths, and approximately 87% when another CO producing product may have also contributed.

The health impact of CO is caused by anoxia: deprivation of oxygen supply. When inhaled, CO preferentially binds with the oxygen carrier in the red blood cells, hemoglobin (Hb), to form carboxyhemoglobin (COHb), which causes the anoxia (Stewart 1975). The COHb level reflects the percentage of the body's total hemoglobin pool occupied by CO. In considering CO exposure, the COHb level serves as a useful measure of expected poisoning severity.

In previous work, documented in National Institute of Standards and Technology (NIST) Technical Note (TN) 1925, a computer simulation study was conducted to provide CPSC staff with information to support model-based estimates of residential CO exposures reflecting operation of current designs of portable engine-driven electric generators, both inside homes and in attached garages. These results were compared to simulated operation of reduced CO emission generators by CPSC staff to estimate the effectiveness of the reduced CO emission rates in preventing deaths that occurred with current generators. CPSC staff then recommended specific reduced CO emission rates as performance requirements to the Commission in a briefing package for a notice of proposed rulemaking (NPR) as the means to address the CO hazard associated with portable generators. The Commission subsequently voted to approve the NPR. (Proposed *Safety Standard for Portable Generators*, Federal Register, 81 FR 83556, November 21, 2016.).

After CPSC issued the NPR, two voluntary industry standards were published in 2018 to address portable generator CO safety: *ANSI/PGMA G300-2018*, *Safety and Performance of Portable Generators* (referred to as PGMA G300) and *ANSI/UL 2201-2018*, *Carbon Monoxide (CO) Emission Rate of Portable Generators* (referred to as UL 2201).

PGMA G300 includes a requirement for generators to be equipped with an onboard CO sensor. This sensor, when tested to the requirements in the standard, must shut off the generator before the CO concentration measured at a location 1 inch to 2 inches above the approximate center of the portable generator's top surface exceeds either a rolling 10-minute average of 400 ppmv or an instantaneous reading of 800 ppmv. PGMA G300 also requires notification after a shutoff event, which must be a red indicator that remains active for a minimum of 5 minutes after shutoff occurs, unless the generator is restarted. Furthermore, PGMA G300 requires a label about the automatic shutoff near the indicator, instructing the consumer about moving the generator to an outdoor area and seeking medical help if feeling sick.

UL 2201 includes a requirement for maximum weighted CO emission rate of 150 g/h and an additional requirement for generators to shut off when the CO concentration one foot above the centerline of the top of the generator registers either an average of 150 ppmv of CO for a 10-minute period or an instantaneous reading of 400 ppmv. UL 2201 does not contain a requirement for notification after a shutoff event.

Following publication of the G300 and UL2201 standards, NIST and CPSC conducted a study on generators with prototype shutoff mechanisms based on these standards. The study was meant to provide CPSC staff with information to support model-based estimates of residential CO exposures reflecting operation of current designs of portable engine-driven electric generators, both inside homes and in attached garages. (This study was reported in NIST Technical Note 2049). The current work builds on that reported in NIST TN 2049, as this study was conducted on generators in the marketplace that come equipped with G300/UL 2201-based shutoff mechanisms.

CPSC staff purchased from commercial retail suppliers three different models of portable generators, produced by three different manufacturers, that were advertised as certified to PGMA G300 and equipped with CO safety shutoff systems. In addition, CPSC staff purchased one model advertised as certified to UL 2201, for a total of four models from four different manufacturers. NIST and CPSC staff operated these generators in a test house under various use and environmental conditions, including generator location, load, operating schedules, weather conditions, and ventilation conditions. NIST and CPSC performed this series of tests to measure the CO concentration profiles throughout the house while the generator was operating and after it shut off, from activation of the generator's CO safety shutoff system, or after exhausting a full tank of fuel. This test report documents the CO data from those tests and the resulting calculated COHb profiles of simulated occupants. It also compares the concentration near the onboard sensor built into the unit and the concentration at the PGMA G300 and UL 2201 conformance test location above the generator at the time of shutoff.

Experimental Design

This section describes the experimental work performed, including the test house in which the measurements were made, the instrumentation employed in the test, the generators that were tested, and the testing and analysis methods used.

Test House

The test house used in this study is a manufactured house located on the NIST campus, which was erected in 2002 (Nabinger and Persily 2008, Nabinger et al., 2010). An aerial view and floorplan of the house are shown in Figures 1 and 2. The house includes three bedrooms (MBd, B2, and B3), two bathrooms (MBa and HB), a living room (LR), a dining room (DR), a kitchen (Kit), a family room (FR), a utility room (UR) and an attached garage (Gar). The house has a floor area of 140 m^2 and a volume of 340 m^3. The attached garage, which was built as an addition to the house in 2007, has a floor area of 36.5 m^2 and a volume of 90 m^3. The interior of the garage, including the ceiling, is finished with painted gypsum board. As part of the garage construction, the underlayment and siding of the exterior west wall of the house were removed and replaced with ¾- inch gypsum board on studs with fibrous glass batt insulation in the wall cavity. Figure 3 shows the location of CO sensors, thermocouples and generators, and the generator exhaust direction.

Figure 1 Aerial view of NIST manufactured test house

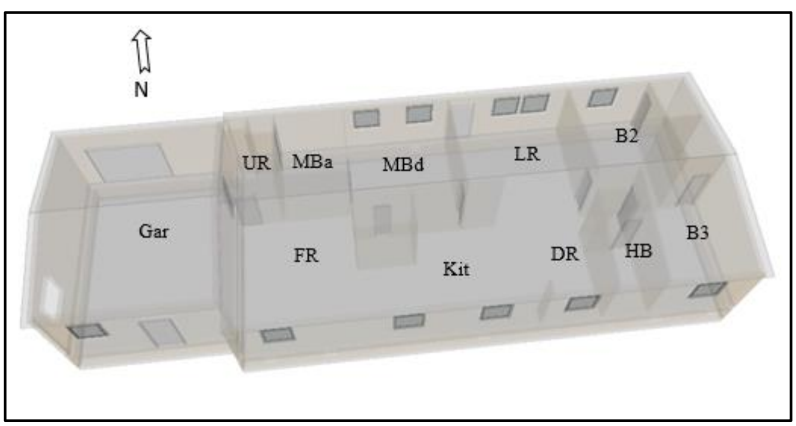


Figure 2 Floorplan of NIST manufactured test house

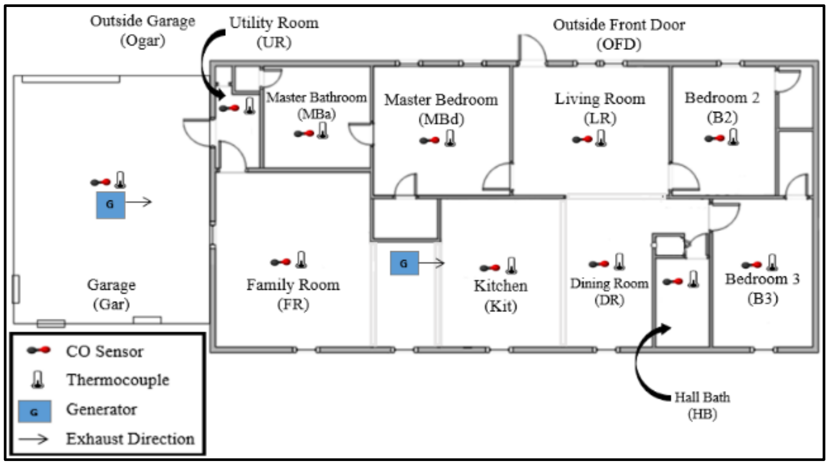


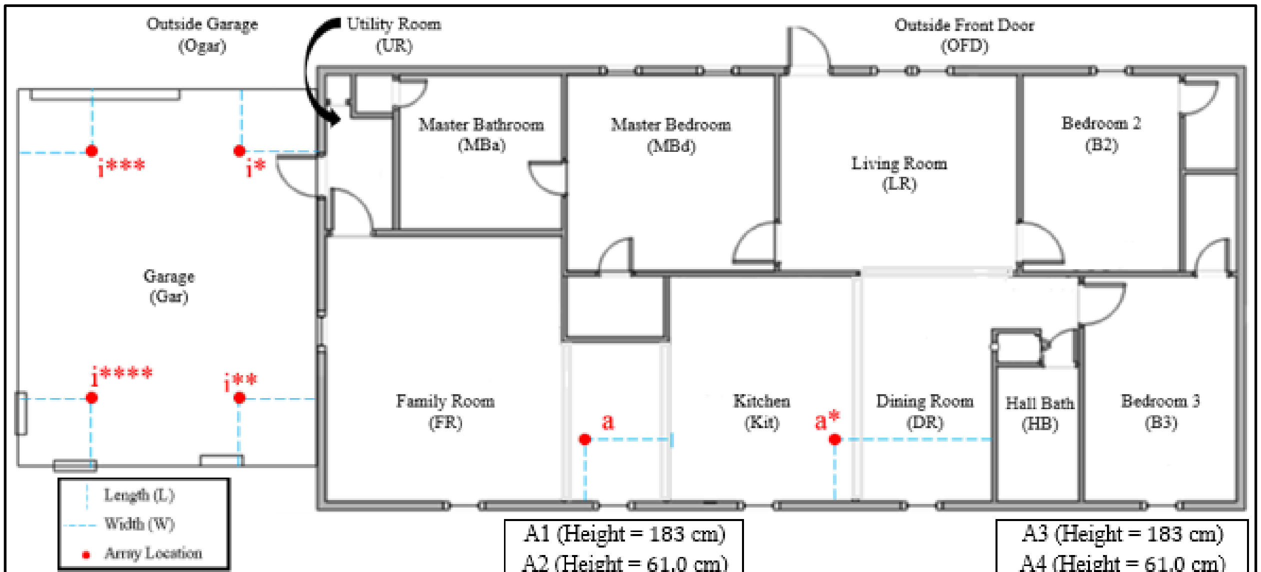
Figure 3 NIST manufactured test house layout showing the location of CO sensors, thermocouples, and generator placement with exhaust direction.

Instrumentation

CO concentrations in the test house were measured using a non-dispersive infrared (NDIR) multi-gas analyzer and arrays of electrochemical sensors. Thermocouples were placed near all electrochemical sensors and within each room. The measurement equipment was connected to a custom data acquisition system. In addition to CO concentrations and interior temperature, weather conditions, including wind and temperature near the test house, were also recorded.

The NDIR analyzer was used with a range of 0 to 1000 ppmv to measure the CO concentration near the generator's CO safety shutoff sensor. Ultra-pure CO with a nitrogen balance was used to calibrate the multi-gas analyzer at the beginning of each test day.

The electrochemical sensors were used to measure CO concentrations in each room of the test house. Either a four-point or an eight-point sensor array was also used to measure concentrations near the generator. Two ranges (a low range and a high range) of sensors were placed at each measurement point. The low-range sensor had a range up to 800 ppmv with integrated temperature correction, and the high-range sensor had a range up to 5000 ppmv without integrated temperature correction. A low-range sensor and high-range sensor were placed in the center of each room, 0.84 m above the floor. The position of the four-point and eight-point sensor array used to measure concentrations around the generator was dependent on the test case (Figure 4). Sensor locations for different tests are indicated with letters and letters with asterisks in Figure 4. For example, when the generator was in the Kitchen, the A1 and A2 sensors for the four-point array were located at position 'a' in Figure 4, and the A3 and A4 sensors were located at position 'a.*' Because the high-range electrochemical sensors were not equipped with integrated temperature correction, type J thermocouples were placed near each of these sensors. Temperature correction was then performed in real-time by the data acquisition program.



			A1 (Height = 183 cm) A2 (Height = 61.0 cm)			A3 (Height = 183 cm) A4 (Height = 61.0 cm)	
Test Location		**Icon**	**L (cm)**	**W (cm)**	**Icon**	**L (cm)**	**W (cm)**
Kitchen		a	183	173	a*	183	371
			A1 (Height = 183 cm) A2 (Height = 61.0 cm) A3 (Height = 183 cm) A4 (Height = 61.0 cm)			A5 (Height = 183 cm) A6 (Height = 61.0 cm) A7 (Height = 183 cm) A8 (Height = 61.0 cm)	
Garage/Outside Garage		i* (A1&A2)	168	137	i*** (A5&A6)	168	137
		i** (A3&A4)	168	137	i**** (A7&A8)	168	137

Figure 4 NIST manufactured test house layout showing positions of the four- and eight-point arrays for measuring CO concentration at each test location.

The electrochemical sensor modules were calibrated against a NDIR gas analyzer in CPSC's Combustion Lab. First, the analyzer was calibrated with NIST traceable primary standard gas across a range up to 800 ppmv for the low-range sensors and 5000 ppmv for the high-range sensors. The sensors were tested in batches inside a sealed conditioning chamber with a high degree of mixing. A sample was withdrawn from the center of the chamber near the center of the set of sensors being calibrated and directed to the NDIR analyzer. The same power supply and data acquisition hardware used in field testing were used to power and read the NDIR analyzer and sensor outputs during these calibrations. The sensors were calibrated by gradually increasing the concentration of CO in the chamber through a series of steps, then gradually decreasing the concentration back to zero. The time series data from the sensors and the analyzer were sampled at 1 Hz. The measurement from each sensor was then compared to the measurement from the analyzer to determine a calibration factor for the sensors. Both the low- and high-range sensors were within +/- 4 % of the concentrations reported by the analyzer. This results in an expanded uncertainty of 8 % with a coverage factor of k = 2. A single calibration factor was applied in the data acquisition system for each low-range and high-range sensor. The sensors were not found to drift significantly during testing based on calibrations performed before and after the test program, as well as random sensor verification during testing.

The data acquisition system consisted of hardware and software with a custom program to record CO concentrations with temperature correction, test start and stop time, generator load, and weather conditions, all at a frequency of 1 Hz. Analog to digital converters with a minimum resolution of 16 bits were used for the CO channel and integrated cold junction correction for the thermocouples.

A local weather station located about 5 m behind the house was used to measure ambient conditions including temperature, humidity, wind speed and wind direction. All air temperature and humidity data were recorded by an automated data acquisition system. Nabinger and Persily (2008) provide more details on the temperature, humidity, and ambient weather condition measurements including uncertainties.

Generators and Loading

Four commercially available (also called production in this report) portable generators from four different manufacturers were tested. These generators are identified throughout this report as G65S, G65C, G85, and G7S. The first three (G65S, G65C, and G85) were advertised as certified to PGMA G300 and the fourth (G7S) was advertised as certified to UL 2201.

G65S: 6.5 kW continuous power gasoline-powered generator (G300)
G65C: 6.5 kW continuous power gasoline-powered generator (G300)
G85: 6.25 kW continuous power gasoline-powered generator (G300)
G7S: 7 kW continuous power gasoline-powered generator (UL 2201)

The generators were operated using commercially available gasoline with 10 % ethanol obtained from an off-campus fueling station. The generators were cold-started for all tests in this report except as specifically noted.

A portable alternating current (AC) resistive load bank connected to the generator's 120-volt receptacle was used to draw electrical power, and thereby, act as a surrogate for consumer appliance loads. The load bank has manual switches for specific loads and a variable transformer for infinite load step resolution with a maximum setting of 20 kW.

Testing and Analysis Methods

To characterize the emission and transport of CO and the resulting COHb profiles, the generators were operated until either their CO safety shutoff system shut the generator off or the generator ran out of fuel. Ventilation conditions, including window and door opening, were specified for each scenario, including any changes during the tests, as described in the results section. Exterior doors and windows were closed, and interior doors were fully open, except as specifically noted. The test house HVAC system was off at all times during tests. Upon activation of the CO safety shutoff system, the generator was left in place but not running. Ventilation conditions were not changed unless specifically noted.

Estimated COHb profiles were calculated from the CO measurements 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. These input values include a respiratory minute volume (RMV) value of 10 L/min (representing a time-weighted average 24-hour value for males and females 16 to 80 years old, for residential indoor activity) (CPSC 2016). COHb levels were calculated assuming an individual remained in the same room for the duration of the test. Calculations were performed for all rooms except the bathrooms, utility room and the garage;

however, COHb calculations were performed for the garage when the generator was in the garage or outside but near the garage. Additional details on the % COHb calculation are included in Appendix 1 of this report. According to Inkster 2012, "The % COHb can serve as a useful approximation of expected CO poisoning severity in healthy adults during acute uptake of CO, although it is recognized that the relationship is not absolute, and there is variation among individuals due to different physiological characteristics and/or health status. It should also be noted that measured COHb levels are influenced by the timing of the COHb measurement, relative to cessation of the CO exposure, and by provision of any oxygen therapy in the intervening period. Notwithstanding these caveats, increasing % COHb levels are generally related to progressively worsening symptoms." See the table below from Burton 1996.

% COHb	Symptoms
<10	No perceptible ill effects (Some studies have reported adverse health effects in some cardiac patients at 2 % to 5 % COHb
10 to 20	Mild headache, labored breathing, decreased exercise tolerance
20 to 30	Throbbing headache, mild nausea
30 to 40	Severe headache, dizziness, nausea, vomiting, cognitive impairment
40 to 50	Confusion, unconsciousness, coma, possible death
50 to 70	Coma, brain damage, seizures, death
>70	Typically fatal

Test Results

As described above, NIST conducted a series of tests to provide empirical data to characterize the emission and transport of CO in the NIST manufactured test house, as well as the resulting calculated COHb profiles, when operating PGMA G300 or UL 2201 certified portable generators in the living space and attached garage. The resulting data, presented in this section, are organized by the location of the generator. The tests performed at each location are summarized in Tables 1 and 2. The tables include columns listing the generator location, the generator tested, the load (as a % of the maximum continuous generator capacity), the case (a combination of generator location, load and ventilation condition) and test number (PCase#/Test# in the tables), the voluntary standards the generator was advertised as certified to, the average outdoor temperature, the average wind speed, the peak CO concentration in the house or garage, the CO concentration measured near the sensor of the onboard safety shutoff system at the time of shutoff, the calculated shutoff ratio, the range of peak COHb values reached, the ventilation settings of the house, and notes. The column labeled "Peak CO in House and Garage" is the maximum CO concentration measured by any sensor located within the test house and garage (*i.e.*, the four-point or eight-point arrays and the centrally located room sensors) during the test. The "Shutoff Ratio" column presents the ratio of the average source room CO concentration to the CO concentration measured near the generator's CO safety shutoff sensor at the time of shutoff. The average source room concentration is determined by averaging the values at the time of shutoff from the centrally located room sensor and any sensors from the sensor array that were in the source room. Note that these results apply to the specific generators tested and that other generators, houses, and test conditions may produce different results. Also note that the combinations of generator location, load, exhaust direction, and door/window positions were selected to represent a wide range of possible conditions and with consideration of reported incidents.

The following sections contain the individual test results organized by generator location. In each of these sections, four to five figures are presented for each test, designated as Figure Xa, Xb, Xc, Xd and Xe. Figure Xa shows the position of the generator, the generator exhaust direction, and the position of the CO sensor array used to measure CO around the generator. Figure Xb, for the cases where the generator is positioned in the kitchen, shows the CO concentrations measured near the generator's CO safety shutoff sensor, by the CO sensor array, and by the centrally located room sensor. Figure Xb, for the cases where the generator is positioned in the garage, shows CO concentrations measured near the generator's CO safety shutoff sensor, by the CO sensor array, by the G300 height sensor (3 cm to 5 cm above the centerline of the top of the generator), and by the UL 2201 height sensor (30 cm above the centerline of the top of the generator). Figure Xc shows the CO concentrations measured by the centrally located room sensors in each room. Figure Xd shows the CO concentrations averaged over a 1-minute time step measured by the centrally located room sensors in the areas of the home likely to be occupied (*i.e.*, not including bathrooms, hallways, utility room, and closets). This figure also presents projected CO concentrations after the test was ended. These estimates are obtained for each room by applying the equation $C=C_0e^{-rt}$, where C is the concentration of CO in the room at time t, C_0 is the last CO measurement taken from the room (the initial CO concentration for projected values), and r is the exponential decay constant of the room (calculated by an exponential fit to the measured data typically over the last hour of the test). These data were used to develop the COHb profiles in the corresponding Figure Xe, assuming a simulated occupant stays in each room for the duration of the test.

Generator Location: Kitchen

Table 1 summarizes the results for all tests performed with a generator located in the test house kitchen. The details are discussed below and shown in **Figures 5** through **16**.

Generator Location	Generator	Load (%)	PCase # / Test #	Voluntary Standard	Avg Temp Out (C)	Avg Wind Speed (m/s)	Peak CO in House and Garage (µL/L)	Concentration @ Shutoff ┼ (µL/L)	Shutoff Ratio (Zone Avg : Near Shutoff Sensor)	Range of Peak COHb Values ┼┼ (%)	Ventilation ┼┼┼ (W=window open, D=door open)	Shutoff Activation (min)
Kitchen (Kit)	G65S	100	1 / 1	G300	27.7	1.0	1038	535	1.33	25 to 30	W (Kit) - 10 cm	≈4
	G65C	100	1 / 1	G300	25.3	0.9	543	245	1.74	10 to 13		≈4
	G7S	100	1 / 1	UL2201	23.1	1.3	189	114	1.33	5 to 7		≈39
	G85	100	1 / 1	G300	27.6	1.2	588	492	1.26	14 to 16		≈3
	G65S	50	2 / 1	G300	22.2	3.4	1161	486	1.36	18 to 22		≈7
	G65C	50	2 / 1	G300	23.5	1.2	440	311	1.26	15 to 18		≈23
	G7S	50	2 / 1	UL2201	23.1	3.2	219	131	1.26	6 to 8		≈38
	G85	50	2 / 1	G300	26.6	1.3	439	339	1.20	6 to 8		≈3
	G65S	10	3 / 1	G300	31.1	2.0	631	453	1.05	15 to 18		≈10
	G65C	10	3 / 1	G300	20.9	1.3	289	230	1.16	12 to 16		≈171
	G7S	10	3 / 1	UL2201	22.9	1.2	145	-	-	5 to 8		≈294 ┼┼┼┼
	G85	10	3 / 1	G300	31.8	2.2	509	329	1.33	8 to 10		≈4

┼Measured by the low-range electrochemical sensor placed near the sensor of onboard shutoff system.
┼┼Peak COHb Values are for house zones only.
┼┼┼Ventilation Note: Unless specified otherwise, during the test - all exterior doors are closed, all interior doors are fully open, and all windows are closed.
┼┼┼┼ Shutoff not activated, generator manually shut down due to high temperatures in the house (approaching 50ºC)

Table 1. Summary of test results for Kitchen (Kit) tests

Production Case 1 Test 1 – G65S G300

The following figures illustrate the results for Production Case 1 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 100 % load (6,500 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 4 min. **Figure 5a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 5b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 5c** shows the CO concentration measured in each room of the house over the test. **Figure 5d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 5e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

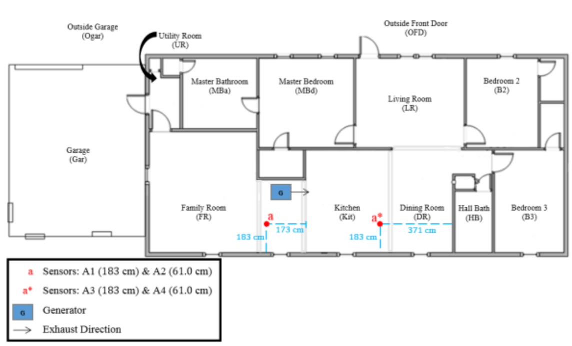


Figure 5a. Generator, exhaust direction, and sensor array layout during Production Case 1 Test 1 – G65S G300.

