Letter Report to U.S. CPSC

Measured CO Concentrations at NIST IAQ Test House from Operation of Portable Electric Generators in Attached Garage – Interim Report

July 6, 2011

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Introduction

The U.S. Consumer Product Safety Commission (CPSC) is concerned about the hazard of acute residential carbon monoxide (CO) exposures from portable gasoline powered generators that can result in death or serious and/or lasting adverse health effects in exposed individuals. As of June 2010, CPSC databases contain records of at least 542 deaths from CO poisoning associated with consumer use of generators in the period of 1999 through 2009 (Hnatov 2010). In addition, the percentage of estimated non-fire, consumer product-related CO poisoning deaths specifically associated with generators for CPSC's three most recent years of data are 51 % (2005), 49 % (2006), and 39 % (2007) (Hnatov 2011). 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.

As an initial approach to characterizing the hazard, CPSC measured the emissions from generators by testing them in a small test chamber (Brown 2006). CPSC subsequently contracted with the University of Alabama (UA) to develop and construct low CO-emission prototype generators using off-the-shelf technologies installed on commercially-available portable generators. In conjunction with these efforts, CPSC established an interagency agreement with the National Institute of Standards and Technology (NIST), in part, to conduct a series of tests to provide empirical data to further characterize the hazard by measuring the generation and transport of CO when generators are operated in an actual building. This interim report presents data from this series of tests of both unmodified and UA-modified prototype generators operated in the garage attached to NIST's manufactured house, a test facility designed for conducting residential indoor air quality (IAQ) studies. This double-wide manufactured house is similar in size to homes commonly involved in fatal consumer incidents (Hnatov 2010). The results from this work will enable CPSC to assess the efficacy of the prototype in reducing the CO poisoning hazard. Future work that NIST will perform under this IAG includes modeling the CO generation and its transport under a variety of other conditions, including different ambient conditions, longer generator run times, and possibly other house configurations. This modeling will be performed using NIST's multi-zone airflow and indoor air quality simulation program CONTAM, and the results will be presented in a future report.

Method

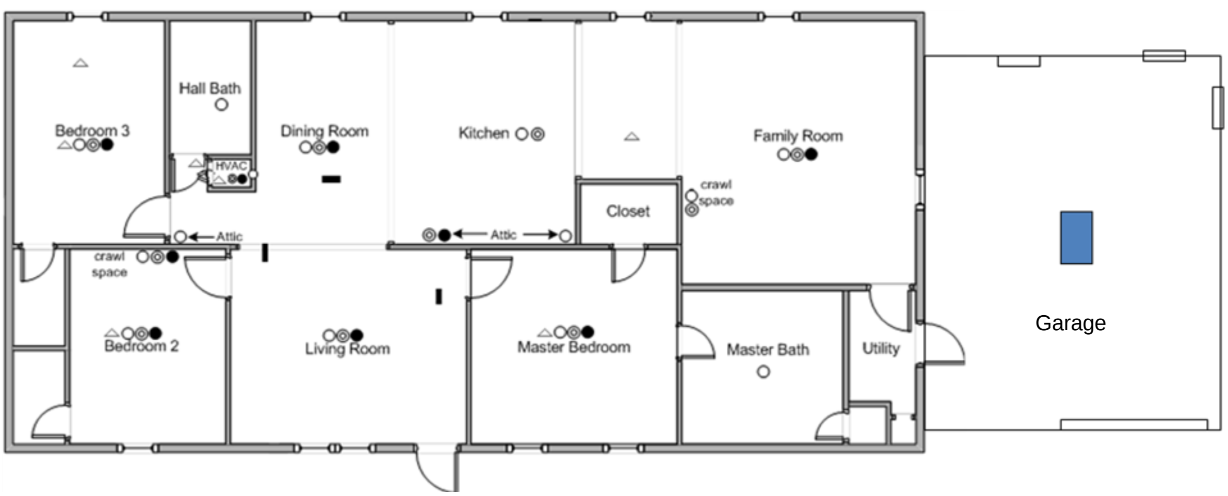
House

The test house used in this study was a manufactured house located on the NIST campus (Nabinger and Persily 2008). An aerial view and floorplan of the house are shown in Figures

1and 2. The house includes three bedrooms, a living room (LR), a family room (FAM), a kitchen (KIT), and an attached garage. The house has a floor area of 140 m^2 (1500 ft^2) and a volume of 340 m^3 (12,000 ft^3). The attached garage has a floor area of 36.5 m^2 (390 ft^2) and a volume of 90 m^3 (3200 ft^3).