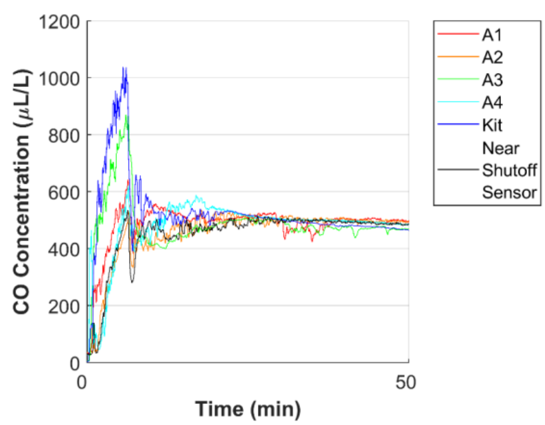


Figure 5b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 1 Test 1 – G65S G300.

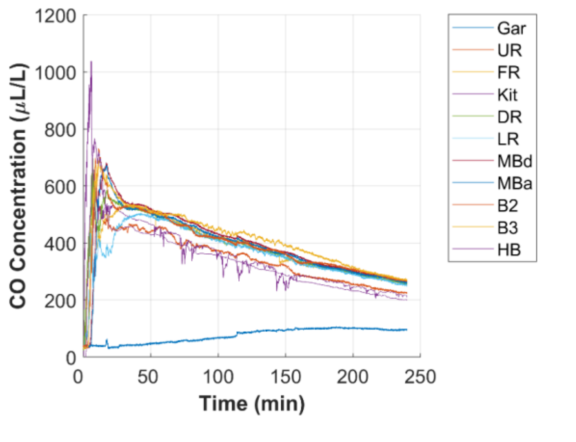


Figure 5c. CO concentration measured in each room of the house during Production Case 1 Test 1 – G65S G300.

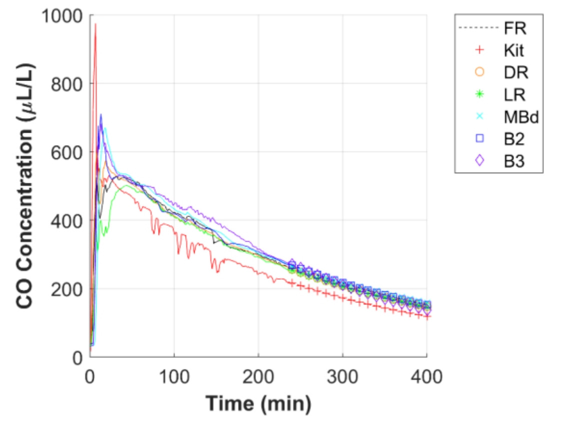


Figure 5d. CO concentration (measured & projected) in the house during Production Case 1 Test 1 – G65S G300.

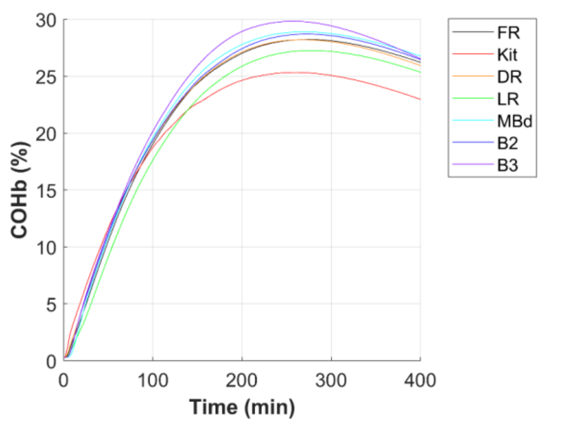


Figure 5e. COHb of simulated house occupants during Production Case 1 Test 1 – G65S G300.

Production Case 1 Test 1 – G65C G300

The following figures illustrate the results for Production Case 1 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 100 % load (6,500 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 4 min. **Figure 6a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 6b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 6c** shows the CO concentration measured in each room of the house over the test. **Figure 6d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 6e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

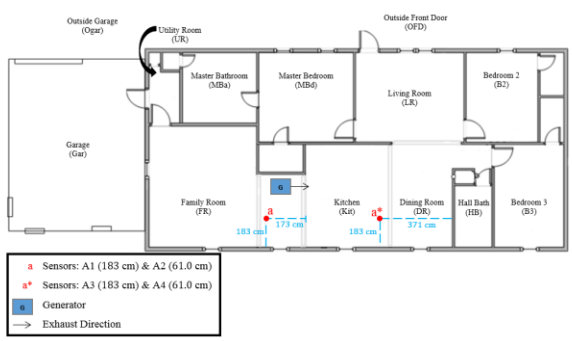


Figure 6a. Generator, exhaust direction, and sensor array layout during Production Case 1 Test 1 – G65C G300.

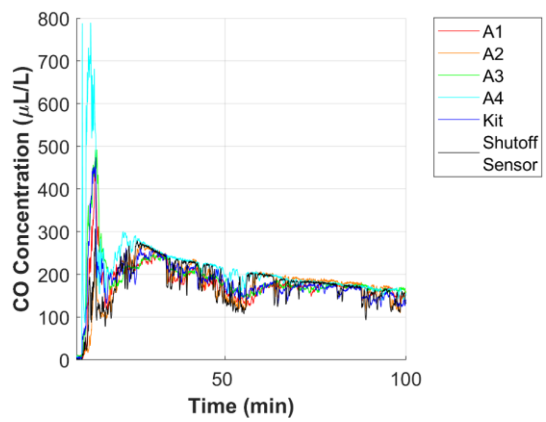


Figure 6b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 1 Test 1 – G65C G300.

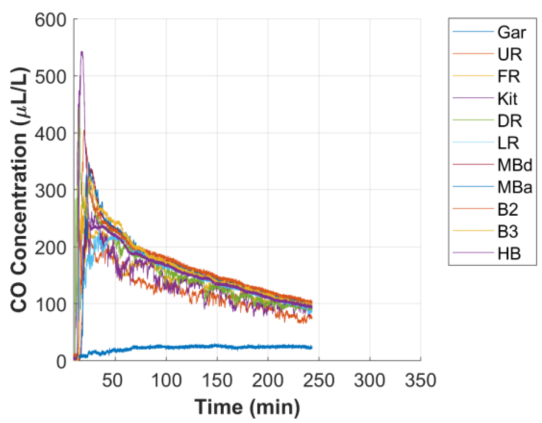


Figure 6c. CO concentration measured in each room of the house during Production Case 1 Test 1 – G65C G300.

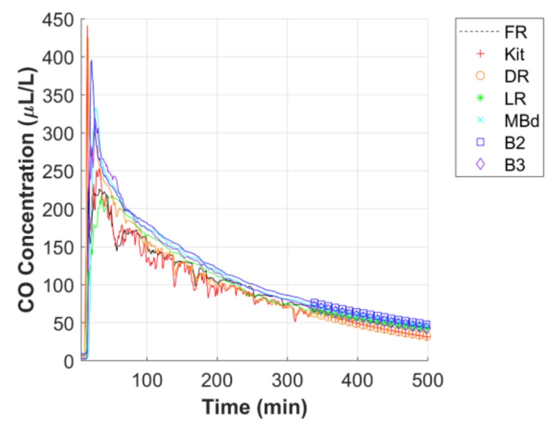


Figure 6d. CO concentration (measured & projected) in the house during Production Case 1 Test 1 – G65C G300.

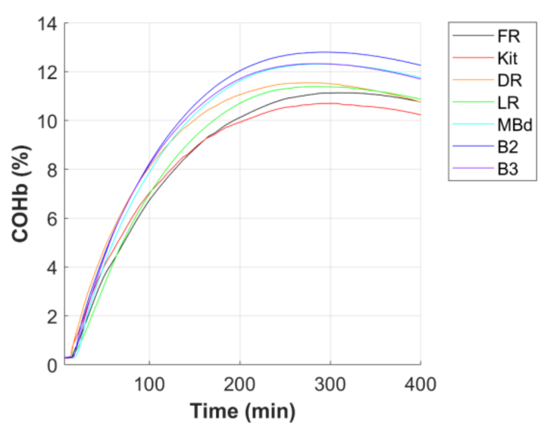


Figure 6e. COHb of simulated house occupants during Production Case 1 Test 1 – G65C G300.

Production Case 1 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 1 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 100 % load (7,000 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 39 min. **Figure 7a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 7b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 7c** shows the CO concentration measured in each room of the house over the test. **Figure 7d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 7e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

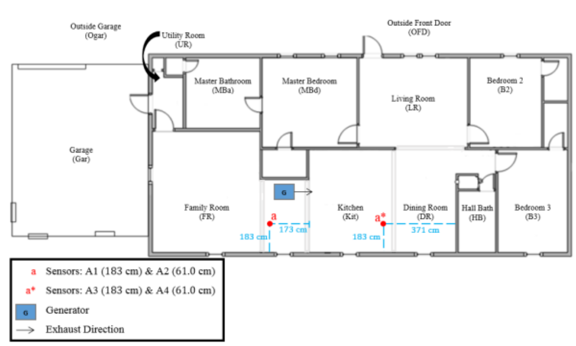


Figure 7a. Generator, exhaust direction, and sensor array layout during Production Case 1 Test 1 – G7S UL 2201.

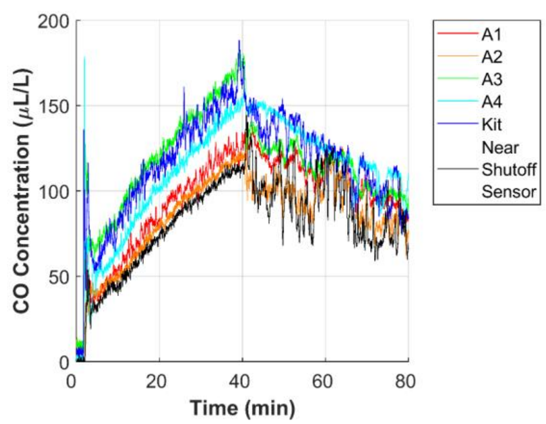


Figure 7b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 1 Test 1 – G7S UL 2201.

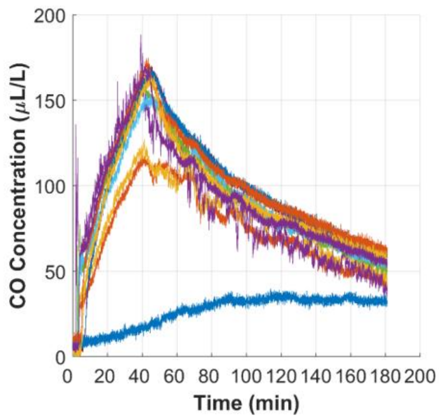


Figure 7c. CO concentration measured in each room of the house during Production Case 1 Test 1 – G7S UL 2201.

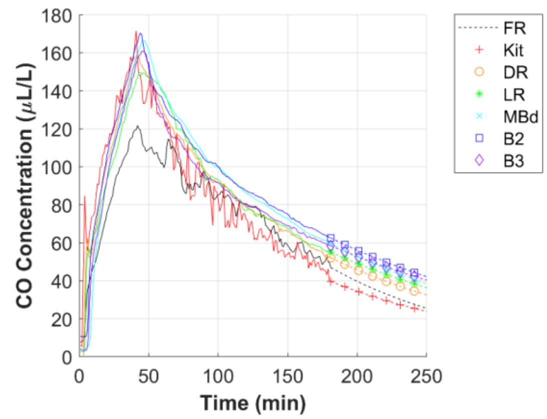


Figure 7d. CO concentration (measured & projected) in the house during Production Case 1 Test 1 – G7S UL 2201.

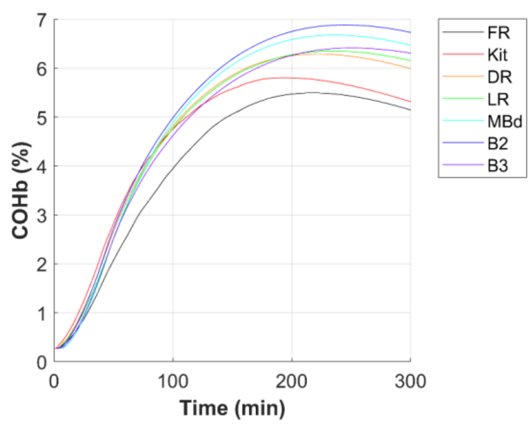


Figure 7e. COHb of simulated house occupants during Production Case 1 Test 1 – G7S UL 2201.

Production Case 1 Test 1 – G85 G300

The following figures illustrate the results for Production Case 1 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 100 % load (6,250 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 3 min. **Figure 8a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 8b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 8c** shows the CO concentration measured in each room of the house over the test. **Figure 8d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 8e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

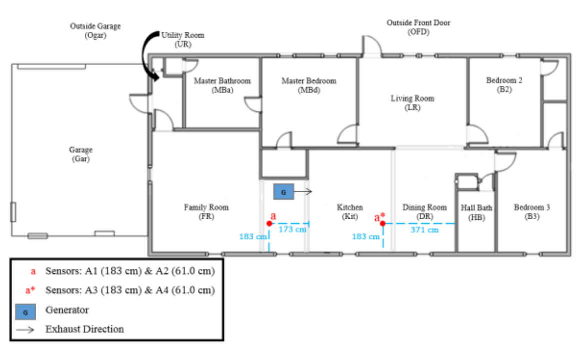


Figure 8a. Generator, exhaust direction, and sensor array layout during Production Case 1 Test 1 – G85 G300.

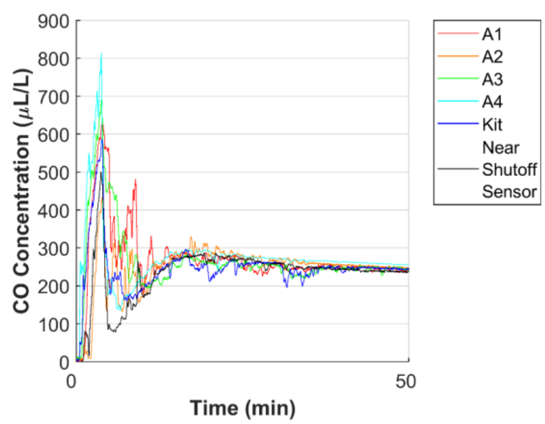


Figure 8b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 1 Test 1 – G85 G300.

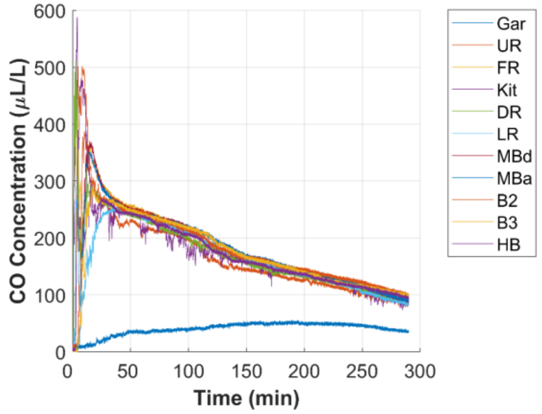


Figure 8c. CO concentration measured in each room of the house during Production Case 1 Test 1 – G85 G300.

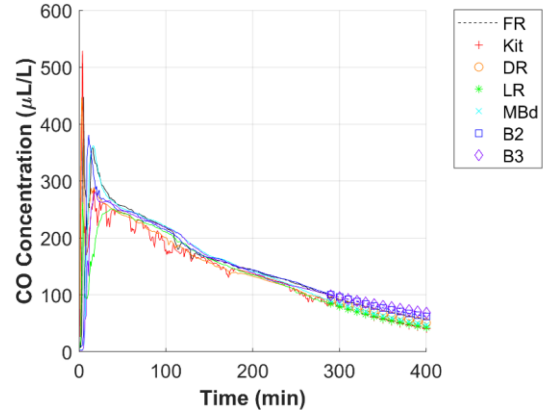


Figure 8d. CO concentration (measured & projected) in the house during Production Case 1 Test 1 – G85 G300.

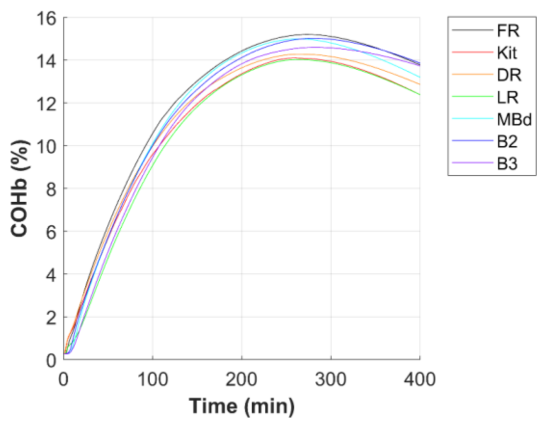


Figure 8e. COHb of simulated house occupants during Production Case 1 Test 1 – G85 G300.

Production Case 2 Test 1 – G65S G300

The following figures illustrate the results for Production Case 2 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 50 % load (3,250 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 7 min. **Figure 9a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 9b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 9c** shows the CO concentration measured in each room of the house over the test. **Figure 9d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 9e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

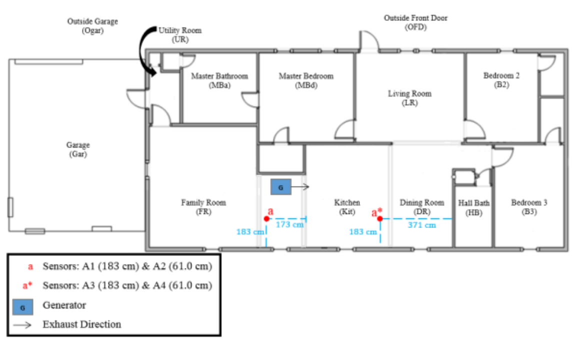


Figure 9a. Generator, exhaust direction, and sensor array layout during Production Case 2 Test 1 – G65S G300.

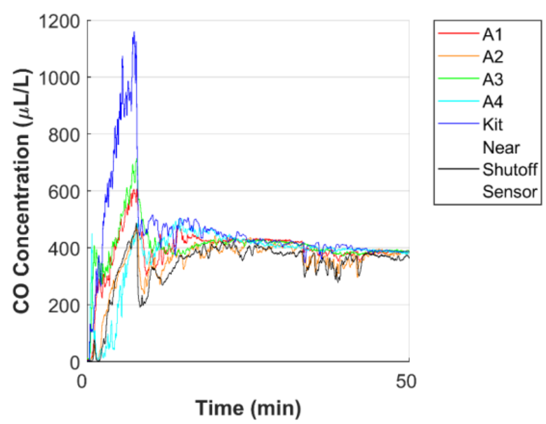


Figure 9b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 2 Test 1 – G65S G300.

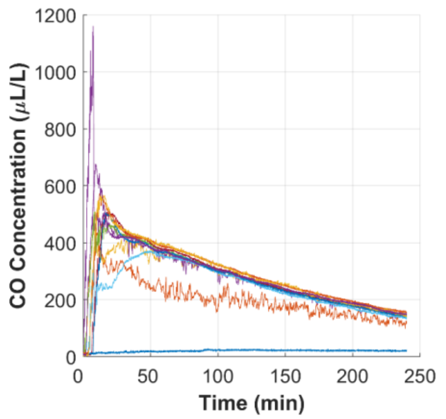


Figure 9c. CO concentration measured in each room of the house during Production Case 2 Test 1 – G65S G300.

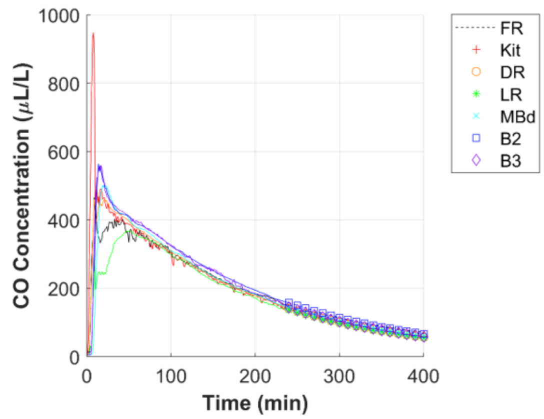


Figure 9d. CO concentration (measured & projected) in the house during Production Case 2 Test 1 – G65S G300.

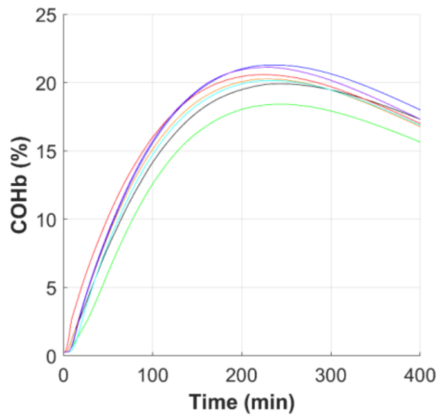


Figure 9e. COHb of simulated house occupants during Production Case 2 Test 1 – G65S G300.

Production Case 2 Test 1 – G65C G300

The following figures illustrate the results for Production Case 2 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 50 % load (3,250 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 23 min. **Figure 10a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 10b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 10c** shows the CO concentration measured in each room of the house over the test. **Figure 10d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 10e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

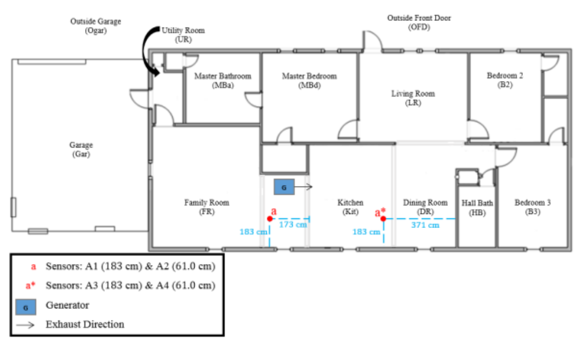


Figure 10a. Generator, exhaust direction, and sensor array layout during Production Case 2 Test 1 – G65C G300.

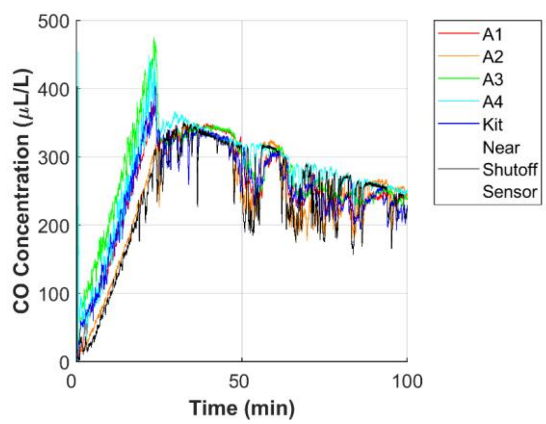


Figure 10b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 2 Test 1 – G65C G300.