Figure 1 Aerial view of NIST manufactured test house

Figure 2 Floorplan of NIST manufactured test house



Generators
Tests were conducted on two different generators that were configured in multiple ways. One unmodified 'stock' (i.e., in its as-purchased condition) generator was tested. The generator is powered by a carbureted 11 horsepower single-cylinder gasoline engine and has an advertised full-load electric power rating of 5.0 kW. This power rating is in the range most commonly noted in fatal consumer incidents (Hnatov 2010). This unmodified generator with carburetor fuel delivery (referred to as unmod Gen X), operates at air-fuel ratios (AFR, ratio of mass of air to mass of fuel) in the range of 10 to 13 AFR depending on the load, which is common for small

air-cooled carbureted engines. After it was tested in its unmodified stock configuration (referred to as unmod Gen X), the unit was shipped to UA where it was modified into the prototype configuration (referred to as mod Gen X) by adding an engine management system (EMS) and associated sensors and actuators, fuel system components, an electric start system, and a muffler with a small catalyst integrated into it. The function of the EMS is to control ignition timing and fuel delivery through an engine control unit (ECU) microcomputer that receives input from a variety of system sensors UA calibrated the ECU on the modified prototype to operate around a 14.6 AFR over the full range of loads. This AFR fuel control strategy is the primary means by which the prototype aims to achieve its reduction in CO emissions. The catalyst has relatively low catalytic activity because the EMS significantly reduces the available oxidation constituents in the exhaust stream. Mod Gen X was then shipped back to NIST and tested at the manufactured test house.

The second generator tested (referred to as Gen SO1) was an updated model similar to unmod Gen X with an identical original engine. It was tested after UA modified it into a low emission prototype with the same catalyst and fuel control strategy described above. It has a different model ECU than that used on mod Gen X. One of the notable differences on this ECU is that its manufacturer included programming to maintain rich AFR operation until the oil temperature rose above approximately 60 °C (140 °F). This ECU also includes an algorithm developed by UA that can be switched on or off. The algorithm was intended to sense when the generator was operating in an enclosed space, based on engine operation parameters; when enabled, it is intended to shut off the engine before a life-threatening CO hazard develops. Only tests with the shut-off algorithm disabled, i.e., in which the test operator manually shut the generator off, are included in this report. Gen SO1 was also tested in a configuration with a muffler that did not contain a catalytic converter (referred to as the noncat muffler).

A full description of the prototype configuration of both mod Gen X and Gen SO1 will be provided in greater detail in a future report from UA to CPSC.

Measurements

Measurements of gas concentrations were made at various points throughout the house using sample lines suspended in the center of each of the three bedrooms, the living room, the kitchen, and the family room, as well as five sample lines located near the four corners and center of the garage. The garage sample locations were measured separately, as well as a single mixed sample, the latter of which is reported here. Indoor air temperature and humidity were measured by sensors in each room of the house and on two opposite walls of the garage. The outdoor temperature was measured at a weather station located about 6 m (20 ft) behind the house. Wind speed and direction data were collected from a weather station located on the roof of Building 226 on the NIST campus (about a mile from the test house). The wind speed and direction and the temperature differences between the ambient and interior (and between interior spaces) create pressure differences which, along with pressure differences created by any operating fans, are primary drivers of airflow into a building and between internal zones.

Gas concentrations were measured with two multi-gas engine exhaust analyzers (NOVA Analytics Model 7464: combination non-dispersive infrared (NDIR) and electrochemical sensor technologies (called N1 and N2 in the rest of this report)) that measured CO on two channels covering different ranges of 0 % to 1 % and 0 % to 10 %, CO_2 from 0 % to 20 %, hydrocarbons (as hexane) from 0 % to 2 % and O_2 from 0 % to 25 % [reported accuracy of 1 % of full scale for all five channels]; an electrochemical sensor CO analyzer (NOVA Analytics Model 7461 – called N3 in this report) with a range of 0 ppm_v to 2000 ppm_v and reported accuracy of 1 % of full scale; two additional NDIR CO analyzers (Thermoelectron Model 48 (called T1) and Rosemount Model 880A (called R1)) with ranges of 0 ppm_v to 1000 ppm_v and reported accuracy of 1 % of full scale; and a separate portable O_2 analyzer (Sybron Servomex O_2 Analyzer OA 580). Not all instruments were used during every test. Repeated calibrations during the test periods found that typical measurement uncertainties were consistent with the manufacturers' reported instrument accuracies. See Appendix A for more detail on calibrations. To protect the analyzers from condensed water and/or soot particles, desiccant and high efficiency particulate air (HEPA) filters were used in the sampling system.