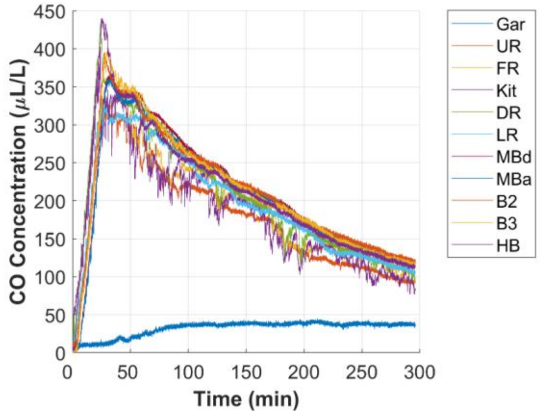


Figure 10c. CO concentration measured in each room of the house during Production Case 2 Test 1 – G65C G300.

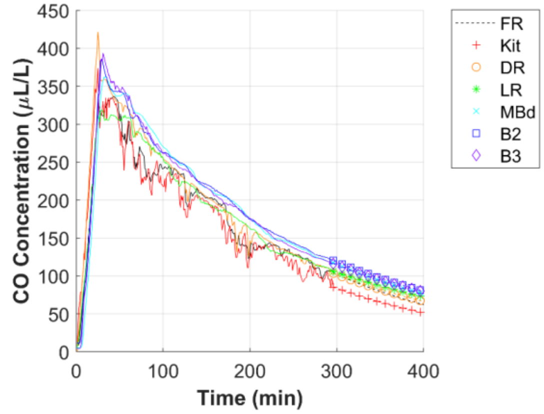


Figure 10d. CO concentration (measured & projected) in the house during Production Case 2 Test 1 – G65C G300.

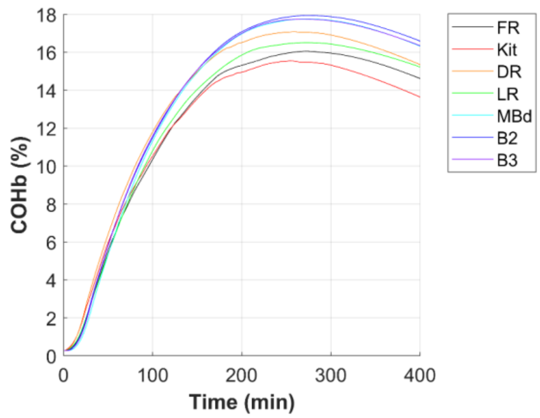


Figure 10e. COHb of simulated house occupants during Production Case 2 Test 1 – G65C G300.

Production Case 2 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 2 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 50 % load (3,500 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 38 min. **Figure 11a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 11b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 11c** shows the CO concentration measured in each room of the house over the test. **Figure 11d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 11e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

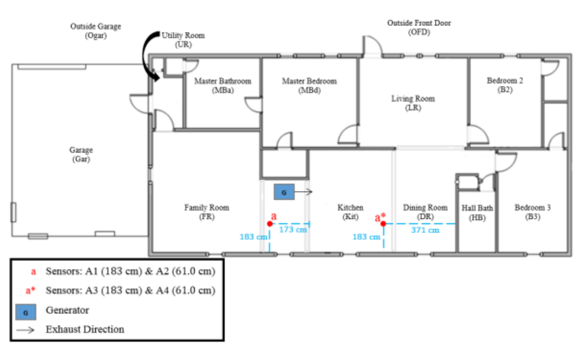


Figure 11a. Generator, exhaust direction, and sensor array layout during Production Case 2 Test 1 – G7S UL 2201.

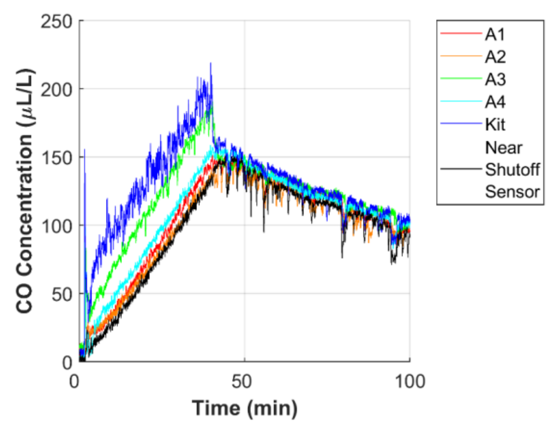


Figure 11b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 2 Test 1 – G7S UL 2201.

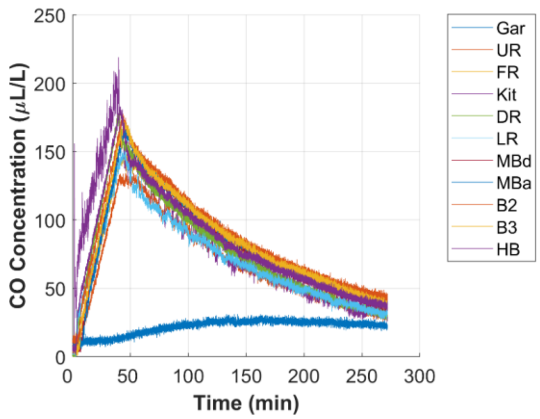


Figure 11c. CO concentration measured in each room of the house during Production Case 2 Test 1 – G7S UL 2201.

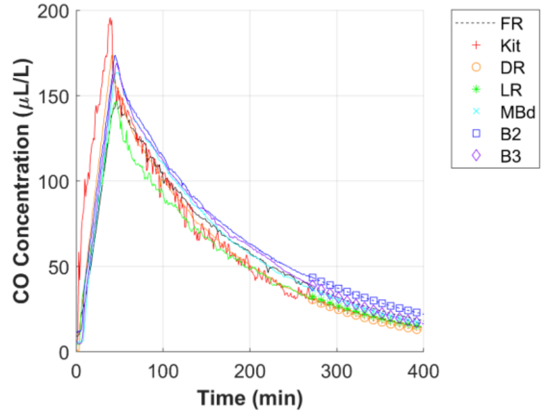


Figure 11d. CO concentration (measured & projected) in the house during Production Case 2 Test 1 – G7S UL 2201.

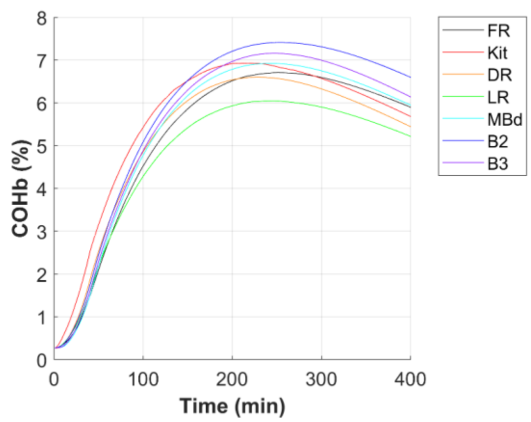


Figure 11e. COHb of simulated house occupants during Production Case 2 Test 1 – G7S UL 2201.

Production Case 2 Test 1 – G85 G300

The following figures illustrate the results for Production Case 2 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 50 % load (3,125 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 3 min. **Figure 12a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 12b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 12c** shows the CO concentration measured in each room of the house over the test. **Figure 12d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 12e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

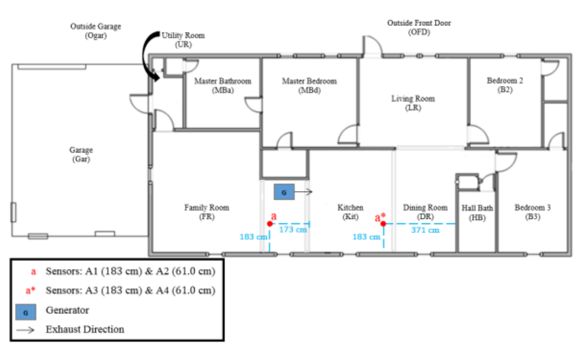


Figure 12a. Generator, exhaust direction, and sensor array layout during Production Case 2 Test 1 – G85 G300.

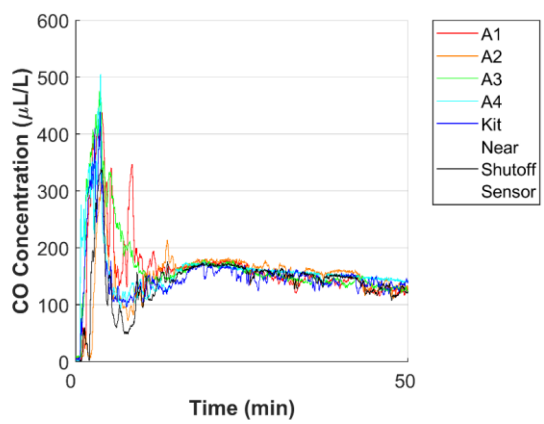


Figure 12b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 2 Test 1 – G85 G300.

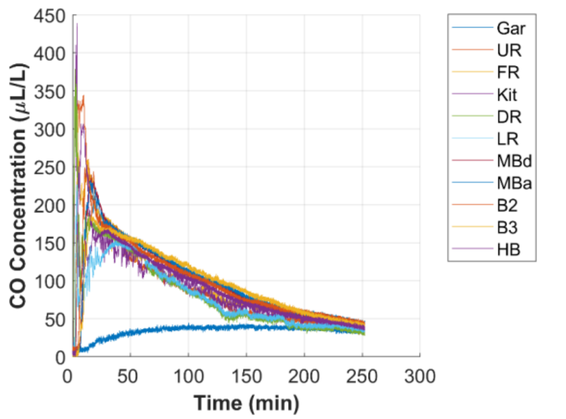


Figure 12c. CO concentration measured in each room of the house during Production Case 2 Test 1 – G85 G300.

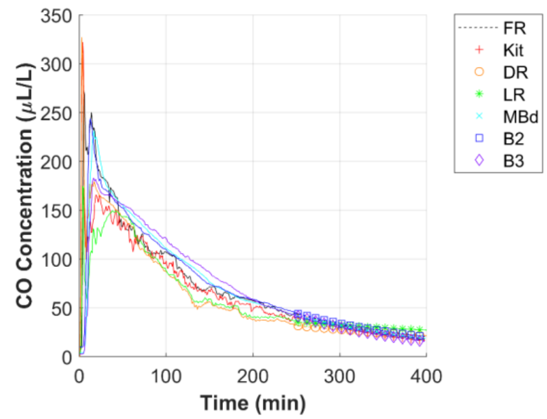


Figure 12d. CO concentration (measured & projected) in the house during Production Case 2 Test 1 – G85 G300.

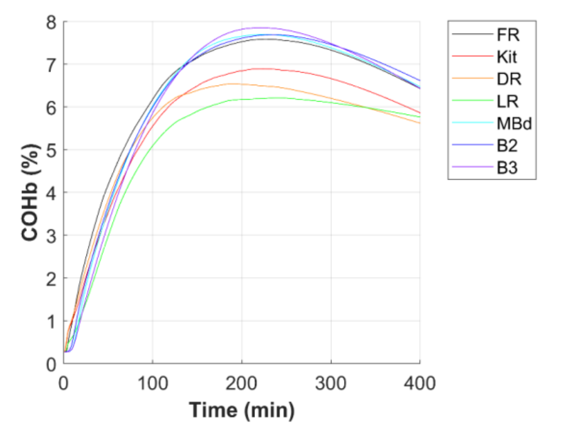


Figure 12e. COHb of simulated house occupants during Production Case 2 Test 1 – G85 G300.

Production Case 3 Test 1 – G65S G300

The following figures illustrate the results for Production Case 3 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 10 % load (650 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 10 min. **Figure 13a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 13b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 13c** shows the CO concentration measured in each room of the house over the test. **Figure 13d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 13e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

Figure 13a. Generator, exhaust direction, and sensor array layout during Production Case 3 Test 1 – G65S G300.

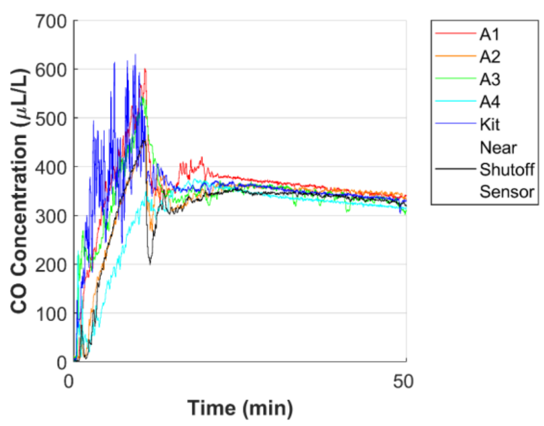


Figure 13b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 3 Test 1 – G65S G300.

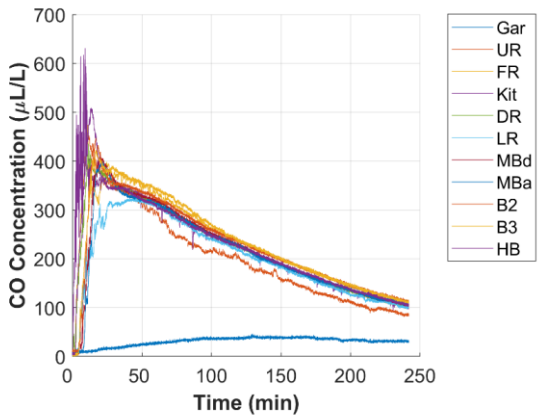


Figure 13c. CO concentration measured in each room of the house during Production Case 3 Test 1 – G65S G300.

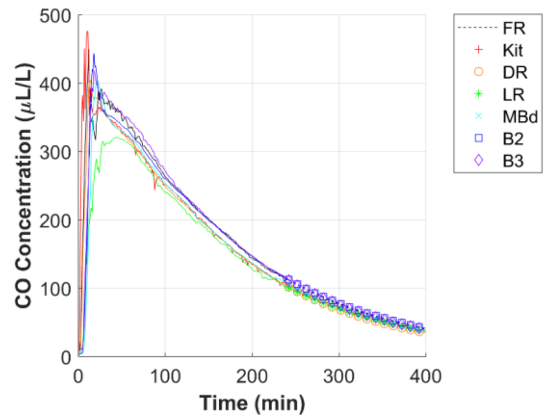


Figure 13d. CO concentration (measured & projected) in the house during Production Case 3 Test 1 – G65S G300.

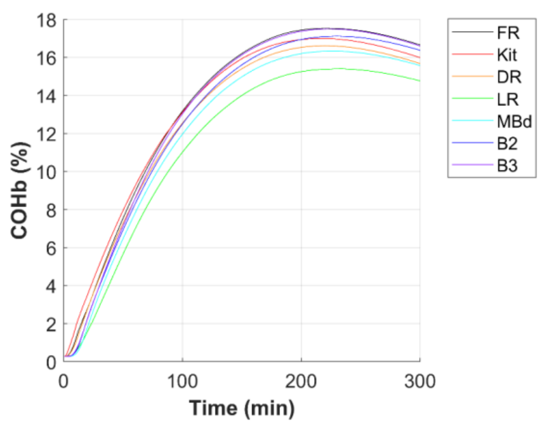


Figure 13e. COHb of simulated house occupants during Production Case 3 Test 1 – G65S G300.

Production Case 3 Test 1 – G65C G300

The following figures illustrate the results for Production Case 3 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 10 % load (650 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 171 min. **Figure 14a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 14b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 14c** shows the CO concentration measured in each room of the house over the test. **Figure 14d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 14e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

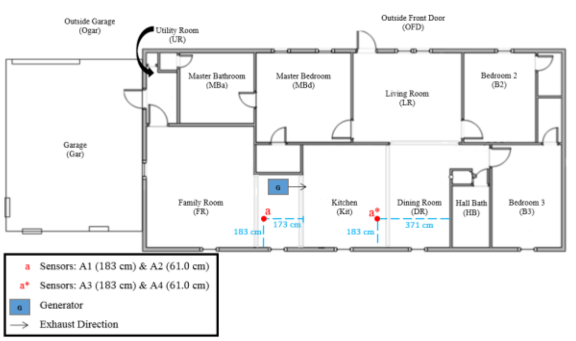


Figure 14a. Generator, exhaust direction, and sensor array layout during Production Case 3 Test 1 – G65C G300.

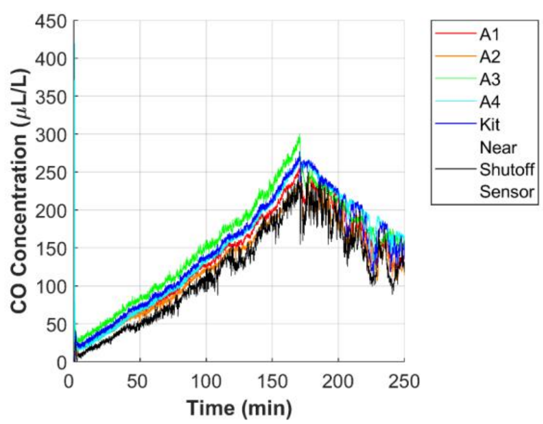


Figure 14b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 3 Test 1 – G65C G300.

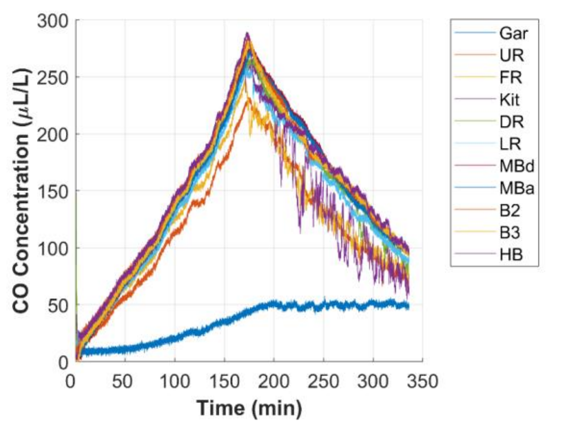


Figure 14c. CO concentration measured in each room of the house during Production Case 3 Test 1 – G65C G300.

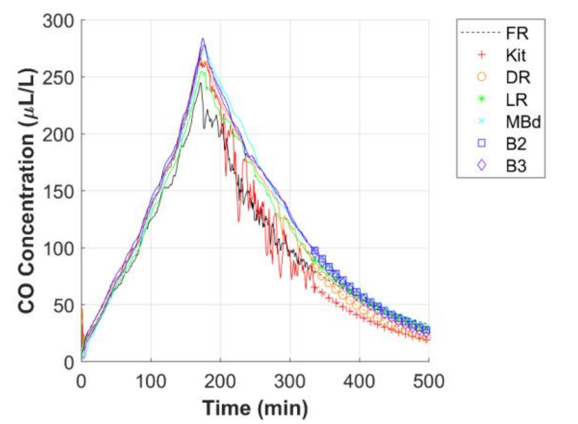


Figure 14d. CO concentration (measured & projected) in the house during Production Case 3 Test 1 – G65C G300.

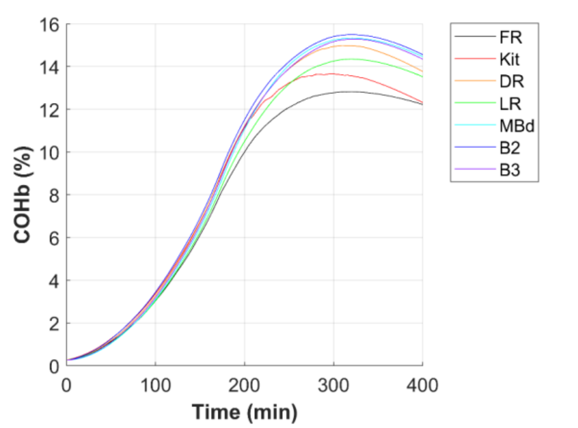


Figure 14e. COHb of simulated house occupants during Production Case 3 Test 1 – G65C G300.

Production Case 3 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 3 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 10 % load (700 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system was not activated, and the generator was manually shut down after approximately 294 min due to high temperatures in the house (approaching 50ºC). **Figure 15a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 15b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 15c** shows the CO concentration measured in each room of the house over the test. **Figure 15d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

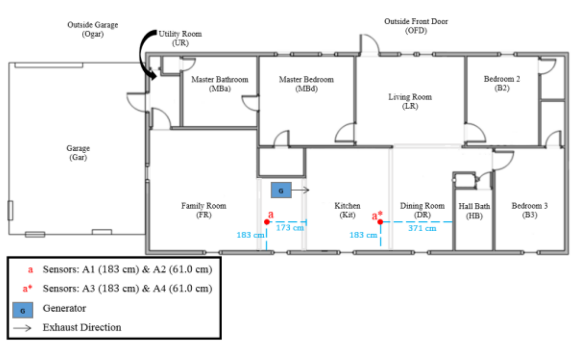


Figure 15a. Generator, exhaust direction, and sensor array layout during Production Case 3 Test 1 – G7S UL 2201.

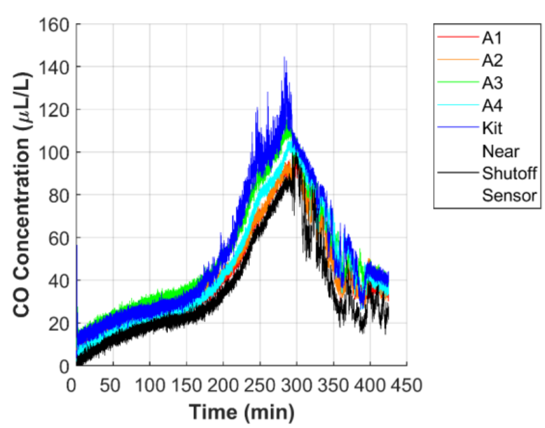


Figure 15b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 3 Test 1 – G7S UL 2201.

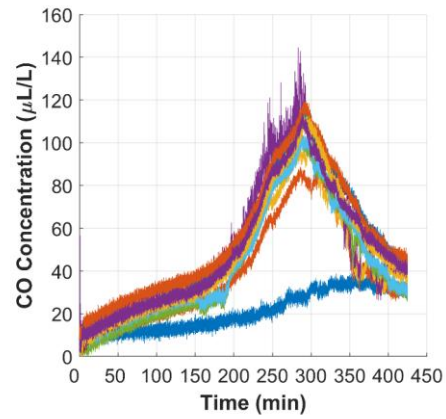


Figure 15c. CO concentration measured in each room of the house during Production Case 3 Test 1 – G7S UL 2201.

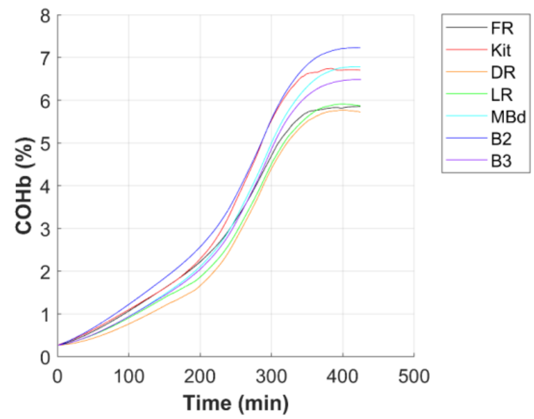


Figure 15d. COHb of simulated house occupants during Production Case 3 Test 1 – G7S UL 2201.

Production Case 3 Test 1 – G85 G300

The following figures illustrate the results for Production Case 3 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the kitchen (30 cm from the master bedroom closet wall with the exhaust facing the dining room), and tested at 10 % load (625 W). The kitchen window nearest to the generator was open 10 cm. The generator's CO safety shutoff system activated to shut off the generator after approximately 4 min. **Figure 16a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 16b** shows the CO concentrations measured in the kitchen (by the dedicated room sensor), by two sensors located on the kitchen-family room boundary (A1: height 183 cm, A2: height 61 cm), by the other two sensors located on the kitchen-dining room boundary (A3: height 183 cm, A4: height 61 cm), and by an electrochemical sensor measuring CO near the generator's CO safety shutoff sensor. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 16c** shows the CO concentration measured in each room of the house over the test. **Figure 16d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 16e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

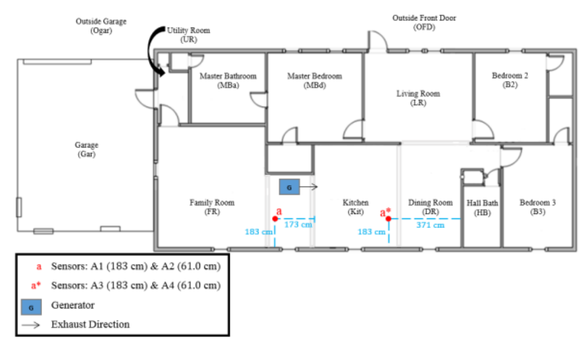


Figure 16a. Generator, exhaust direction, and sensor array layout during Production Case 3 Test 1 – G85 G300.

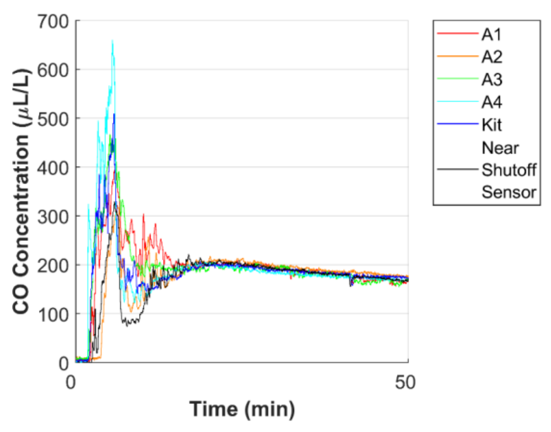


Figure 16b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the designated Kitchen sensor during Production Case 3 Test 1 – G85 G300.

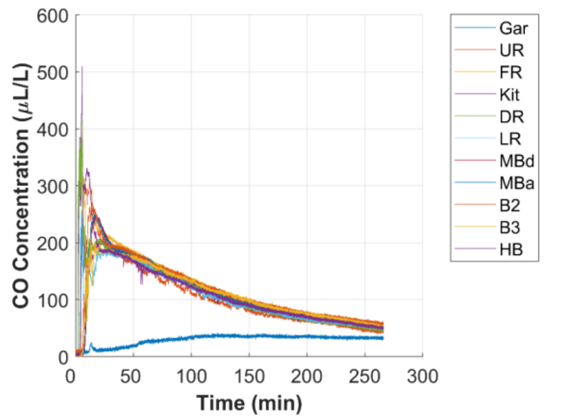


Figure 16c. CO concentration measured in each room of the house during Production Case 3 Test 1 – G85 G300.

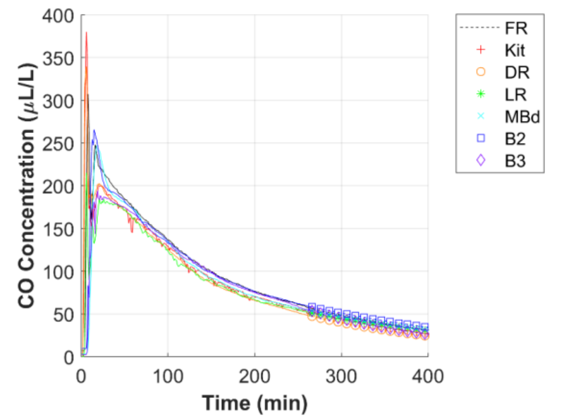


Figure 16d. CO concentration (measured & projected) in the house during Production Case 3 Test 1 – G85 G300.

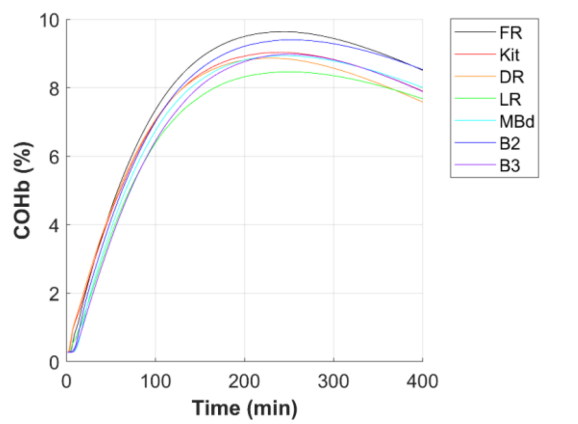


Figure 16e. COHb of simulated house occupants during Production Case 3 Test 1 – G85 G300.

Generator Location: Garage

Table 2 summarizes the results for all tests performed with a generator located in the test house garage. The details are discussed below and shown in **Figures 17** through **36**. For these tests, the designated Garage sensor was set at the G300 standard's test height (3 cm to 5 cm above the centerline of the top of the generator) to evaluate the difference between this location and the onboard sensor location. An additional electrochemical sensor was set at the UL 2201 standard's test height (30 cm above the centerline of the top of the generator) to evaluate the difference between this location and the onboard sensor location.

Generator Location	**Generator**	**Load** (%)	**PCase # / Test #**	**Voluntary Standard**	**Avg Temp Out** (C)	**Avg Wind Speed** (m/s)	**Peak CO in House and Garage** (µL/L)	**Concentration @ Shutoff †** (µL/L)	**Shutoff Ratio** (Zone Avg : Near Shutoff Sensor)	**Range of Peak COHb Values ††** (%)	**Ventilation †††** (W=window open, D=door open)	**Shutoff Activation** (min)
Garage (Gar)	G65S	100	4 / 1	G300	18.5	1.7	721	566	1.08	4 to 7	D (int. person) - 10 cm	≈3
	G65C	100	4 / 1	G300	12.5	2.7	545	254	1.10	<5		≈1
	G7S	100	4 / 1	UL2201	16.3	2.5	197	177	1.09	<5		≈15
	G85	100	4 / 1	G300	12.9	2.1	370	251	1.22	4 to 6		≈2
	G65S	50	5 / 1	G300	20.5	1.2	628	533	1.09	6 to 9		≈4
	G65C	50	5 / 1	G300	15.0	3.2	466	436	1.05	<5		≈12
	G7S	50	5 / 1	UL2201	18.2	3.4	225	211	1.04	<5		≈14
	G85	50	5 / 1	G300	14.9	2.5	396	293	1.14	<5		≈3
	G65S	10	6 / 1	G300	12.6	4.0	569	543	1.01	<5		≈5
	G65C	10	6 / 1	G300	15.6	4.4	261	244	1.04	4 to 7		≈58
	G7S	10	6 / 1	UL2201	18.8	3.2	115	98	1.17	5 to 7		≈166
	G85	10	6 / 1	G300	5.3	3.6	504	437	1.01	4 to 6		≈4
	G65S	100	7 / 1	G300	9.8	2.5	547	-	-	27 to 37	D (int. person) - 10 cm D (garage bay) - fully	≈329 ††††
	G65C	100	7 / 1	G300	12.8	3.5	471	200	1.01	<5		≈2
	G7S	100	7 / 1	UL2201	7.7	1.2	124	-	-	<5		≈225 †††††
	G85	100	7 / 1	G300	10.0	1.9	511	346	1.34	<5		≈8
	G65S	50	8 / 1	G300	10.2	3.3	267	-	-	5 to 8		≈467 ††††††
	G65C	50	8 / 1	G300	15.7	2.1	96	-	-	5 to 8		≈320 †††††
	G7S	50	8 / 1	UL2201	6.7	3.2	44	-	-	<5		≈357 †††††
	G85	50	8 / 1	G300	10.5	4.7	395	-	-	20 to 26		≈468 †††††

†Measured by the NDIR channel placed near the sensor of onboard shutoff system.
††Peak COHb Values are for house zones only.
†††Ventilation Note: Unless specified otherwise, during the test - all exterior doors are closed, all interior doors are fully open, and all windows are closed.
†††† Shutoff not activated, generator ran out of fuel
††††† Shutoff not activated, generator manually shut down due to low levels of CO in the house and anticipated long runtime before generator running out of fuel
†††††† Shutoff not activated, generator manually shut down due to reaching peak COHb in the house

Table 2. Summary of test results for Garage (Gar) tests

Production Case 4 Test 1 – G65S G300

The following figures illustrate the results for Production Case 4 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,500 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 3 min. **Figure 17a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 17b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 17a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO concentrations near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 17c** shows the CO concentration measured in each room of the house over the test. **Figure 17d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 17e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

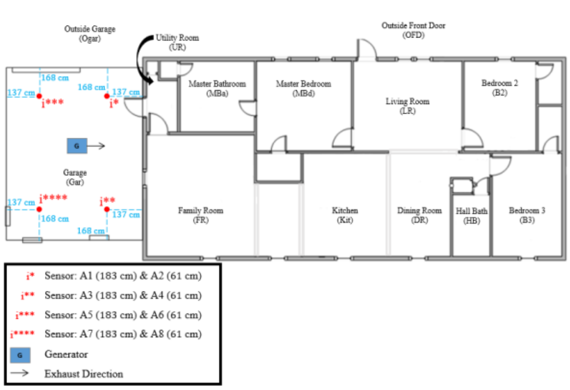


Figure 17a. Generator, exhaust direction, and sensor array layout during Production Case 4 Test 1 – G65S G300.

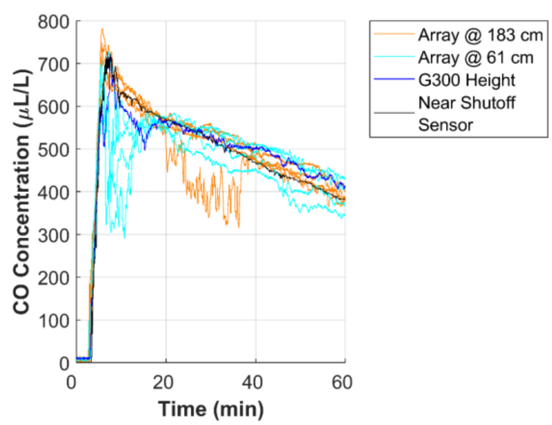


Figure 17b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, and the G300 sensor during Production Case 4 Test 1 – G65S G300.

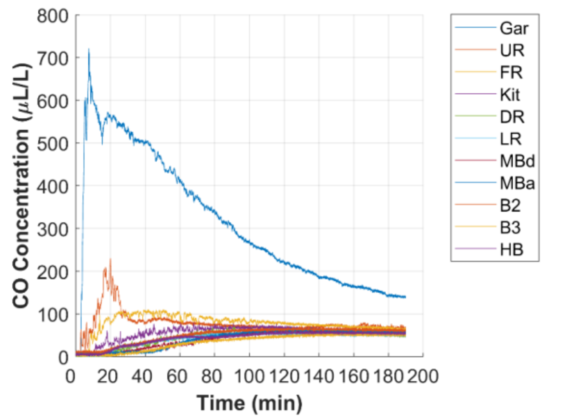


Figure 17c. CO concentration measured in each room of the house during Production Case 4 Test 1 – G65S G300.

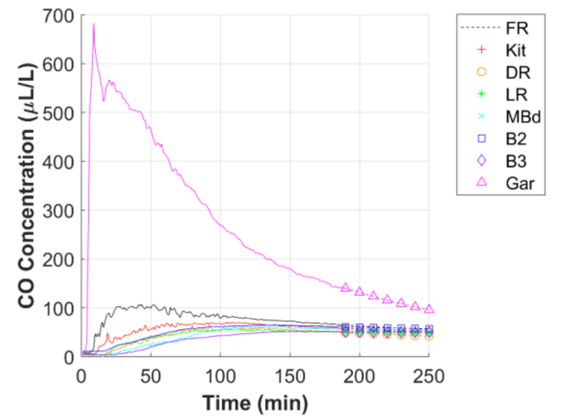


Figure 17d. CO concentration (measured & projected) in the house during Production Case 4 Test 1 – G65S G300.

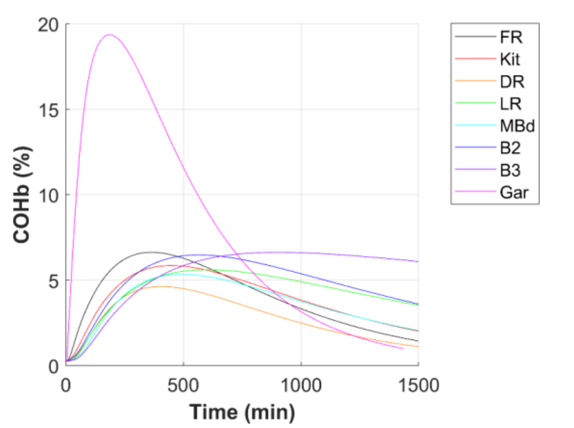


Figure 17e. COHb of simulated house occupants during Production Case 4 Test 1 – G65S G300.

Production Case 4 Test 1 – G65C G300

The following figures illustrate the results for Production Case 4 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,500 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 1 min. **Figure 18a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 18b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 18a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 18c** shows the CO concentration measured in each room of the house over the test. **Figure 18d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

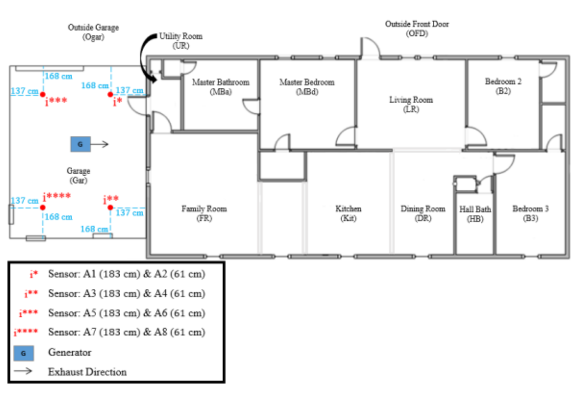


Figure 18a. Generator, exhaust direction, and sensor array layout during Production Case 4 Test 1 – G65C G300.

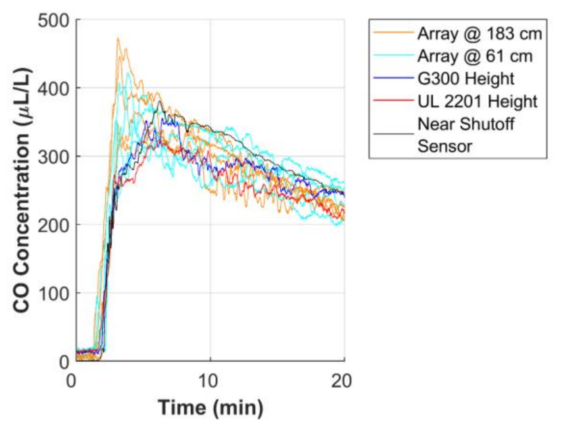


Figure 18b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 4 Test 1 – G65C G300.

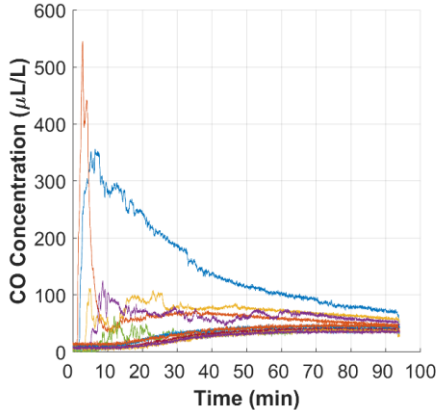


Figure 18c. CO concentration measured in each room of the house during Production Case 4 Test 1 – G65C G300.

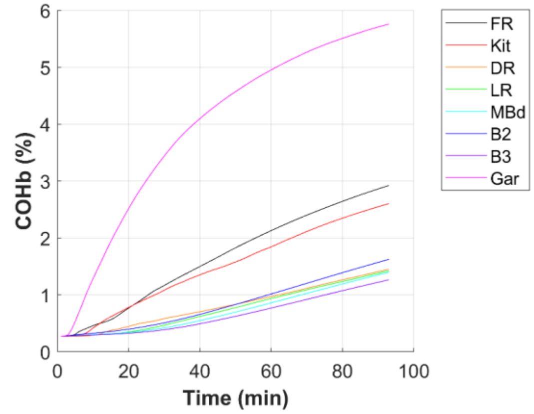


Figure 18d. COHb of simulated house occupants during Production Case 4 Test 1 – G65C G300.

Production Case 4 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 4 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (7,000 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 15 min. **Figure 19a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 19b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 19a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 19c** shows the CO concentration measured in each room of the house over the test. **Figure 19d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 19e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

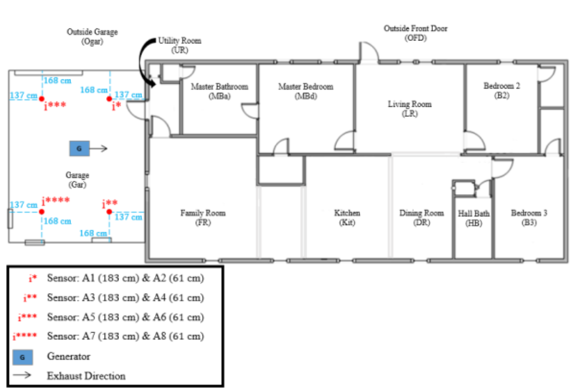


Figure 19a. Generator, exhaust direction, and sensor array layout during Production Case 4 Test 1 – G7S UL 2201.

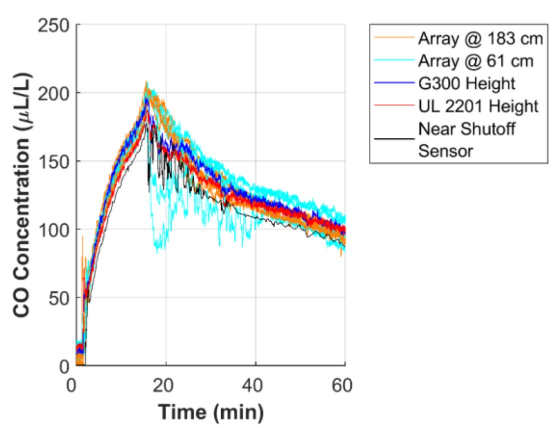


Figure 19b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 4 Test 1 – G7S UL 2201.

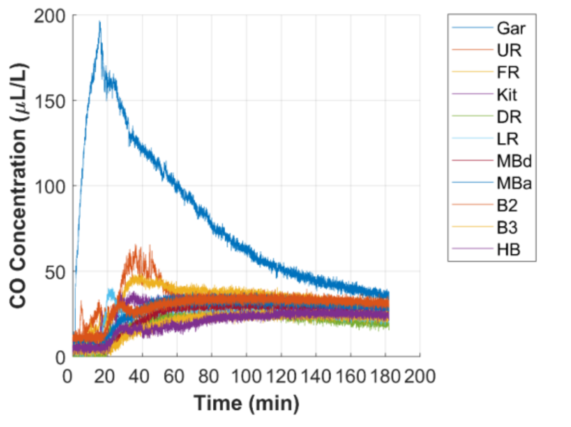


Figure 19c. CO concentration measured in each room of the house during Production Case 4 Test 1 – G7S UL 2201.

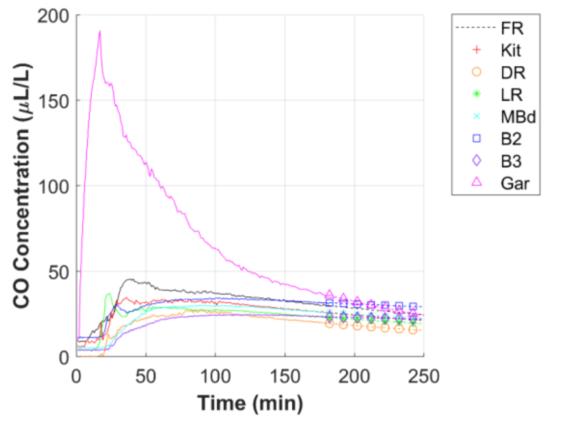


Figure 19d. CO concentration (measured & projected) in the house during Production Case 4 Test 1 – G7S UL 2201.

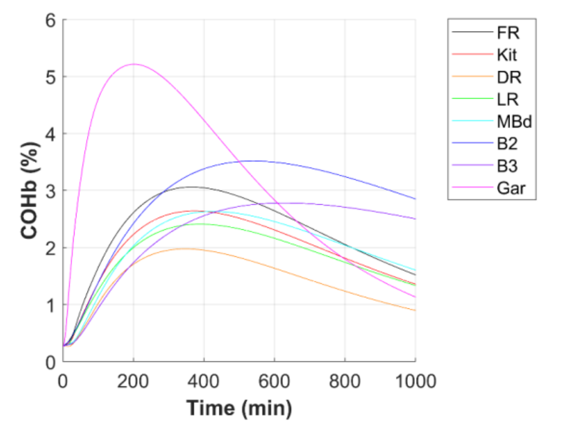


Figure 19e. COHb of simulated house occupants during Production Case 4 Test 1 – G7S UL 2201.

Production Case 4 Test 1 – G85 G300

The following figures illustrate the results for Production Case 4 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,250 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 2 min. **Figure 20a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 20b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 20a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 20c** shows the CO concentration measured in each room of the house over the test. **Figure 20d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 20e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

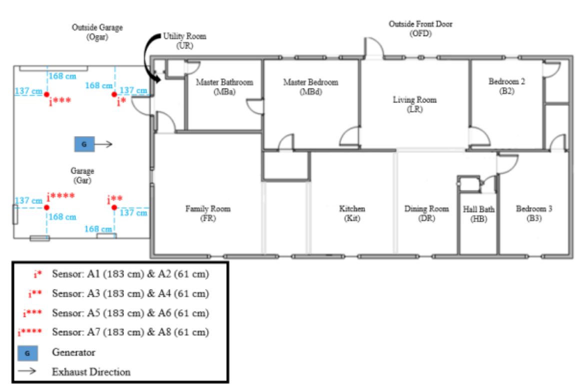


Figure 20a. Generator, exhaust direction, and sensor array layout during Production Case 4 Test 1 – G85 G300.

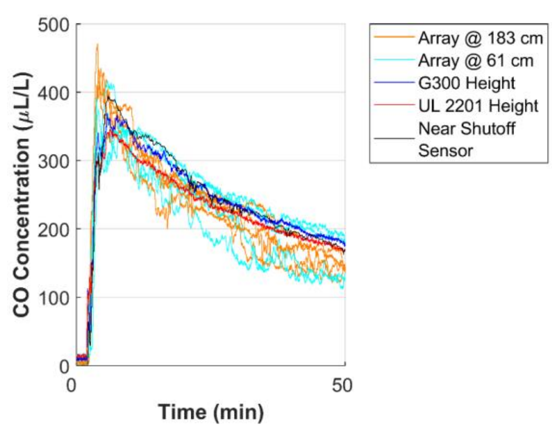


Figure 20b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 4 Test 1 – G85 G300.