The generators were operated using reformulated gasoline with 10 % ethanol obtained from the NIST motor pool, which is purchased to the same specification year-round. The generators were placed on a spill-catching platform in the middle of the garage with the exhaust pipe pointing towards the garage wall adjoining the house.

To monitor prototype engine operation, generators mod GenX and Gen SO1 were outfitted with thermocouples and a Lambda sensor to measure AFR (ECM Model Lambda 5220 with an AFR range of 6 to 364 and reported accuracy of 0.2 for $12 < AFR < 18$). The Lambda sensor and a thermocouple for measuring engine-out exhaust temperature were mounted through ports that UA provided on the exhaust manifold pipe between the engine and muffler. Cylinder head temperature was measured with a ring thermocouple mounted under the spark plug. Engine oil temperature was measured with a thermocouple inserted into the sump. For some of the tests, muffler and shroud temperatures were also measured, using thermocouples mounted directly on their surfaces at the hottest locations previously identified by UA with infrared cameras during their prototype tests.

A portable alternating current (AC) resistive load bank connected to the generator's 240-volt receptacle was used to draw electrical power and so act as a surrogate for consumer appliance loads. The load bank has manual switches in 250 W increments with a maximum setting of 10 kW. Table 1 describes the hourly cyclic load profile that was applied using the load bank. This profile is an adaptation of the load profile used by UA during the durability and emission testing of their low CO emission prototype generator. Because the actual delivered power did not always match the load bank settings, particularly when oxygen depletion was occurring in the garage, the delivered power was measured during all tests.

Table 1 Hourly cyclic load profile

Load bank setting (W)	Duration (min)
no load	3
500	4
1500	18
3000	17.5
4500	12
5500	5.5

Testing Configurations

Testing was conducted under seven different test house configurations to evaluate their impacts on the buildup of CO in the garage and its transport into the different rooms in the house. These configurations included two different garage bay door positions (fully closed or open nominally 0.6 m (24 in)), two connecting door settings between the garage and the family room (fully closed or open nominally 50 mm (2 in)), and two house central heating, ventilating, and air conditioning (HVAC) fan settings (on or off). All internal house doors were kept open throughout all tests.

There were multiple purposes in conducting tests under these different configurations. The garage-house door positions directly affect the rate of engine exhaust transfer from the garage into the house. The status of the HVAC fan, which circulates the interior air throughout the different rooms of the house, affects the CO distribution within the house. The fan operation also affects the house air change rate due to air distribution ductwork leakage within the crawl space (Nabinger and Persily 2008). It is also relevant to consider the HVAC fan status, even when there is a power outage, because the consumer may use the generator to provide power to the home's central heating system, which includes providing power to the HVAC fan. Another reason for testing under these different configurations is that, with the generator operating in the garage, it is possible that the engine will consume the oxygen in the garage at a faster rate than the rate at which natural air change replenishes oxygen. The degree of either door's opening will impact whether or not the garage's oxygen level can be maintained at ambient level and, if not, how low it will drop. Testing with different door opening positions enabled observations of the effects of different oxygen levels on generator engine performance. Variations in these conditions can be found in CPSC's investigation reports of fatal CO poisonings involving generators (Hnatov 2010). These reports include cases in which consumers were aware of the CO poisoning hazard but attempted to provide what they considered "proper ventilation" by operating the generator in a partially-open garage. A bay door opening of 61 cm (24 in) was selected in part based on it being within the range of openings that can be modeled using CONTAM. The house door opening of 5.1 cm (2 in) was selected because it is a reasonable opening to allow the passage of an extension cord from the generator into the house.

Table 2 includes a summary of the tests conducted including information on the generator tested, the test house configuration (defined by door positions and fan status), a test identification code, the date the test was conducted, the average ambient temperature and wind speed, and the CO analyzers used.