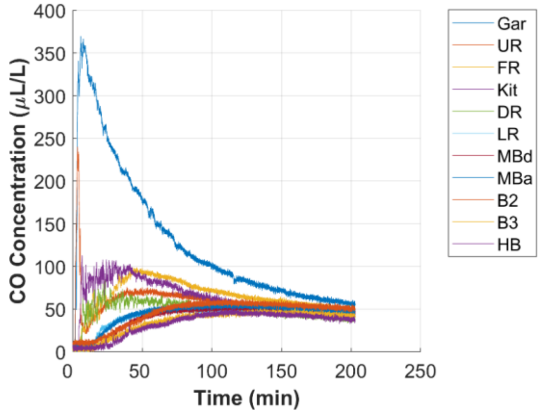


Figure 20c. CO concentration measured in each room of the house during Production Case 4 Test 1 – G85 G300.

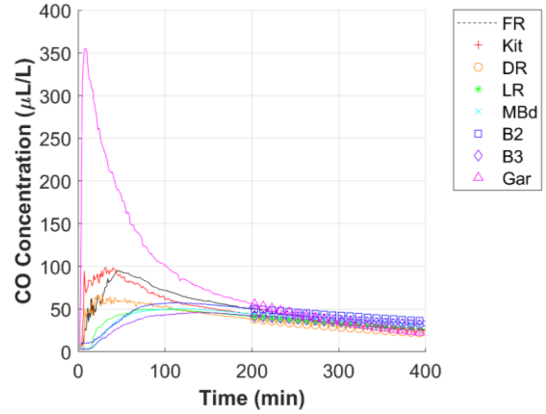


Figure 20d. CO concentration (measured & projected) in the house during Production Case 4 Test 1 – G85 G300.

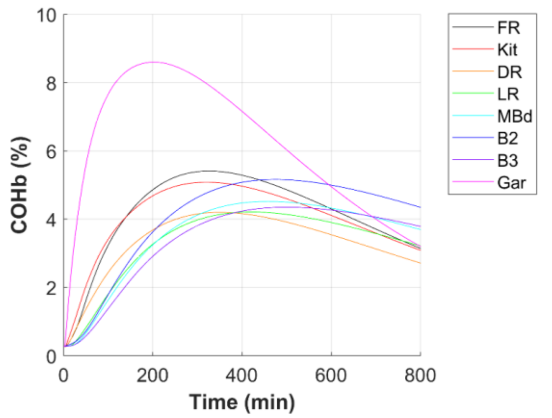


Figure 20e. COHb of simulated house occupants during Production Case 4 Test 1 – G85 G300.

Production Case 5 Test 1 – G65S G300

The following figures illustrate the results for Production Case 5 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,250 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 4 min. **Figure 21a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 21b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 21a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 21c** shows the CO concentration measured in each room of the house over the test. **Figure 21d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 21e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

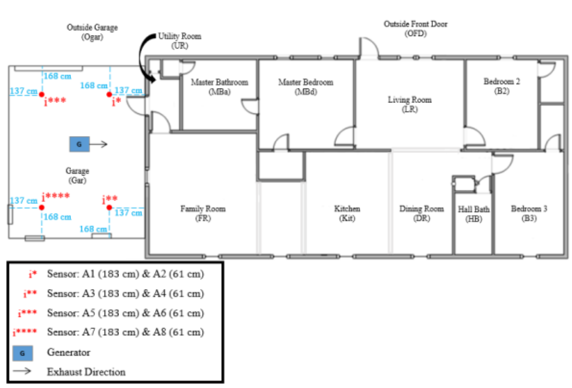


Figure 21a. Generator, exhaust direction, and sensor array layout during Production Case 5 Test 1 – G65S G300.

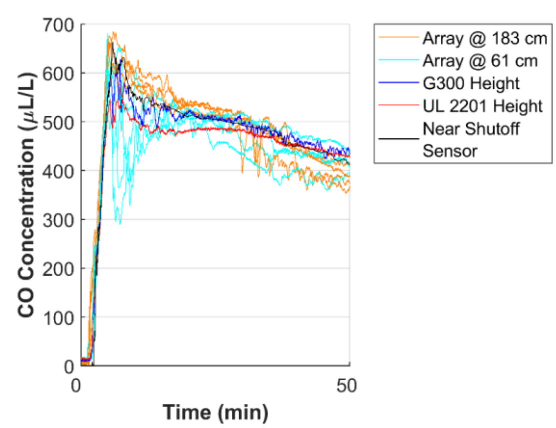


Figure 21b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 5 Test 1 – G65S G300.

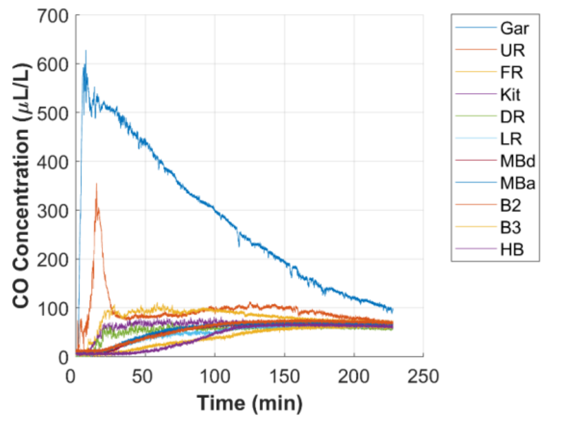


Figure 21c. CO concentration measured in each room of the house during Production Case 5 Test 1 – G65S G300.

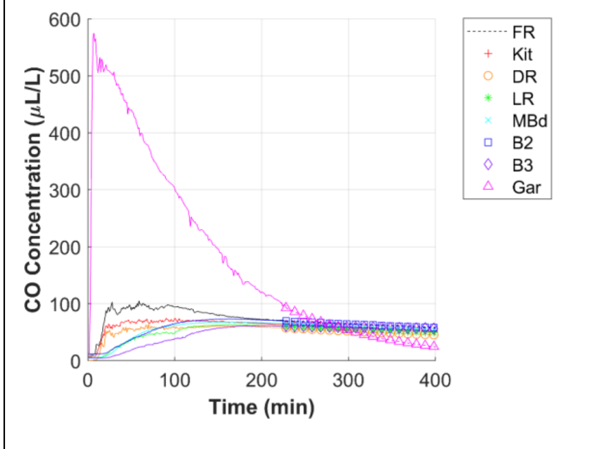


Figure 21d. CO concentration (measured & projected) in the house during Production Case 5 Test 1 – G65S G300.

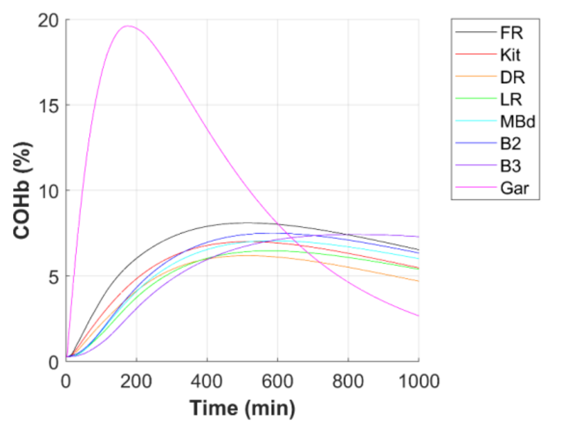


Figure 21e. COHb of simulated house occupants during Production Case 5 Test 1 – G65S G300.

Production Case 5 Test 1 – G65C G300

The following figures illustrate the results for Production Case 5 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,250 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 12 min. **Figure 22a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 22b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 22a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 22c** shows the CO concentration measured in each room of the house over the test. **Figure 22d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 22e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

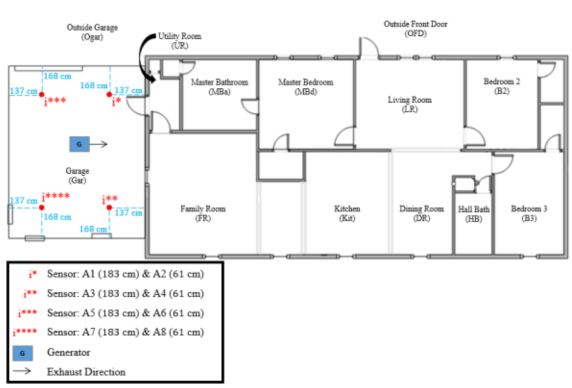


Figure 22a. Generator, exhaust direction, and sensor array layout during Production Case 5 Test 1 – G65C G300.

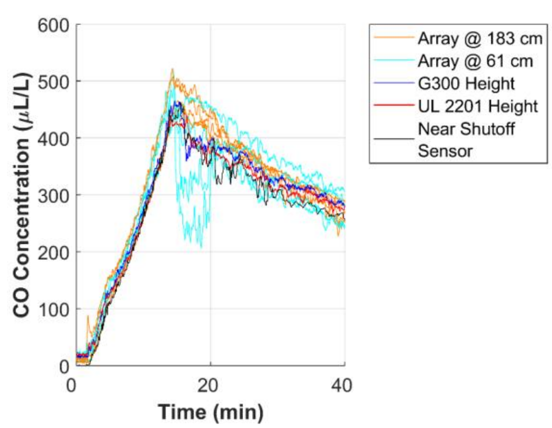


Figure 22b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 5 Test 1 – G65C G300.

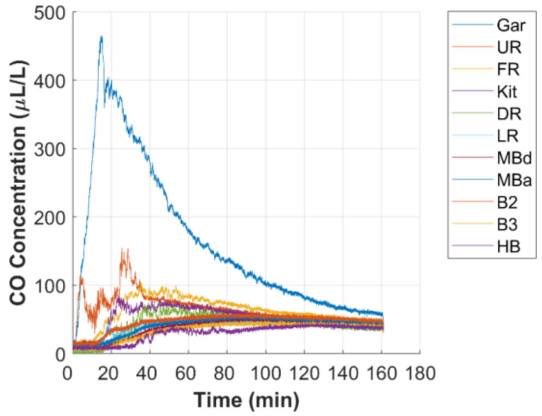


Figure 22c. CO concentration measured in each room of the house during Production Case 5 Test 1 – G65C G300.

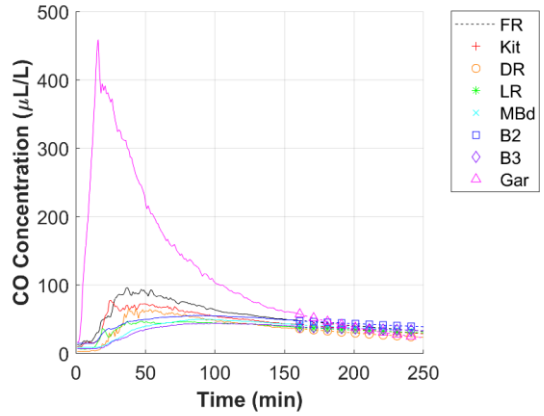


Figure 22d. CO concentration (measured & projected) in the house during Production Case 5 Test 1 – G65C G300.

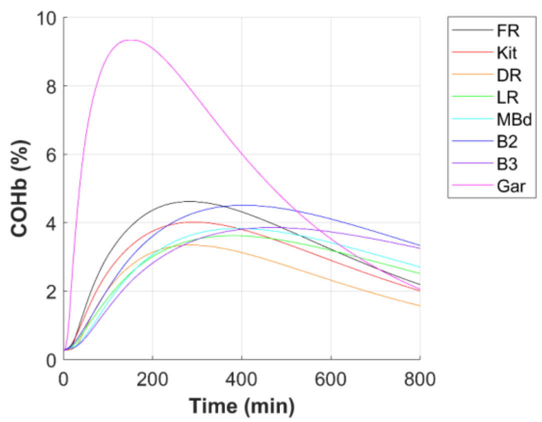


Figure 22e. COHb of simulated house occupants during Production Case 5 Test 1 – G65C G300.

Production Case 5 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 5 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,500 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 14 min. **Figure 23a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 23b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 23a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 23c** shows the CO concentration measured in each room of the house over the test. **Figure 23d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 23e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

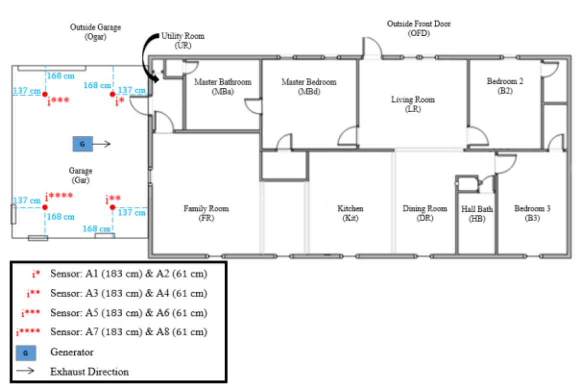


Figure 23a. Generator, exhaust direction, and sensor array layout during Production Case 5 Test 1 – G7S UL 2201.

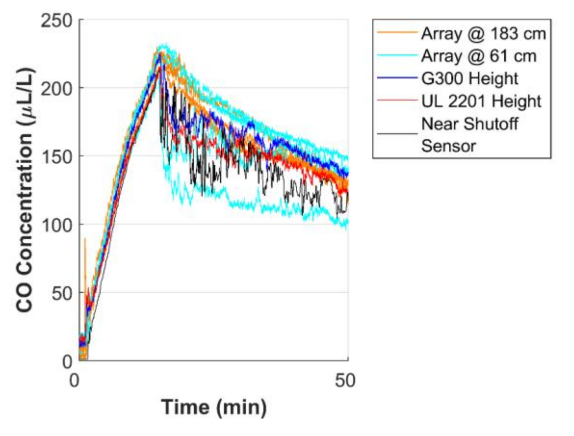


Figure 23b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 5 Test 1 – G7S UL 2201.

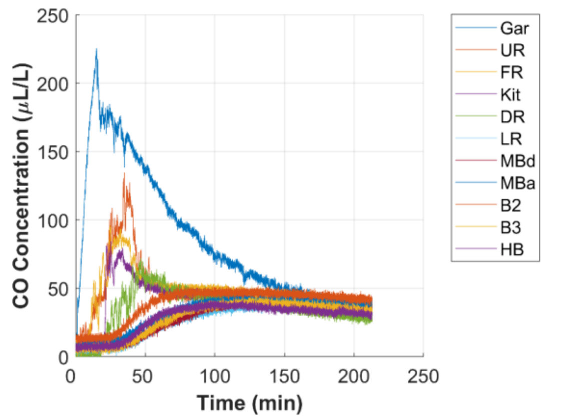


Figure 23c. CO concentration measured in each room of the house during Production Case 5 Test 1 – G7S UL 2201.

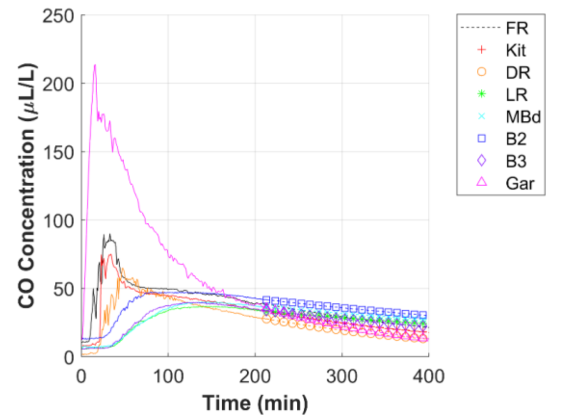


Figure 23d. CO concentration (measured & projected) in the house during Production Case 5 Test 1 – G7S UL 2201.

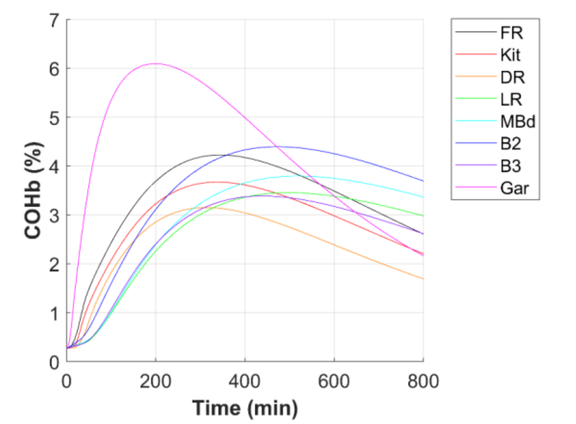


Figure 23e. COHb of simulated house occupants during Production Case 5 Test 1 – G7S UL 2201.

Production Case 5 Test 1 – G85 G300

The following figures illustrate the results for Production Case 5 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,125 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 3 min. **Figure 24a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 24b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 24a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 24c** shows the CO concentration measured in each room of the house over the test. **Figure 24d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 24e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

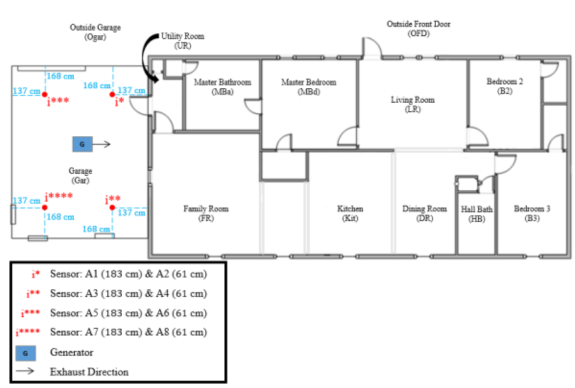


Figure 24a. Generator, exhaust direction, and sensor array layout during Production Case 5 Test 1 – G85 G300.

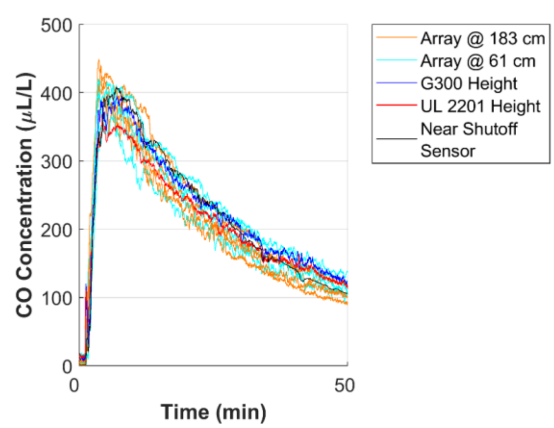


Figure 24b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 5 Test 1 – G85 G300.

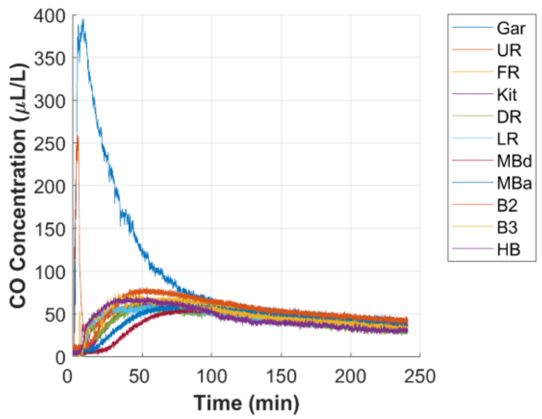


Figure 24c. CO concentration measured in each room of the house during Production Case 5 Test 1 – G85 G300.

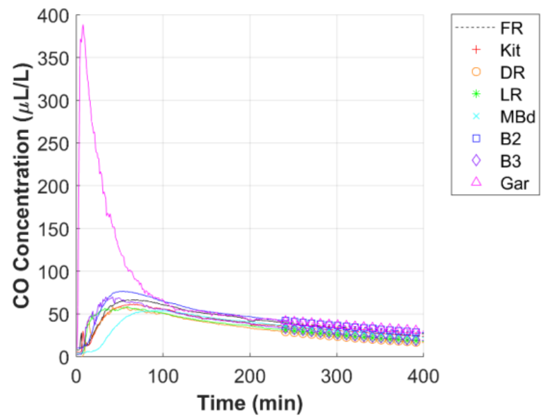


Figure 24d. CO concentration (measured & projected) in the house during Production Case 5 Test 1 – G85 G300.

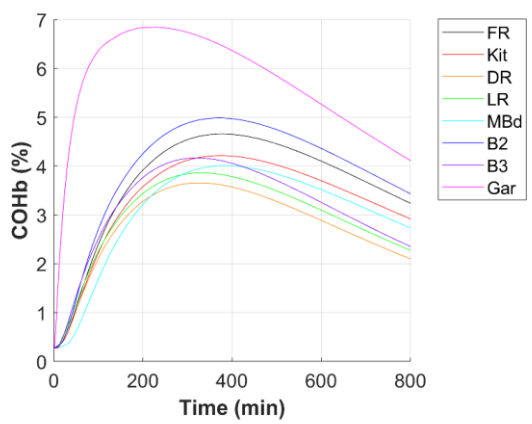


Figure 24e. COHb of simulated house occupants during Production Case 5 Test 1 – G85 G300.

Production Case 6 Test 1 – G65S G300

The following figures illustrate the results for Production Case 6 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 10 % load (650 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 5 min. **Figure 25a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 25b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 25a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 25c** shows the CO concentration measured in each room of the house over the test. **Figure 25d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 25e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

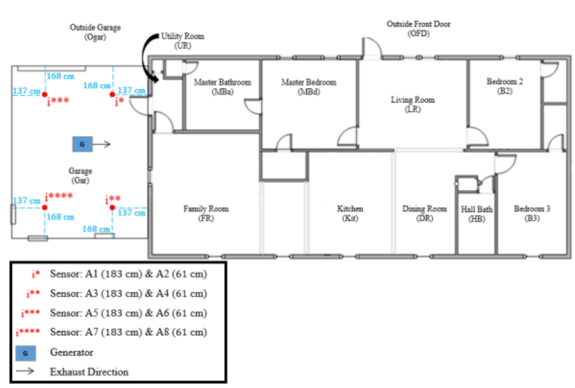


Figure 25a. Generator, exhaust direction, and sensor array layout during Production Case 6 Test 1 – G65S G300.

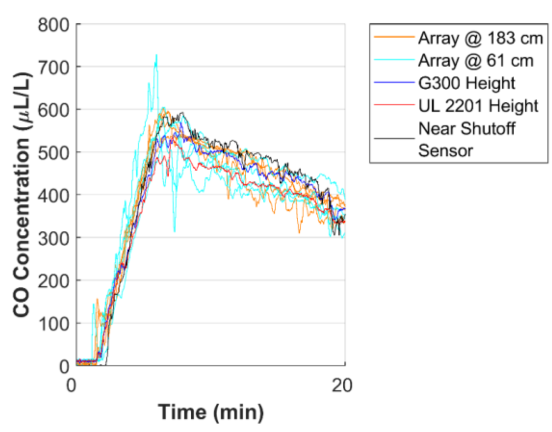


Figure 25b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 6 Test 1 – G65S G300.

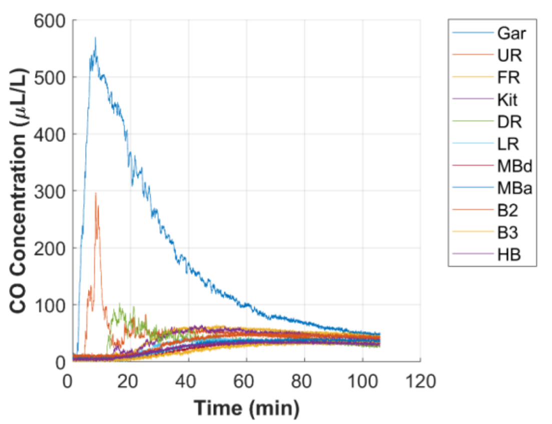


Figure 25c. CO concentration measured in each room of the house during Production Case 6 Test 1 – G65S G300.

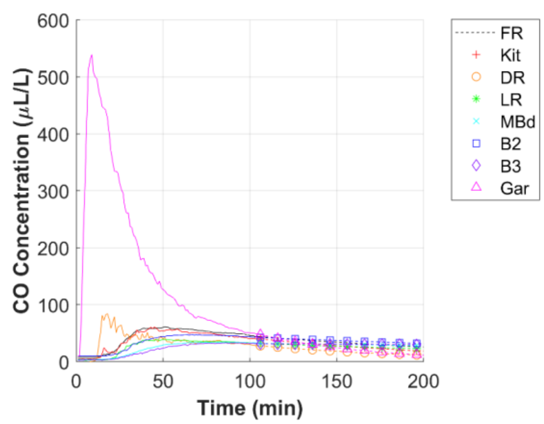


Figure 25d. CO concentration (measured & projected) in the house during Production Case 6 Test 1 – G65S G300.

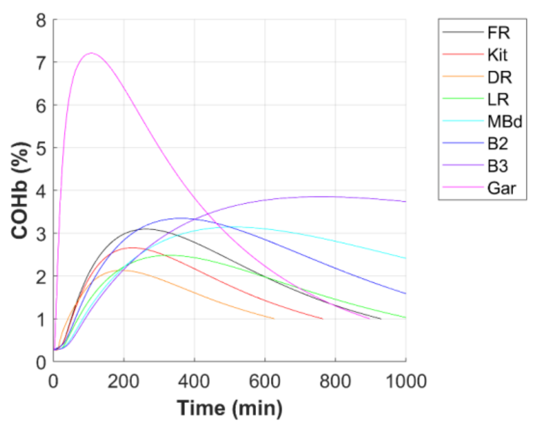


Figure 25e. COHb of simulated house occupants during Production Case 6 Test 1 – G65S G300.

Production Case 6 Test 1 – G65C G300

The following figures illustrate the results for Production Case 6 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 10 % load (650 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 58 min. **Figure 26a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 26b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 26a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 26c** shows the CO concentration measured in each room of the house over the test. **Figure 26d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 26e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

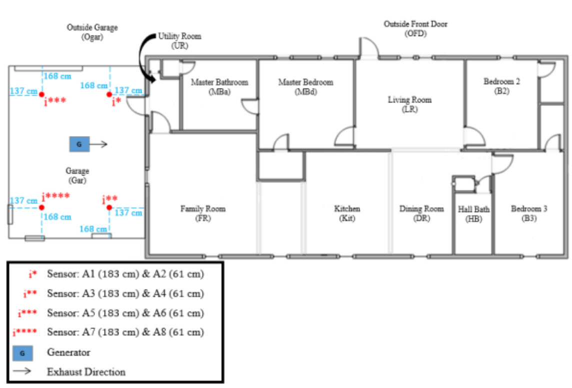


Figure 26a. Generator, exhaust direction, and sensor array layout during Production Case 6 Test 1 – G65C G300.

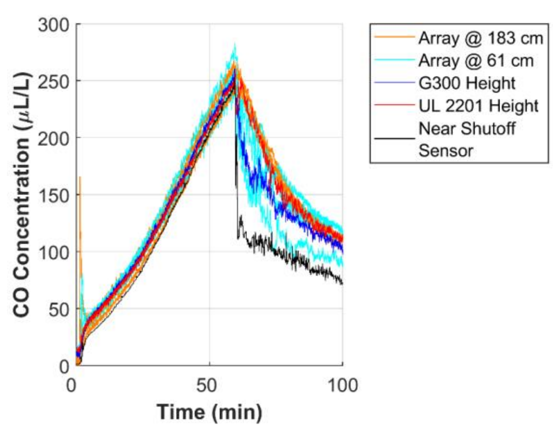


Figure 26b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 6 Test 1 – G65C G300.

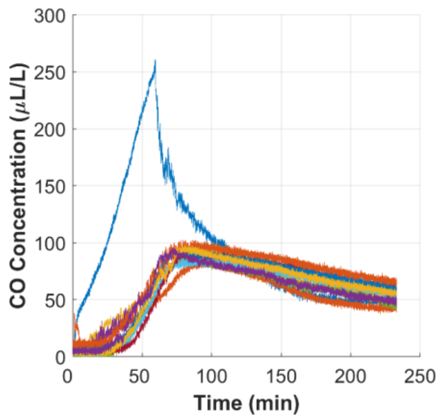


Figure 26c. CO concentration measured in each room of the house during Production Case 6 Test 1 – G65C G300.

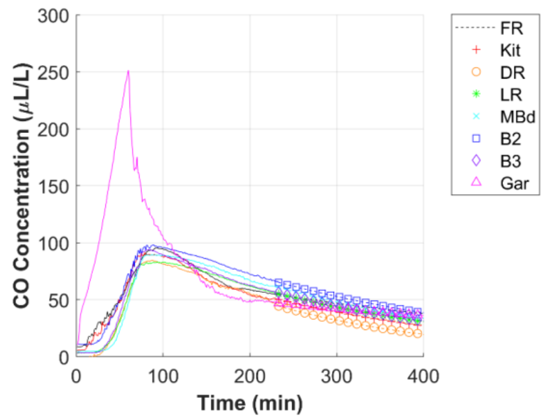


Figure 26d. CO concentration (measured & projected) in the house during Production Case 6 Test 1 – G65C G300.

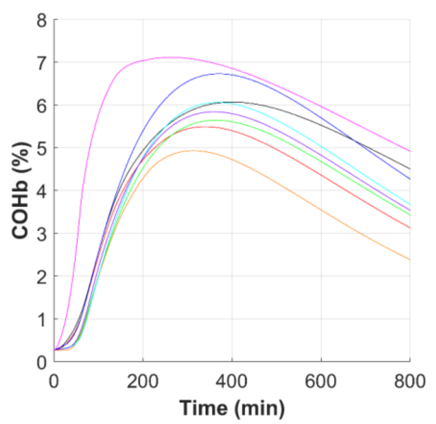


Figure 26e. COHb of simulated house occupants during Production Case 6 Test 1 – G65C G300.

Production Case 6 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 6 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 10 % load (700 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 166 min. **Figure 27a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 27b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 27a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 27c** shows the CO concentration measured in each room of the house over the test. **Figure 27d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 27e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

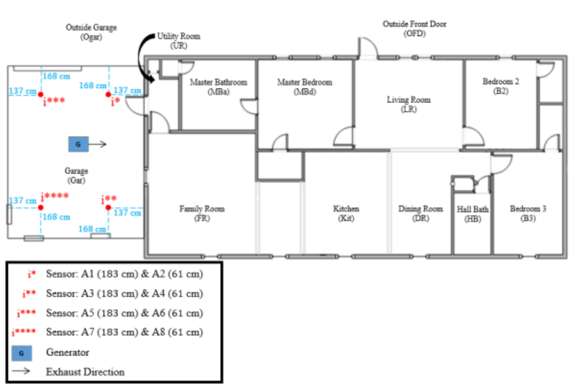


Figure 27a. Generator, exhaust direction, and sensor array layout during Production Case 6 Test 1 – G7S UL 2201.

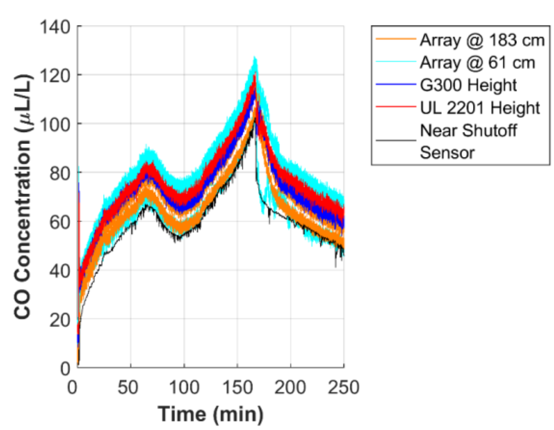


Figure 27b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 6 Test 1 – G7S UL 2201.

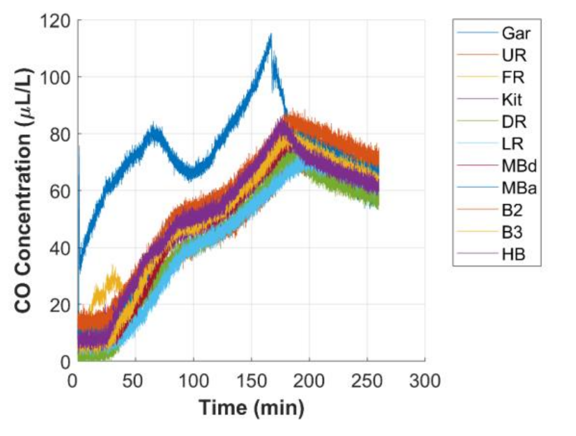


Figure 27c. CO concentration measured in each room of the house during Production Case 6 Test 1 – G7S UL 2201.

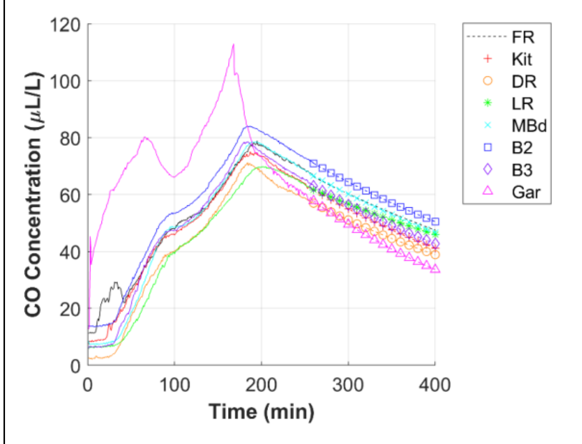


Figure 27d. CO concentration (measured & projected) in the house during Production Case 6 Test 1 – G7S UL 2201.

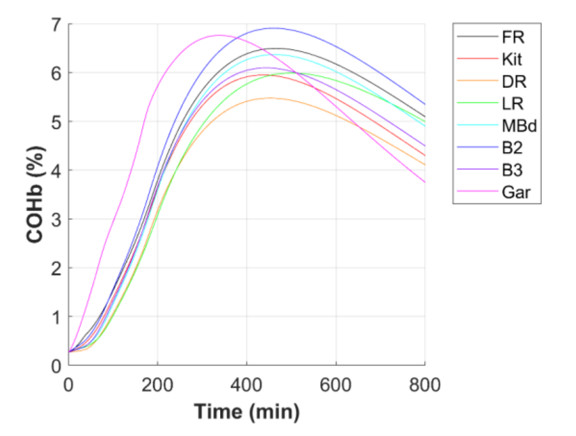


Figure 27e. COHb of simulated house occupants during Production Case 6 Test 1 – G7S UL 2201.

Production Case 6 Test 1 – G85 G300

The following figures illustrate the results for Production Case 6 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 10 % load (625 W). The interior person door (from garage to utility room) was open 10 cm and both the exterior person door (from garage to backyard) and the garage bay door were closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 4 min. **Figure 28a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 28b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 28a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 28c** shows the CO concentration measured in each room of the house over the test. **Figure 28d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 28e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

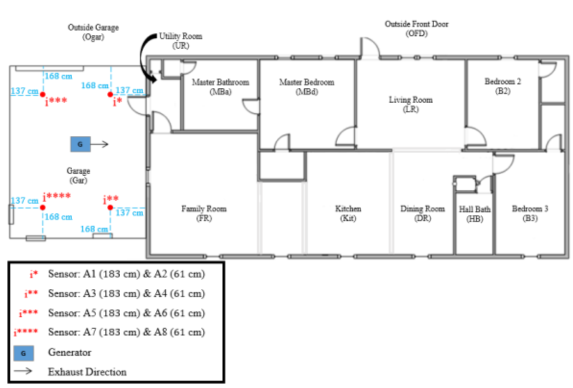


Figure 28a. Generator, exhaust direction, and sensor array layout during Production Case 6 Test 1 – G85 G300.

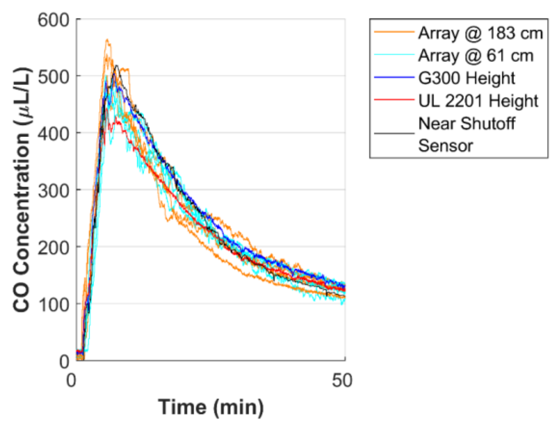


Figure 28b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 6 Test 1 – G85 G300.

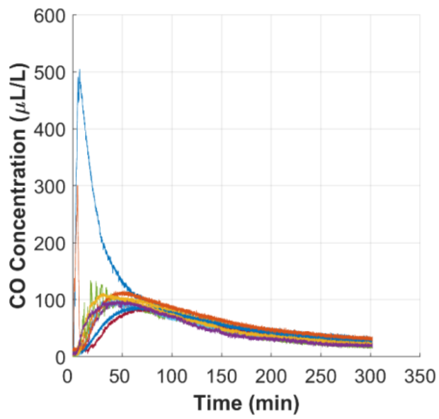


Figure 28c. CO concentration measured in each room of the house during Production Case 6 Test 1 – G85 G300.

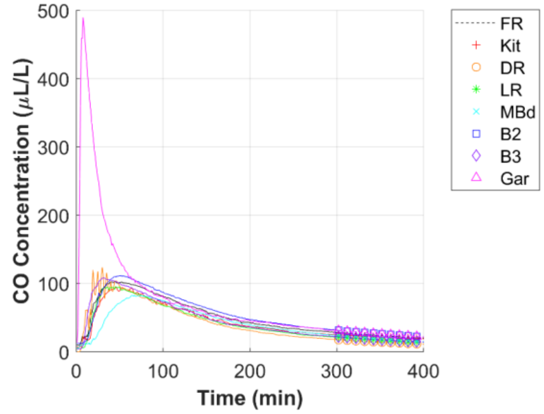


Figure 28d. CO concentration (measured & projected) in the house during Production Case 6 Test 1 – G85 G300.

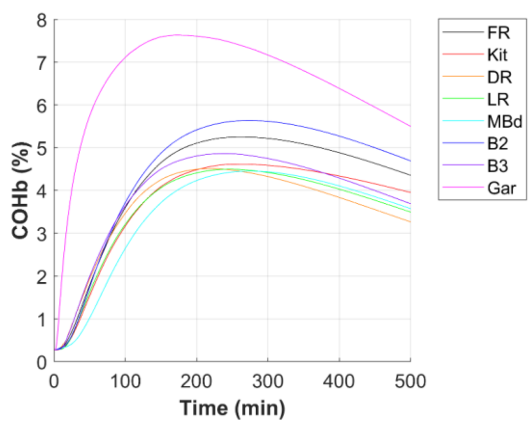


Figure 28e. COHb of simulated house occupants during Production Case 6 Test 1 – G85 G300.

Production Case 7 Test 1 – G65S G300

The following figures illustrate the results for Production Case 7 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,500 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator ran out of fuel after approximately 329 min. **Figure 29a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 29b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 29a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 29c** shows the CO concentration measured in each room of the house over the test. **Figure 29d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

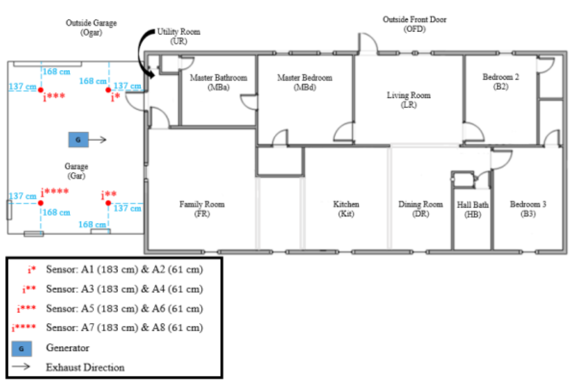


Figure 29a. Generator, exhaust direction, and sensor array layout during Production Case 7 Test 1 – G65S G300.

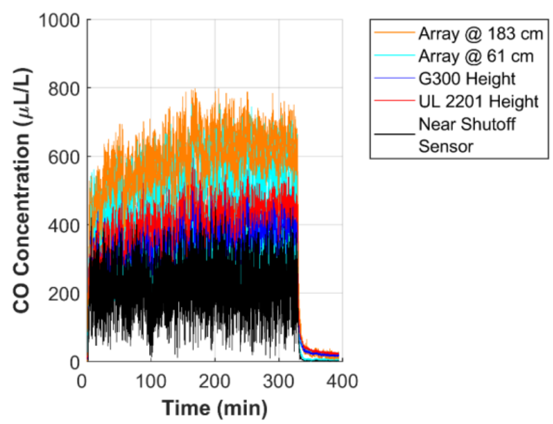


Figure 29b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 7 Test 1 – G65S G300.

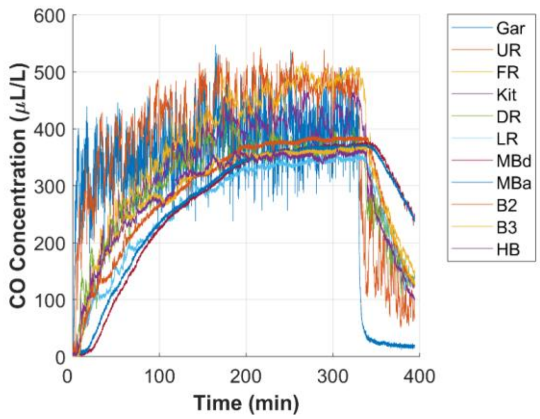


Figure 29c. CO concentration measured in each room of the house during Production Case 7 Test 1 – G65S G300.

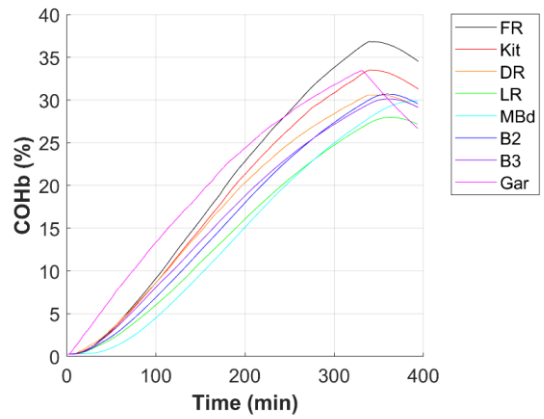


Figure 29d. COHb of simulated house occupants during Production Case 7 Test 1 – G65S G300.

Production Case 7 Test 1 – G65C G300

The following figures illustrate the results for Production Case 7 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,500 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 2 min. **Figure 30a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 30b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 30a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 30c** shows the CO concentration measured in each room of the house over the test. **Figure 30d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 30e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

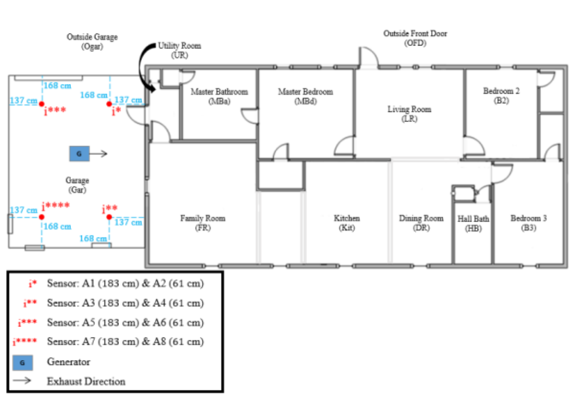


Figure 30a. Generator, exhaust direction, and sensor array layout during Production Case 7 Test 1 – G65C G300.

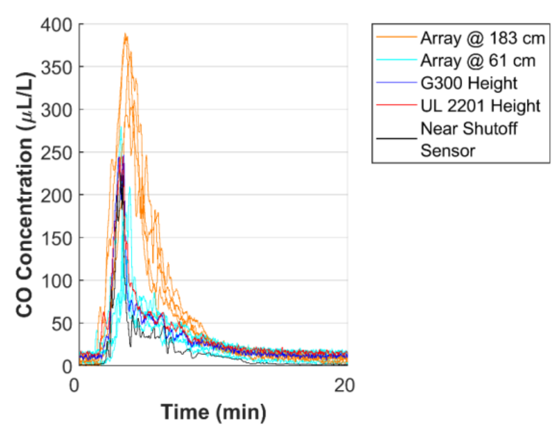


Figure 30b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 7 Test 1 – G65C G300.

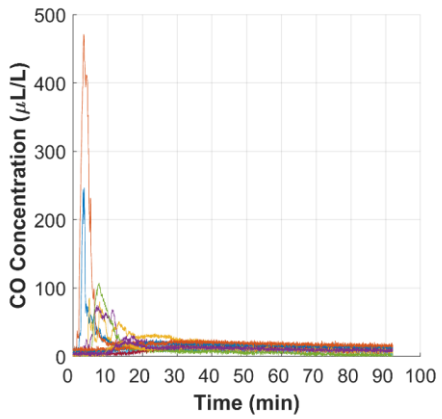


Figure 30c. CO concentration measured in each room of the house during Production Case 7 Test 1 – G65C G300.

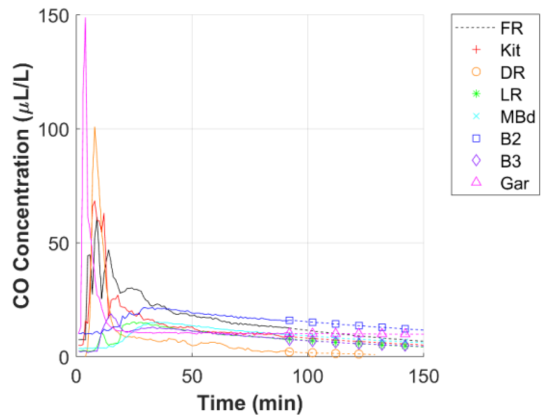


Figure 30d. CO concentration (measured & projected) in the house during Production Case 7 Test 1 – G65C G300.