Table 2 Tests Conducted

Generator	House Configuration	Garge bay door	Garage to house entry door	HVAC fan	Test ID	Date	Outdoor Temp (°C)	Wind speed (m/s)	CO analyzers in garage	CO analyzers in house
unmod GenX	1	Closed	Open	OFF	B	04/22/08	20.1	6.5	N1	N2, N3
modGenX	1	Closed	Open	OFF	O	04/02/10	22.0	6.5	N2, N3	N1, R1
SO1	1	Closed	Open	OFF	N	04/01/10	19.9	6.3	N2, N3	N1, R1
unmod GenX	2	Open	Closed	OFF	F	05/06/08	22.8	7.7	N1	N2, N3
modGenX	2	Open	Closed	OFF	R	04/12/10	19.9	6.7	N2, N3	N1, R1
SO1	2	Open	Closed	OFF	T	04/14/10	13.4	6.9	N2, N3	N1, R1
unmod GenX	3	Closed	Open	ON	I	05/15/08	22.8	7.4	N1	N2, N3
SO1 with noncat muffler	3	Closed	Open	ON	Z	05/05/10	28.3	6.7	N2, N3	N1, R1
unmod GenX	4	Closed	Closed	ON	J	05/21/08	18.2	9.6	N1	N2, N3
SO1	4	Closed	Closed	ON	W	04/29/10	17.8	9.5	N2, N3	N1, R1
unmod GenX	5	Closed	Closed	OFF	D	04/30/08	12.2	8.2	N1	N2, N3
SO1 with noncat muffler	5	Closed	Closed	OFF	AH	05/13/10	15.6	6.5	N2, N3	N1, R1
unmod GenX	6	Open	Open	ON	G	05/07/08	25.1	7.0	N1	N2, N3
SO1	6	Open	Open	ON	U	04/22/10	20.4	7.8	N2, N3	N1, R1
unmod GenX	7	Open	Open	OFF	K	05/23/08	13.84	7.0	N1, T1	N2, N3
SO1 with noncat muffler	7	Open	Open	OFF	V	04/23/10	15.8	6.5	N2, N3	N1, R1

Results

Figures 3 through 18 show the key measured values for all 16 tests listed in Table 2, including CO concentration in the house and garage, O_2 concentration in the garage and the measured electric load supplied by the generator. As described in the Method Section, several different analyzers were used during the tests to span the full range of CO concentrations, but data is presented only from the analyzer considered most appropriate for the CO concentration range in each test. In all tests, the generator was started at time 0 and was manually shut off by the test operator using a wireless switch that interrupted the engine's ignition. Also, the data in the figures are plotted up until the time mechanical venting was initiated, which typically immediately followed generator shut-off. In some tests, where time and circumstances permitted, natural decay was allowed to occur for some length of time after the generator was stopped, before mechanical venting was initiated. In those tests, the natural decay is plotted.

Figures 3a, 3b, and 3c show the results for Test B, which was a three hour test of unmod Gen X in Configuration 1 (garage bay door closed, garage access door to house open nominally two inches, and the house central HVAC fan off). Since it was a three hour test, the hourly cyclic load profile in Table 1 was repeated three times. At the end of the third cycle, the generator was stopped, and the garage was mechanically vented.

Figure 3a CO and O_2 concentrations in the garage and measured load for Test B **(unmod Gen X, Configuration 1)**

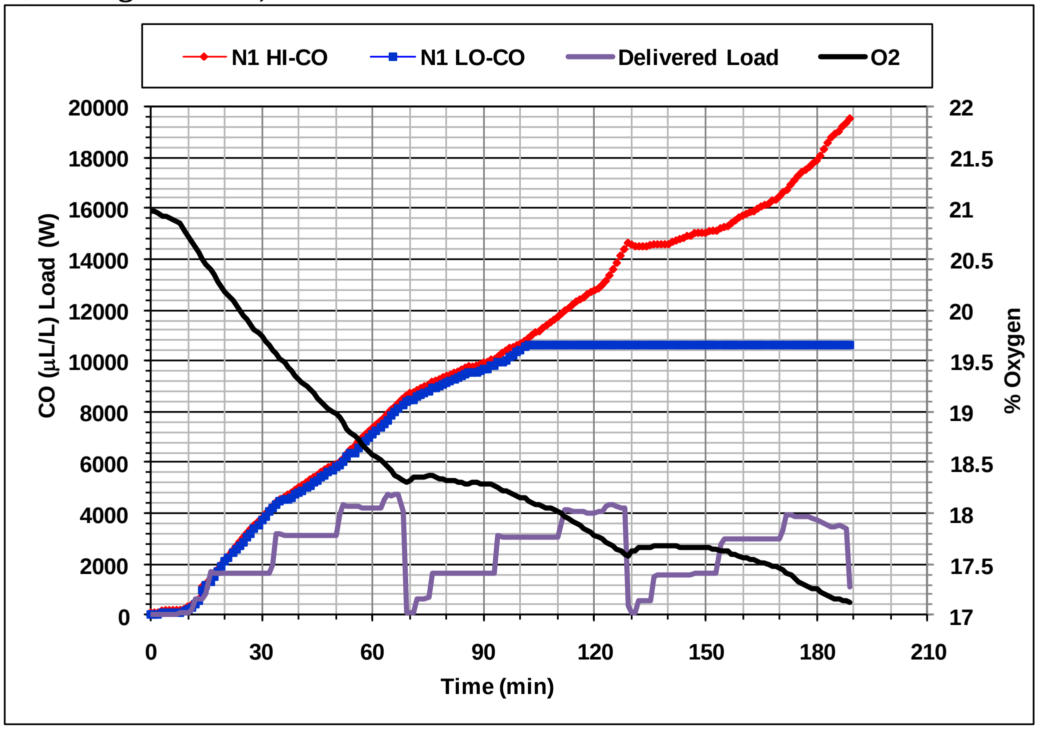


Figure 3a shows the concentration of CO in the garage reached a peak of over 19,500 µL/L (note that µL/L are equivalent to the commonly used unit ppm_v) and the volume fraction of O_2 in the garage dropped by 3.8 % to nearly 17 % when the generator was stopped. It also shows that in the first load cycle, the delivered electrical output was less than the load bank settings for the two highest loads in the load cycle, 4500 W and 5500 W, which were applied when the oxygen was below 19 %. As the oxygen continued to drop in the subsequent load cycles, the delivered power for these load points decreased further.

Figure 3b CO (ppm range) concentrations in the house for Test B (unmod Gen X, Configuration 1)

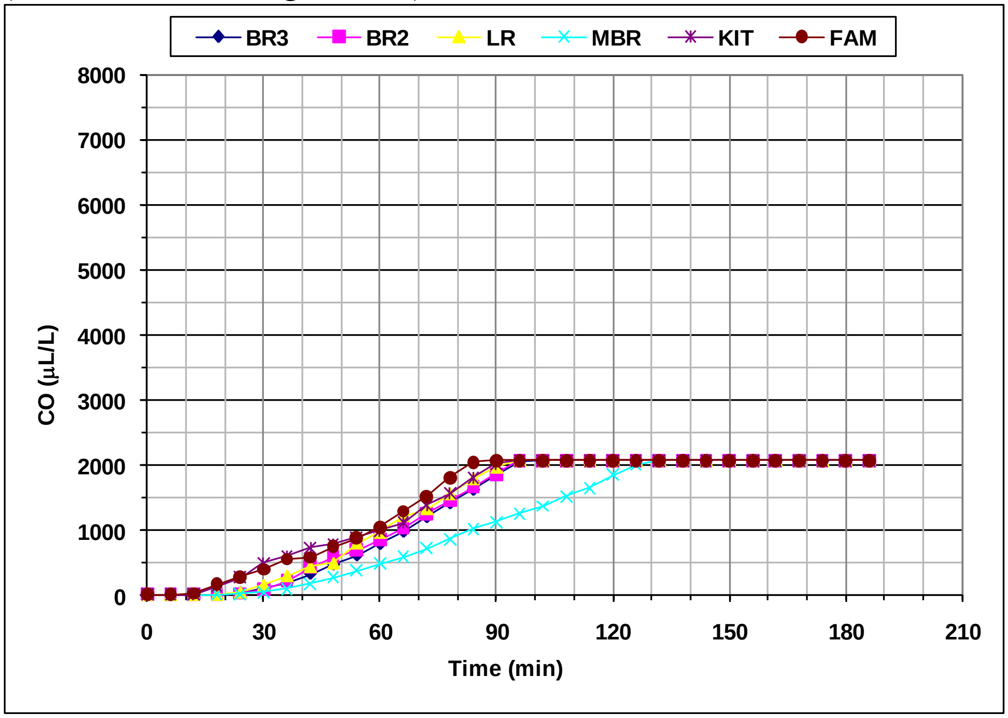
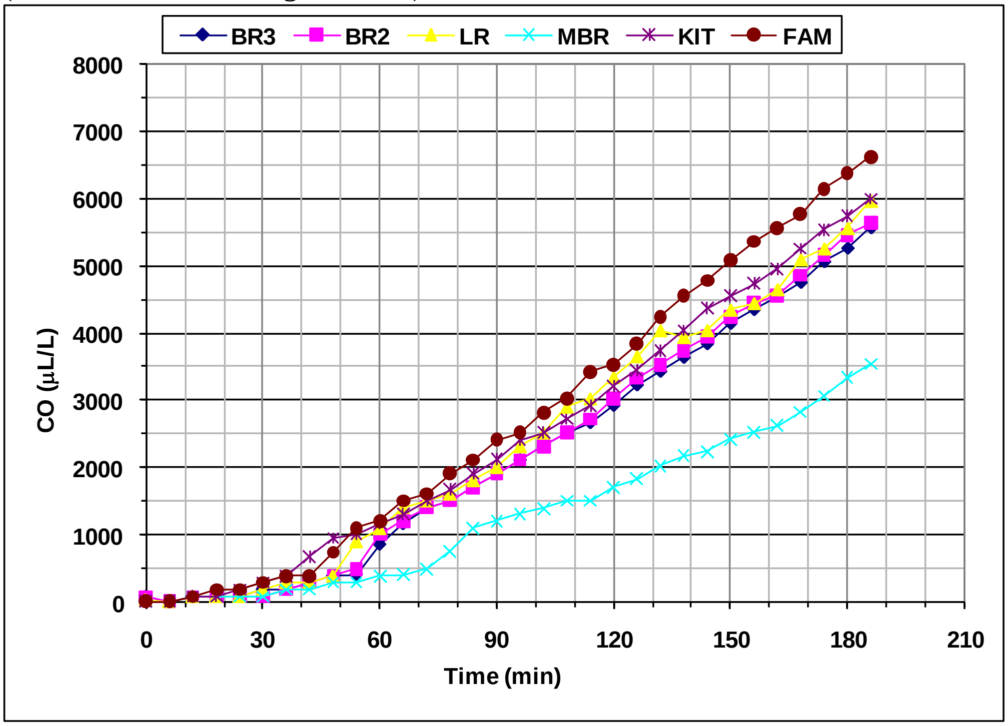