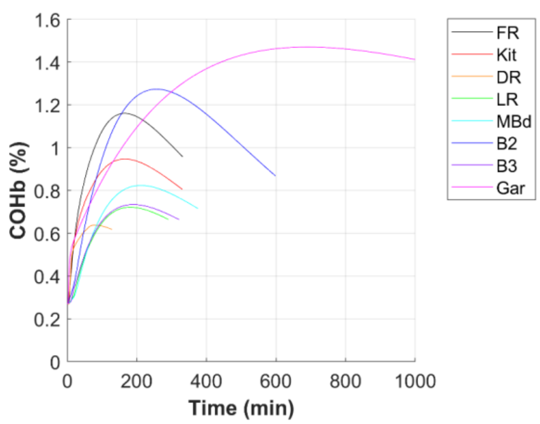


Figure 30e. COHb of simulated house occupants during Production Case 7 Test 1 – G65C G300.

Production Case 7 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 7 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (7,000 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator was manually shutdown after approximately 225 min due to low CO levels in the house and anticipated long runtime before running out of fuel. **Figure 31a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 31b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 31a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 31c** shows the CO concentration measured in each room of the house over the test. **Figure 31d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

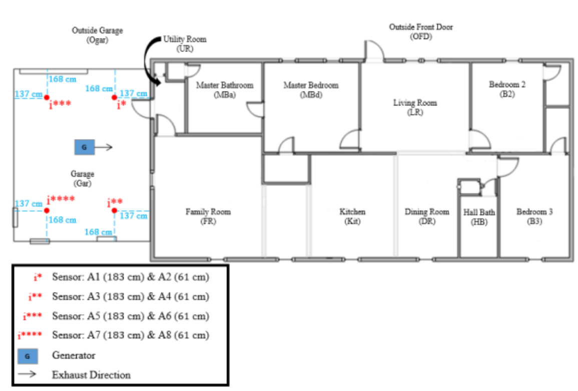


Figure 31a. Generator, exhaust direction, and sensor array layout during Production Case 7 Test 1 – G7S UL 2201.

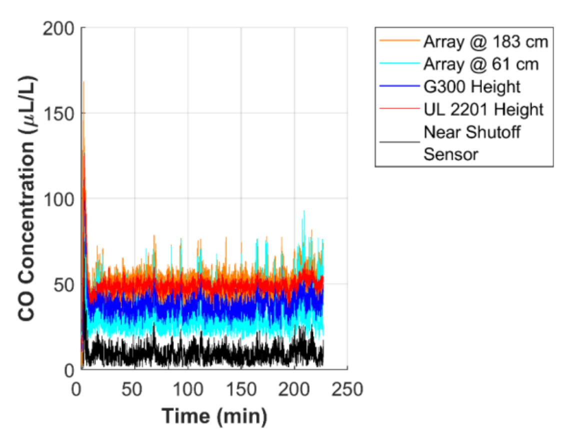


Figure 31b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 7 Test 1 – G7S UL 2201.

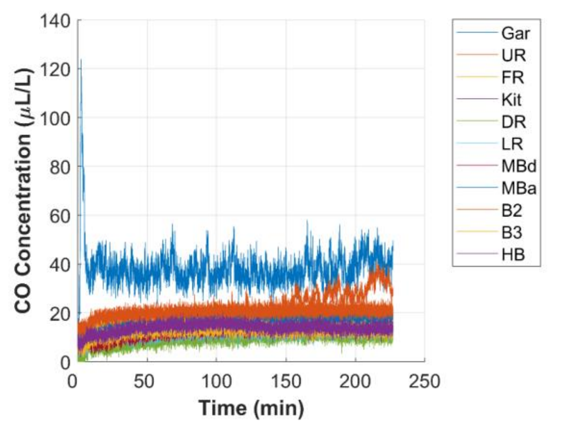


Figure 31c. CO concentration measured in each room of the house during Production Case 7 Test 1 – G7S UL 2201.

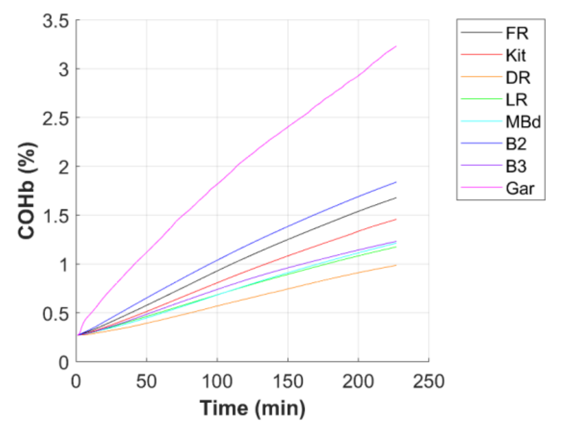


Figure 31d. COHb of simulated house occupants during Production Case 7 Test 1 – G7S UL 2201.

Production Case 7 Test 1 – G85 G300

The following figures illustrate the results for Production Case 7 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 100 % load (6,250 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system activated to shut off the generator after approximately 8 min. **Figure 32a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 32b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 32a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The timeframe of the figure has been selected to show the degree of CO uniformity among these locations near the time of shutoff. **Figure 32c** shows the CO concentration measured in each room of the house over the test. **Figure 32d** shows the CO concentration in the house, with each room represented by a single line composed of both a 'solid-line' pattern (showing measured CO concentration) and a 'dotted-line with a symbol' pattern (showing projected CO concentration). **Figure 32e** shows the calculated COHb profiles of simulated house occupants in each room of the house.

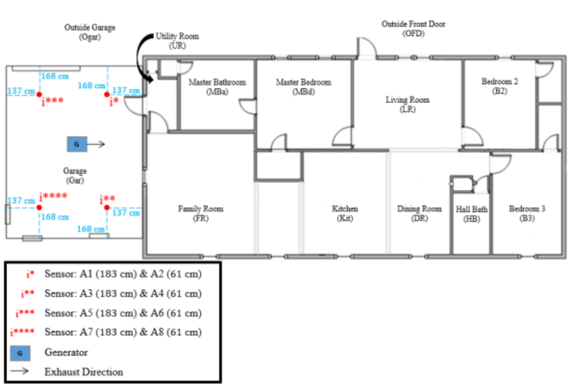


Figure 32a. Generator, exhaust direction, and sensor array layout during Production Case 7 Test 1 – G85 G300.

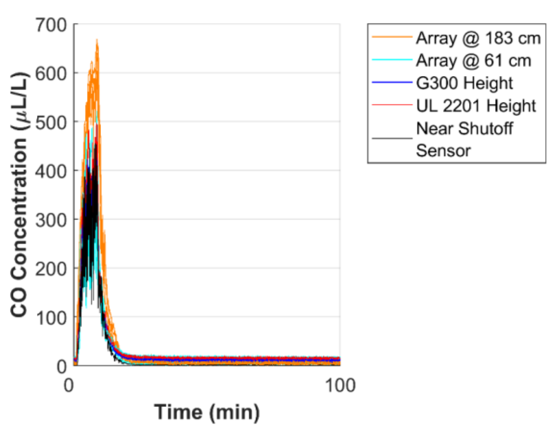


Figure 32b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 7 Test 1 – G85 G300.

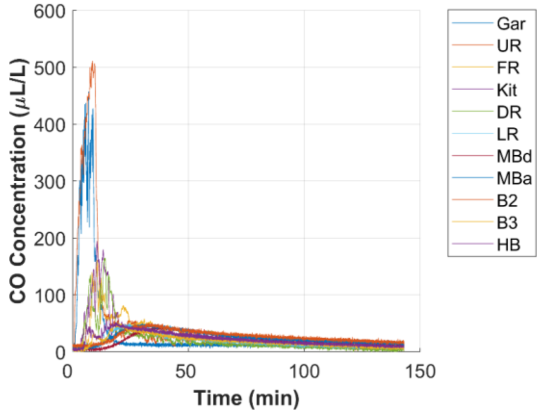


Figure 32c. CO concentration measured in each room of the house during Production Case 7 Test 1 – G85 G300.

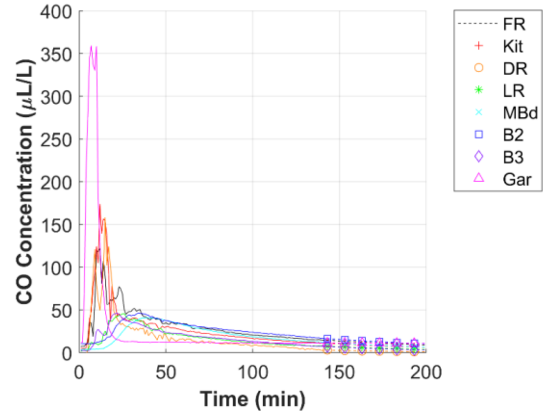


Figure 32d. CO concentration (measured & projected) in the house during Production Case 7 Test 1 – G85 G300.

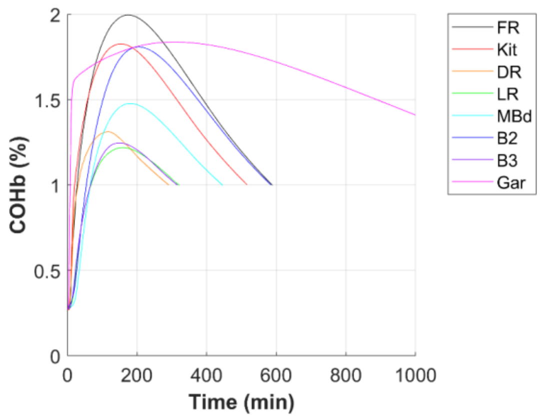


Figure 32e. COHb of simulated house occupants during Production Case 7 Test 1 – G85 G300.

Production Case 8 Test 1 – G65S G300

The following figures illustrate the results for Production Case 8 Test 1. The G65S generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,250 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator was manually shutdown after approximately 467 min due to reaching peak COHb levels throughout the house. **Figure 33a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 33b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 33a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 33c** shows the CO concentration measured in each room of the house over the test. **Figure 33d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

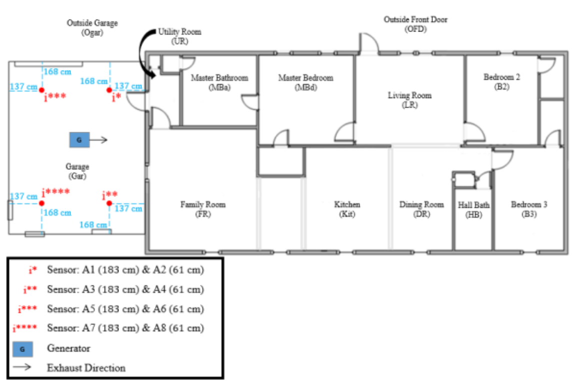


Figure 33a. Generator, exhaust direction, and sensor array layout during Production Case 8 Test 1 – G65S G300.

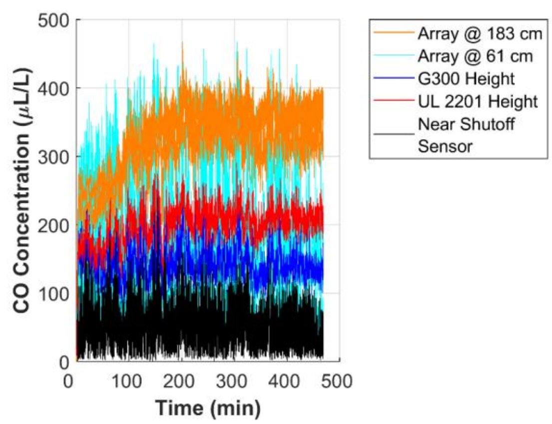


Figure 33b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 8 Test 1 – G65S G300.

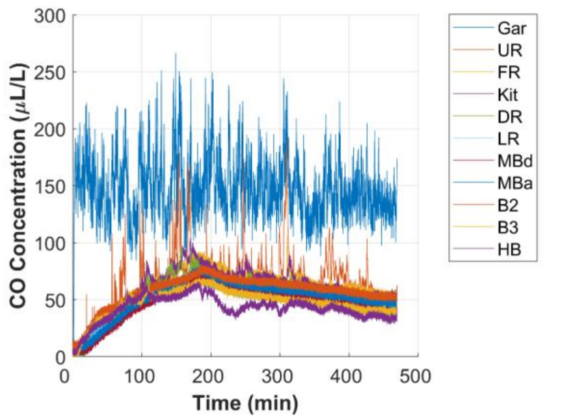


Figure 33c. CO concentration measured in each room of the house during Production Case 8 Test 1 – G65S G300.

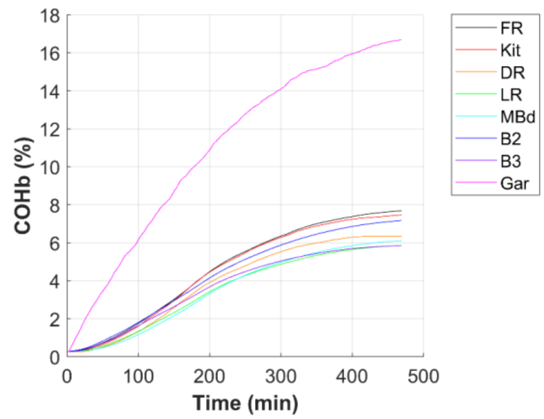


Figure 33d. COHb of simulated house occupants during Production Case 8 Test 1 – G65S G300.

Production Case 8 Test 1 – G65C G300

The following figures illustrate the results for Production Case 8 Test 1. The G65C generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,250 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator was manually shutdown after approximately 320 min due to low CO levels in the house and anticipated long runtime before running out of fuel. **Figure 34a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 34b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 34a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 34c** shows the CO concentration measured in each room of the house over the test. **Figure 34d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

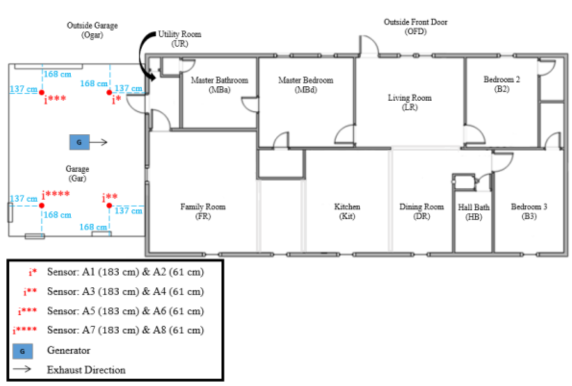


Figure 34a. Generator, exhaust direction, and sensor array layout during Production Case 8 Test 1 – G65C G300.

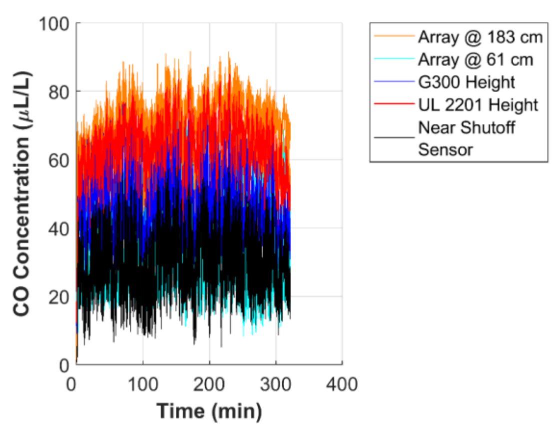


Figure 34b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 8 Test 1 – G65C G300.

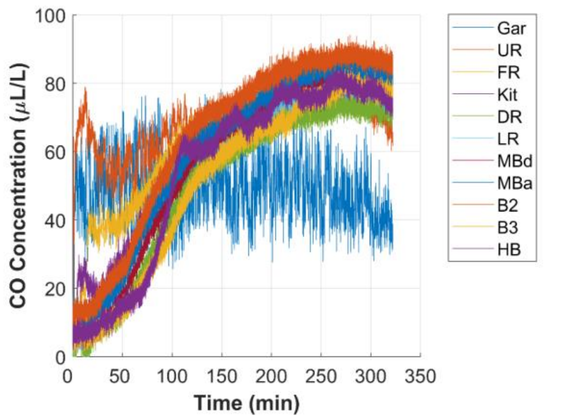


Figure 34c. CO concentration measured in each room of the house during Production Case 8 Test 1 – G65C G300.

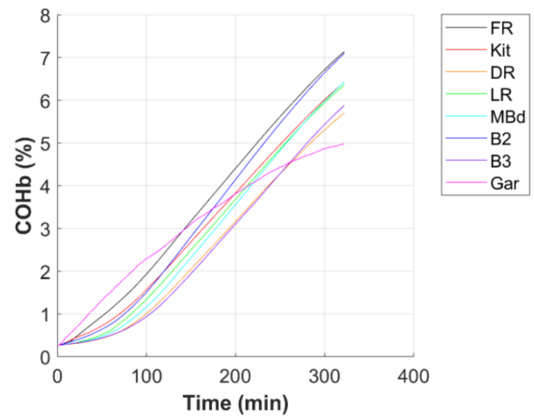


Figure 34d. COHb of simulated house occupants during Production Case 8 Test 1 – G65C G300.

Production Case 8 Test 1 – G7S UL 2201

The following figures illustrate the results for Production Case 8 Test 1. The G7S generator, which the manufacturer stated as being certified to UL 2201, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,500 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator was manually shutdown after approximately 357 min due to low CO levels in the house and anticipated long runtime before running out of fuel. **Figure 35a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 35b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 35a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 35c** shows the CO concentration measured in each room of the house over the test. **Figure 35d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

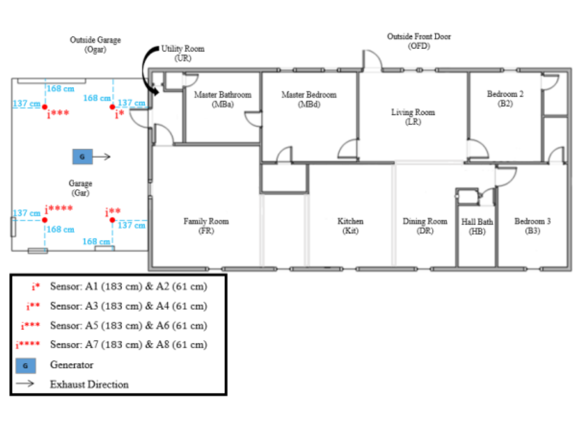


Figure 35a. Generator, exhaust direction, and sensor array layout during Production Case 8 Test 1 – G7S UL 2201.

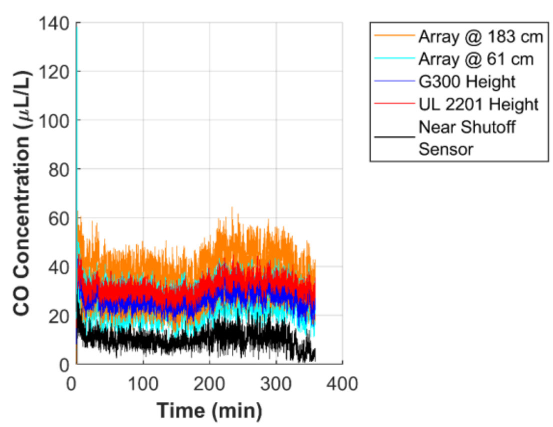


Figure 35b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 8 Test 1 – G7S UL 2201.

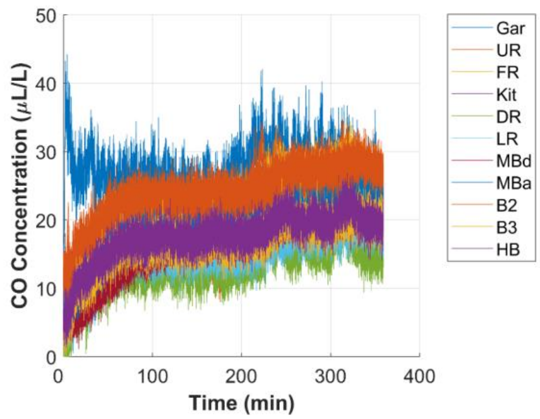


Figure 35c. CO concentration measured in each room of the house during Production Case 8 Test 1 – G7S UL 2201.

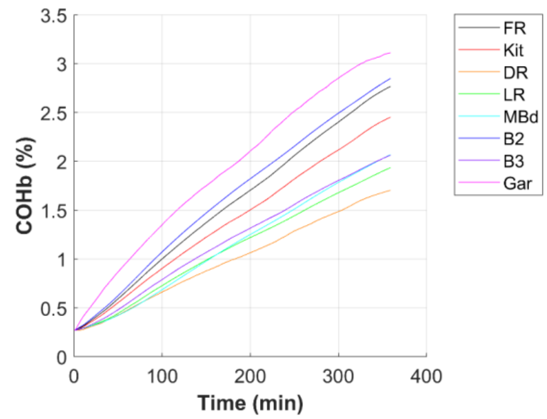


Figure 35d. COHb of simulated house occupants during Production Case 8 Test 1 – G7S UL 2201.

Production Case 8 Test 1 – G85 G300

The following figures illustrate the results for Production Case 8 Test 1. The G85 generator, which the manufacturer stated as being certified to PGMA G300, was fully fueled, positioned in the garage (centered, with the exhaust facing towards the family room), and tested at 50 % load (3,125 W). The interior person door (from garage to utility room) was open 10 cm, the garage bay door was fully open, and the exterior person door (from garage to backyard) was closed. The generator's CO safety shutoff system was not activated, and the generator was manually shutdown after approximately 468 min due to low CO levels in the house and anticipated long runtime before running out of fuel. **Figure 36a** shows the test house layout with generator location, generator exhaust direction, and sensor array locations. **Figure 36b** shows the CO concentrations measured in the garage by the G300 sensor (placed 3 to 5 cm above the approximate center of the generator's top surface), by the UL sensor (placed 30 cm above the approximate center of the generator's top surface), by the sensor array placed in the garage located as shown in **Figure 36a** (A1, A3, A5, and A7: height 183 cm; A2, A4, A6 and A8: height 61 cm), and by the NDIR analyzer sample line measuring CO near the generator's CO safety shutoff sensor. All array sensors set to a height of 183 cm are illustrated as orange lines whereas the array sensors set to a height of 61 cm are illustrated as turquoise lines. The figure shows the degree of CO uniformity among these locations near the time of shutdown. **Figure 36c** shows the CO concentration measured in each room of the house over the test. **Figure 36d** shows the calculated COHb profiles of simulated house occupants in each room of the house.

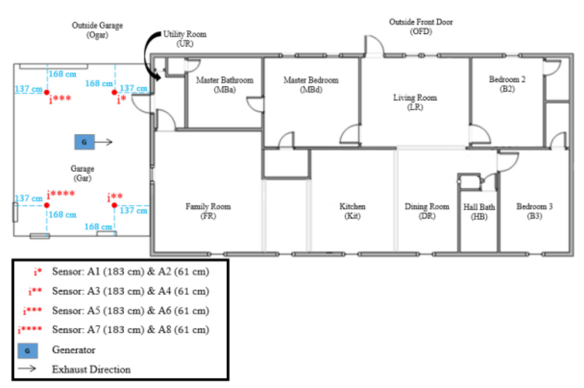


Figure 36a. Generator, exhaust direction, and sensor array layout during Production Case 8 Test 1 – G85 G300.