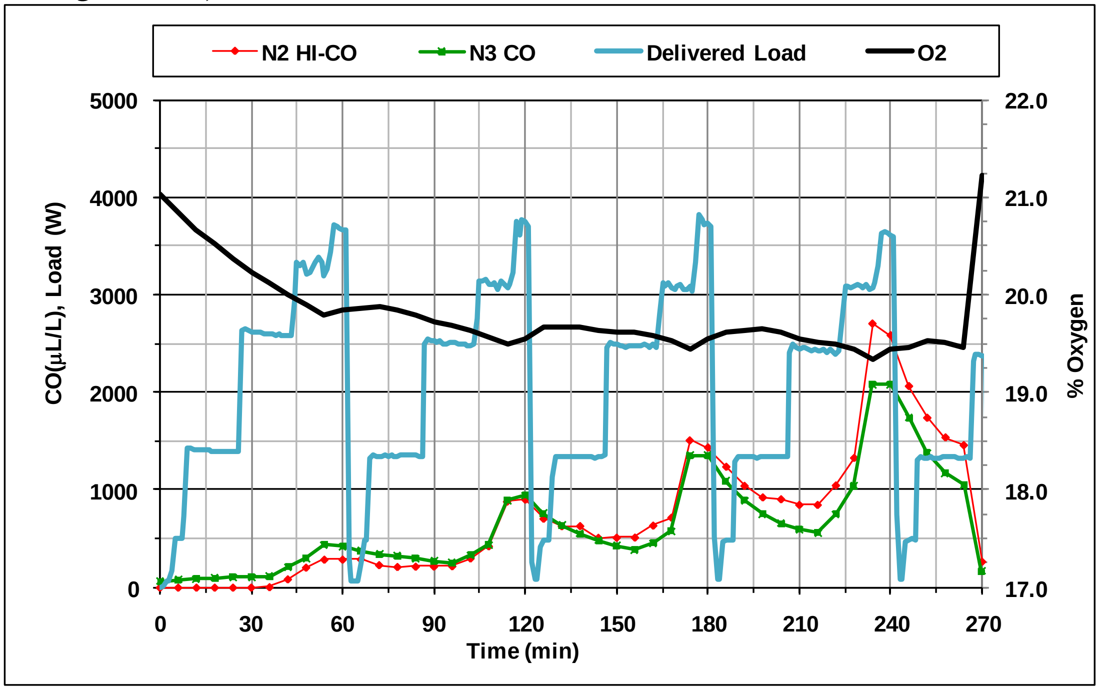
Figure 3c CO (high range) concentrations in the house for Test B (unmod Gen X, Configuration 1)



Figures 3b and 3c show the CO concentration in six rooms of the test house (see Figure 2 for room locations) as measured on the 'ppm range' (where the CO concentration plot plateaus at the instrument's 2000 µL/L limit) and 'high range' CO instruments, respectively. The CO reached a peak concentration of over 6500 µL/L in the family room, with peak concentrations in the other rooms ranging from about 3500 µL/L to 6000 µL/L.

Figures 4a, 4b, and 4c show the results for Test O, which was a four and a half hour test of mod Gen X with the same test house configuration as used in Test B of unmod Gen X (Configuration 1). After the generator was stopped, the garage and house were mechanically ventilated.

Figure 4a CO and O_2 concentrations in the garage and measured load for Test O (mod Gen X, Configuration 1)

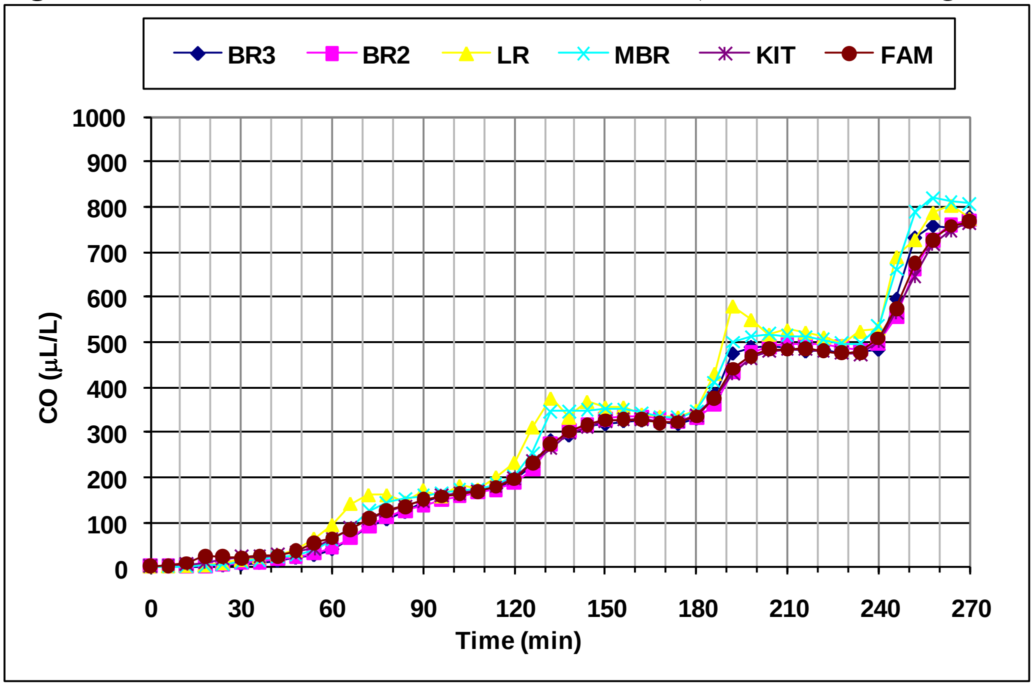


As shown in Figure 4a, the garage CO concentration reached a peak of nearly 3000 µL/L while the garage O_2 concentration dropped by 1.7 % to 19.5 % after completing the fourth cycle of the load profile. Note that the ppm instrument briefly topped out at this time. Also, the initial O_2 concentration is shown as slightly above 20.9 % for some tests due to the instrument accuracy. The generator was intentionally stopped midway through the fifth load cycle.

At three hours into this test, the garage CO concentration was approximately 1400 µL/L. Under fairly similar ambient conditions between this test and Test B, this CO concentration is a 93 % reduction compared to that measured with unmod Gen X in Test B in which the garage CO was over 19,500 µL/L at the same time during the test.

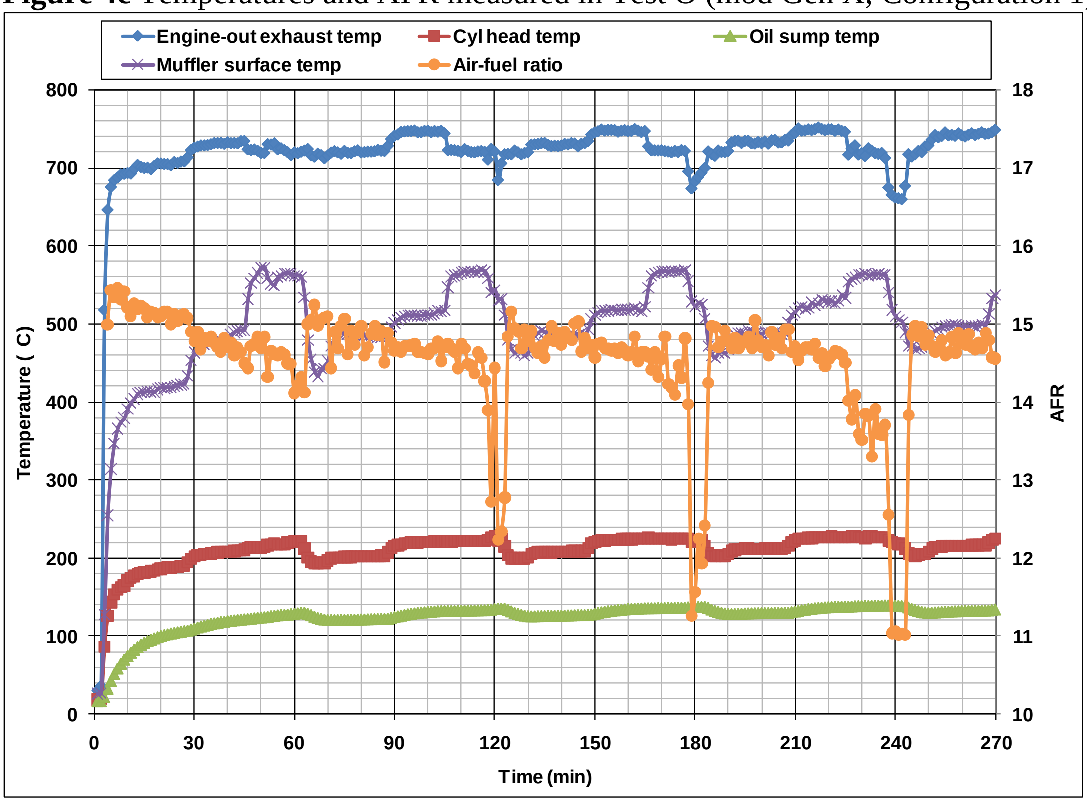
In the first load cycle, as the oxygen dropped, the delivered electrical output was less than the load bank settings for the three highest loads in the load cycle, 3000 W, 4500 W, and 5500 W. While the electrical output stayed near constant for the four cycles, the CO levels increased progressively and the oxygen decreased slightly with each additional cycle.