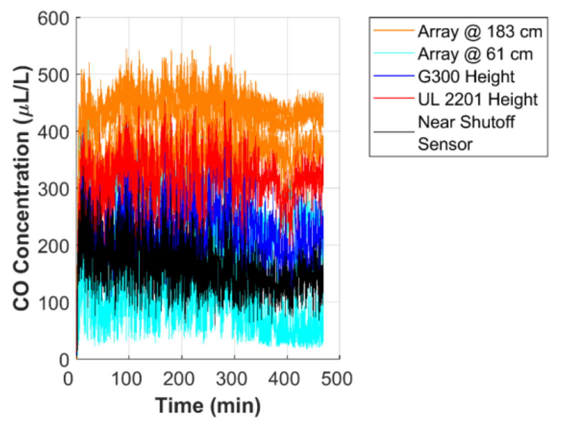


Figure 36b. CO concentration measured by the sensor array, the sensor placed near generator's CO safety shutoff sensor, the G300 sensor, and the UL 2201 sensor during Production Case 8 Test 1 – G85 G300.

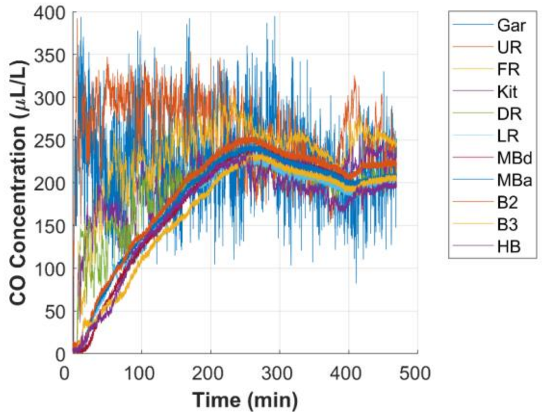


Figure 36c. CO concentration measured in each room of the house during Production Case 8 Test 1 – G85 G300.

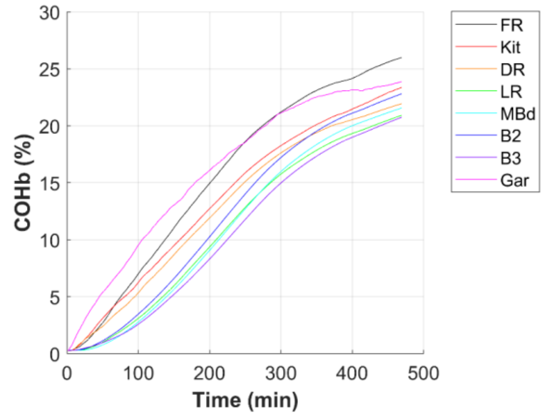


Figure 36d. COHb of simulated house occupants during Production Case 8 Test 1 – G85 G300.

CO Concentrations at Shutoff for Voluntary Standard Test Measurement Locations and the Onboard Sensor

When the generator was tested in the garage with the overhead door closed (Production Case 4 through Production Case 6), CO sensors were placed at various locations around the generator. One such location, 3 cm to 5 cm above the approximate center of the portable generator's top surface, was based on the PGMA G300 voluntary standard. Another location, 30 cm above the approximate center of the portable generator's top surface, was based on the UL 2201 voluntary standard. These two positions are required in the respective standards to measure the CO concentration during conformance testing to the standard. A third location was near the location of the sensor for the generator's CO safety shutoff system (Near Shutoff Sensor, NSS). These locations were measured in a set of tests to evaluate the difference in concentration between these positions at the time of shutoff.

Table 3 summarizes the instantaneous CO concentrations measured at each of the three locations at the time of generator CO safety shutoff system activation for 7 of the tests, for which the generator shut off occurred in under 10 minutes.

Gen	PCase / Test	Load (%)	Time To Shutoff (min)	G300 ┼ (µL/L)	UL 2201 ┼┼ (µL/L)	NSS ┼┼┼ (µL/L)	|Δ| (G300-NSS) (%)	|Δ| (UL 2201-NSS) (%)
G65S	4 / 1	100	3	597	┼┼┼┼	566	5.3	-
	5 / 1	50	4	528	496	533	0.9	7.2
	6 / 1	10	5	527	487	543	3.0	10.9
G65C	4 / 1	100	1	246	272	254	3.2	6.8
G85	4 / 1	100	2	281	275	251	11.3	9.1
	5 / 1	50	3	317	290	293	7.9	1.0
	6 / 1	10	4	448	391	437	2.5	11.1
						Average |Δ| (%)	4.9	7.7

┼ G300 sensor is located 3 to 5 cm above the centerline of the top of the generator.
┼┼ UL 2201 sensor is located 30 cm above the centerline of the top of the generator.
┼┼┼ Near Shutoff Sensor (NSS) is located near the generator's onboard shutoff sensor.
┼┼┼┼ UL 2201 sensor had not yet been implemented at time of test.

Table 3. Summary of instantaneous CO measurements at time of generator shutoff

Table 4 summarizes the 10-min average CO concentrations measured at each of the three locations at the time of generator CO safety shutoff system activation for 5 of the tests, which resulted in generator shut off after 10 minutes.

Gen	PCase / Test	Load (%)	Time To Shutoff (min)	G300 ┼ (µL/L)	UL 2201 ┼┼ (µL/L)	NSS ┼┼┼ (µL/L)	|Δ| (G300-NSS) (%)	|Δ| (UL 2201-NSS) (%)
G65C	5 / 1	50	12	253	241	236	7.0	2.1
	6 / 1	10	58	231	227	222	4.0	2.2
G7S	4 / 1	100	15	154	143	135	13.1	5.8
	5 / 1	50	14	159	151	147	7.8	2.7
	6 / 1	10	46	107	112	95	11.9	16.4
						Average |Δ| (%)	8.8	5.8

┼ G300 sensor is located 3 to 5 cm above the centerline of the top of the generator.
┼┼ UL 2201 sensor is located 30 cm above the centerline of the top of the generator.
┼┼┼ Near Shutoff Sensor (NSS) is located near the generator's onboard shutoff sensor.

Table 4. Summary of 10-min average CO measurements at time of generator shutoff

CONTAM Model Validation

As discussed in the Introduction section of this report, a simulation study using the CONTAM program is planned to evaluate the impact of the generator shutoff requirements in the PGMA and UL voluntary standards on indoor CO exposure. CONTAM (Dols and Polidoro 2015) is a multizone indoor air quality (IAQ) and airflow model developed in the Engineering Laboratory (EL) at NIST. The multizone modeling approach is implemented by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones (primarily rooms) of a building. The network nodes represent the zones, which are modeled with a hydrostatically varying pressure, and uniform temperature and pollutant concentration within each zone. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying pollutant mass balance equations. CONTAM has been used to study a variety of residential IAQ issues in the past (e.g., Emmerich and Persily 1996, Emmerich et al. 2005).

An absolute validation of a complex model, such as CONTAM, is impossible as there are infinite possible building models, contaminants and sources, and other conditions. However, several past studies (e.g., Emmerich and Nabinger (2001) and Emmerich et al. (2004)) have examined multizone IAQ model validation as reviewed in Emmerich (2001). Additionally, previous publications addressed the validation of the ability of the CONTAM model to predict CO levels due to operation of portable generators in the same NIST test house used in this study (Emmerich et al. 2013, Emmerich and Dols 2016).

As noted in Technical Note 2049, CONTAM generally assumes that the CO concentration is uniform within each zone, however for the shutoff analysis, the assumption of uniform concentration may not be valid because the distribution of CO in the space where the generator is operating, particularly near the generator-mounted shutoff sensor, can be dependent on multiple factors. These factors include where the generator is located within the space, how the exhaust is oriented relative to nearby surfaces, and the velocity and temperature of the exhaust jet exiting the exhaust pipe. The non-uniformity of CO concentration is a critical factor because generators equipped with a CO safety shutoff device are intended to shut off in a timely manner when operated in an enclosed space. Extended run-times will result in increased CO mass emitted, which for a given set of ventilation and air leakage conditions in a building will create higher COHb levels compared to cases where the generator shuts off more quickly. Therefore, the simulations that will be performed in the planned study to evaluate the impacts of shutoff requirements will account for the non-uniformity of CO observed in the testing as documented in the Test Results section.

Table 10 of Technical Note 2049 described a model validation effort that was applied to 13 of the experiments described earlier in that report to establish how well the CONTAM model predicts CO levels in the garage and the house compared and to evaluate the impact of any differences between the predictions and measurements on calculated COHB profiles of simulated occupants. Based on these comparisons, options were examined to reduce the uncertainty in the COHb levels calculated from the CO levels predicted by CONTAM, such that they will be more reliable for estimating COHb profiles. In part due to comments on the original simulation plan described in Technical Note 2048, an additional 6 model validation cases are described in Table 5 below. Specifically repeat tests under different weather conditions for 2 cases: Case 47 (Tests 2, 3, and 4) in which the G6 generator (see Technical Note 2049 for description of the generator) was fully loaded and operated outside the garage with the exhaust pointed at the open garage bay door and Case 49 (Tests 1, 2, and 3) in which the G6 generator was operated in the center of the garage with the exhaust pointed in the direction of the wall containing the person door to the house. For both of these cases, the garage bay door was fully open, all windows were closed, the door from the garage to the utility room was open 10 cm, and interior doors were fully open. A seventh test was run for Case 47 (test 1) that is not listed in Table 5 because some test sensor data was not available to allow it to be used for validation purposes. The test house model described in Technical Note 1781 was used in these simulations.

Table 5 Additional Model Validation Tests Conducted

Case/Test Number	Generator/load	Test Date	Generator Location	Average Outdoor Temp (°C)	Average Wind Speed (m/s)
49/1	**G6/50 %**	09/11/19	Garage	29.4	1.7
49/2	**G6/50 %**	11/04/19	Garage	14.9	4.7
49/3	**G6/50 %**	11/13/19	Garage	0.4	1.8
47/2	**G6/100 %**	10/03/19	Outside garage	23.9	2.8
47/3	**G6/100 %**	11/05/19	Outside garage	16.2	1.6
47/4	**G6/100 %**	11/13/19	Outside garage	0.6	1.5

Case 47

Four tests were run for Case 47 with the goal of testing under a range of outdoor conditions, however, as stated above, test 1 was not used as a validation case because some test sensor data was not available; therefore test 1 for Case 47 is not listed in Table 5. The G6 generator was positioned outside the garage (with the termination of its exhaust pipe 1.5 m from the middle of the plane of the bay door facing into garage) and tested at 100 % load. The interior person door (from utility room to garage) was open 10 cm and the garage bay door was fully open; the exterior person door (from garage to backyard) was closed. All interior doors connected to the main living space were fully open. Based on generator characterization tests conducted at CPSC (Brookman 2018), a constant CO emission rate of 1841.6 g/h was applied in this case. The generator was manually shut down after about 3 h. Although the generator was located outside the garage, the source was modeled as inside the garage since the generator exhaust jet was pointed directly into the garage.

Table 6 summarizes the maximum calculated COHb values, based on both predicted and observed CO concentrations, and average percent difference between them. For the Case 47 tests, the average absolute percent difference of the calculated maximum COHb was 39 %.

Table 6 Comparison of maximum calculated COHb values, based on both predicted and observed CO concentrations, for Case 47 Tests 2, 3, and 4

Zone	COHb (% predicted)	COHb (% observed)	% diff
Test 2			
B3	3.1	20.9	-85.1
LFK	3.4	18.3	-81.3
B2	3.1	20.5	-84.6
MBd	2.9	17.5	-83.4
Test 3			
B3	7.4	8.5	-12.8
LFK	8.2	11.3	-27.8
B2	7.8	11.3	-30.8
MBd	7.6	11.1	-31.8
Test 4			
B3	9.7	8.4	15.8
LFK	10.9	11.1	-1.5
B2	10.5	10.4	0.5
MBd	10.2	8.6	19.3
Average |% difference|			**39**

Case 49

For the three validation cases for Case 49 Tests 1, 2, and 3 under a range of weather conditions (see Table 5), the G6 generator was positioned in the garage (centered, with the exhaust facing towards the family room) and tested at 50 % load. The interior person door (from utility room to garage) was open 10 cm, and the garage bay door was fully open; the exterior person door (from garage to backyard) was closed. All interior doors connected to the living space were fully open. Based on generator characterization tests conducted at CPSC (Brookman 2018), a constant CO emission rate of 749.6 g/h was applied in this case. The generator was manually shutdown after about 3 h. These tests were similar to Case 32 but with a lower load to determine if a different fraction of CO emission in the utility room would be more appropriate for smaller generators. After finding that the same 5 % fraction as used in Case 32 (see results in Technical Note 2049) significantly underpredicted CO entering the house, simulations were performed with 15 % of the CO source placed in the utility room and the remaining 85 % in the garage. Table 7 summarizes the maximum COHb values, both predicted and observed, and average percent difference between them for Case 49 tests with the 15 % factor, which resulted in an average percent difference of 24 %.

Table 7 Comparison of maximum calculated COHb values, based on both predicted and observed CO concentrations, for Case 49 Tests 1, 2, and 3

Zone	COHb (% predicted)	COHb (% observed)	% diff
Test 1			
B3	14.9	25.6	-41.9
LFK	15.8	25.7	-38.4
B2	15.2	27.9	-45.6
MBd	14.6	26.5	-44.7
Test 2			
B3	8.1	7.3	10.9
LFK	9.6	10.2	-6.4
B2	9.1	10.6	-14.1
MBd	8.7	9.3	-5.6
Test 3			
B3	18.2	15.5	17.2
LFK	19.2	17.3	10.9
B2	18.4	15.3	20.0
MBd	18.1	14.0	28.6
Average |% difference|			**24**

Summary

This report presents measured CO concentrations, and calculated COHb profiles based on those concentrations, from tests wherein four different commercially available portable generators equipped with CO safety shutoff systems were operated in a test house under various operational and environmental conditions. The tests are intended to provide CPSC staff and other interested parties with information that will enable the comparison of residential CO exposures resulting from the operation of portable generators with a CO hazard mitigation system inside a home or attached garage or outside near a home. Peak living space CO concentrations ranged from under 100 μL/L to over 1100 μL/L and peak living space COHb levels ranged from less than 5 % to over 35 %. Twelve tests were conducted with the generator in the kitchen with one window open 10 cm. Automatic shutoff occurred in 11 tests in a range of 3 min to 171 min with a resulting peak COHb level of 5 % to 30 %. Note that the case that did not shut off had among the lowest peak % COHb levels. Twelve tests were conducted with the generator in the garage with the bay door closed. Automatic shutoff occurred in all 12 tests in 1 min to 166 min with a resulting peak COHb of under 10 %. Eight tests were conducted with the generator in the garage with the bay door open. Automatic shutoff occurred in two cases in 2 min to 8 min and a resulting peak COHb of under 5 %. For the 10 cases that did not shutoff, the peak COHb level ranged from <10 % to 37 %. These results apply to the specific generators and conditions tested; other generators and test conditions may produce different results. In addition, model validation tests and simulations were performed for two Cases (three tests each) to supplement those already reported in NIST Technical Note 2049.

Acknowledgements

NIST's participation in this study was supported by an interagency agreement between the National Institute for Standards and Technology and the Consumer Product Safety Commission (CPSC-I-17-0023). The content of this publication does not necessarily reflect the views of the Commission, nor does the mention of trade names, commercial products, or organizations imply endorsement by the Commission. The authors would like to acknowledge the contributions of Janet Buyer, Matthew Hnatov, and Dr. Andrew Lock from CPSC, Dr. Sandra Inkster formerly of CPSC, and Steven Nabinger formerly of NIST.

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Appendix 1 – COHb Analysis Method

In 1965, Coburn, Forster and Kane developed a differential equation (CFK model) to describe the major physiological variables that determine the *COHb* in blood using data from patients with increased endogenous production of CO due to anemia (Coburn et al., 1965[1]). The CFK model is represented by the following equation:

$$\frac{d(COHb)_t}{dt} = \frac{V_{CO}}{V_b} - \frac{COHb_t * P_{O_2}}{M * B * Vb * OHb} + \frac{P_{CO}}{B * Vb}$$

where

$B = 1 / D_L + P_L / V_A$
M = Ratio of affinity of blood for CO to that for O_2, M = 218
OHb = ml of O_2 per ml blood, OHb = 0.2
$COHb_t$ = ml of CO per ml blood at time
P_{O_2} = average partial pressure of oxygen in the lung capillaries, P_{O_2} = 100 mm Hg
V_{CO} = rate of endogenous CO production, V_{CO} = 0.007 ml/min
D_L = diffusivity of the lung for CO, D_L = 30 ml / min mm Hg
P_L = barometric pressure minus the vapor pressure of water at body temperature, 713 mm Hg
Vb = blood volume, Vb = 5500 ml
P_{CO} = partial pressure of CO in the air inhaled, mm Hg
V_A = alveolar ventilation rate, V_A = 6000 ml/min (awake), 4000 ml (sleeping)
t = exposure duration, min

In another study by Peterson and Stewart (1975), data from a series of human exposures to CO were analyzed to determine the fit to the theoretical CFK equation. 19 men and 3 women were exposed to concentrations of 50 ppm, 100 ppm or 200 ppm for 0.33 h to 5.25 h. Three exercise levels from sedentary or 0 kpm/min, 150 kpm/min or 300 kpm/min on an ergometer were used (15 subjects in total). Note: kpm/min are used in the original reference and 6.116 kpm/min is equal to 1 W. These resulted in mean ventilation rates of 10.1 l/min (9.1 l/min for women), 14.0 l/min, 24.0 l/min (19.7 l/min for women) and 29.7 l/min, respectively. The CFK model predicted *COHb* for both men and women as well as for resting and exercising subjects within a standard error of about 2 %. In contrast to the original model, which assumes all variables to be constant except t, P_L, $COHb_t$ and P_{CO}, the following parameter alterations were introduced:

P_{O_2}: When the partial pressure of oxygen in inspired air (Pi_{O_2}) is less than the 149 mm Hg found under normal conditions, the partial pressure of oxygen in the lung capillaries will be less than the value of 100 mmHg assumed by Coburn and coworkers. From measurements of oxygen partial pressure in arterial blood, which is assumed to be the same as the oxygen partial pressure in lung capillaries, the following equation was derived:

$P_{O_2} = 1/(0.072 - 0.00079\,Pi_{O_2} + 0.000002515\,(Pi_{O_2})^2)$ and

$Pi_{O_2} = Fi_{O_2}(P_B - 47 - Pi_{CO})$ with Fi_{O_2} = fraction of oxygen in inspired air,

P_B = barometric pressure (mm Hg), Pi_{CO} = partial pressure of CO in inspired air

[1] Coburn, R.F., Forster, R.E. and Kane, P.B. 1965. Considerations of the physiological variables that determine the blood carboxyhemoglobin concentration in man. *Journal of Clinical Investigation*, 44 (11), 1899-1910.

D_L: Body size effects on diffusivity at rest were was calculated from published data as:

$$D_L = 1/(-0.0287 + 0.1188 / A)$$ with A = body surface in m^2

Vb: the published blood volume relationship of 74 mg/kg of body weight for men and 73 ml/kg for women was used.

V_A: The alveolar ventilation rate was expressed as: $V_A = V_E - fV_D$; with V_E = total rate of ventilation (ml/min), f = respiration rate (min^{-1}) and V_D = dead space (ml)

OHb_t: At standard concentrations, 1 g of hemoglobin will hold 1.38 ml of oxygen and thus $OHb_{\max} = 1.38[Hb]/100$, with *[2]* being the hemoglobin concentration in blood (g/100 ml). During and after CO exposure, the value of OHb_t that must be used is actually $OHb_t = OHb_{\max} - COHb_t$. In this case, the CFK equation can only be solved by iterative procedures.

$COHb$: This value can be converted to the more conventional, percentage saturation by:

$$\%COHb = COHb * 100 / OHb_{\max}$$

For the calculation of concentration-time combinations that result in a certain *COHb*, the model of Coburn, Forster and Kane (CFK model) was used. Since this model in the formulation of Peterson and Stewart (1975) calculates *COHb* larger than 100 % at high exposure concentrations, the following correction proposed by Peterson and Stewart (1975) was used: the amount of bound oxygen is actually not constant, but is dependent on the *COHb*, therefore:

$$OHb_t = OHb_{\max} - COHb_t$$

Since in this case, the CFK equation can only be solved iteratively (EPA, 2006), calculations were done using time steps (Δt) of 1 minute for the period of 24 hours. In each step, the *COHb* of the step before was used to calculate OHb_t. For the first step, a background *COHb* of 0.24 % was assumed.

Calculations using the following equation were carried out in a NIST-developed computer program:

$$\Delta(COHb)_t = \left(\frac{V_{CO}}{V_b} - \frac{(COHb)_{t-1} * P_{O2}}{M * B * Vb(OHb_{\max} - (COHb)_{t-1})} + \frac{P_{CO}}{B * Vb}\right)\Delta t$$

$$(COHb)_t = (COHb)_{t-1} + \Delta(COHb)_t$$

where

$(COHb)_t$ = ml of CO per ml blood at time t, min

Conversion: $\%COHb = (COHb)_t * 100 / OHb_{\max}$

$(COHb)_0$ =initial level, background=0.0024 for non-smokers

OHb_{max}= ml of O_2 per ml blood under normal conditions, $OHb_{\max} = 1.38[Hb]/100$

[2]= hemoglobin concentration, g/100 ml blood, *[Hb]*=15 for healthy adults

V_{CO} = rate of endogenous CO production, V_{CO} = 0.007 ml/min

Vb = blood volume, ml; Vb (70-kg man) = 5500 ml

M = Ratio of affinity of blood for CO to that for O_2; M = 218 (newborn: M = 240)

$B = 1 / D_L + P_L / V_A$ with:

D_L = diffusivity of the lung for CO, $D_L = 35 * V_{O_2} * exp(0.33)$
P_L = barometric pressure minus the vapor pressure of water at body temperature,
$P_L = Pb - 43mmHg$
V_{O_2}= rate of oxygen consumption, L/min. $V_{O_2} = RMV/22.274 - 0.0309$
V_A = alveolar ventilation rate, ml/min, $V_A = 0.933V_e - 132f$
f= respiration rate, 1/min. $f = exp[0.0165RMV + 2.3293]$
RMV= respiratory minute volume, l/min. $RMV = 15\,l/min$ for the person between light activity (10 l/min) and moderate activity (20 l/min)
P_{iO_2} = partial pressure of inhaled O_2, torr.$Pi_{O_2} = 148.304 - 0.0208P_{CO} = Fi_{O_2}(Pb - 47 - P_{CO})$
P_{O_2} = average partial pressure of oxygen in the lung capillaries; torr
$P_{O_2} = Pi_{O_2} - 49$, for $Pi_{O_2} \geq 149\ torr$
$P_{O_2} = 1/\left[0.072 - 0.00079Pi_{O_2} + 0.000002515\left(Pi_{O_2}\right)^2\right]$, for $Pi_{O_2} < 149\ torr$
Fi_{O_2}= fraction of inhaled O_2, normally $Fi_{O_2} = 0.209$
Pb= barometric pressure, torr, 760 at sea level.
P_{CO} = partial pressure of CO in the air inhaled, mm Hg,
Conversion: $P_{CO}(mmHg) = P_{CO}(ppm)/1316$
Δt = exposure time interval, min; $\Delta t = 1$ min.