Figure 4b CO concentrations in the house for Test O (mod Gen X, Configuration 1)



As seen in Figure 4b, the peak CO concentration throughout the house was about 800 μL/L, with a relatively uniform distribution in all the rooms despite the HVAC fan being off. By comparison, unmod Gen X in Test B produced a peak concentration of over 6500 μL/L in the family room.

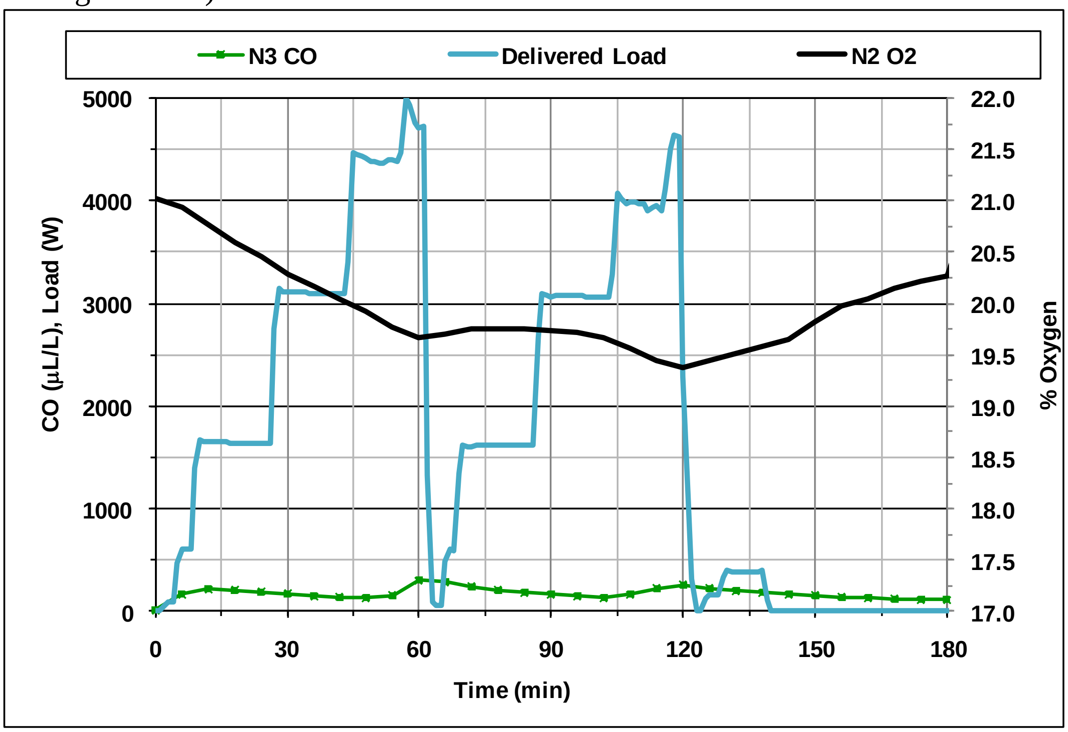
Figure 4c Temperatures and AFR measured in Test O (mod Gen X, Configuration 1)



The AFR (provided as a general indicator of engine performance for this and other tests) and temperatures measured on modGen X during Test O are shown in Figure 4c. During this test, the engine performed off design with AFR largely ranging from around 14 to around 15.4 during each load cycle and dipping lower to rich operation when transitioning between the load cycles as well as during the high loads.

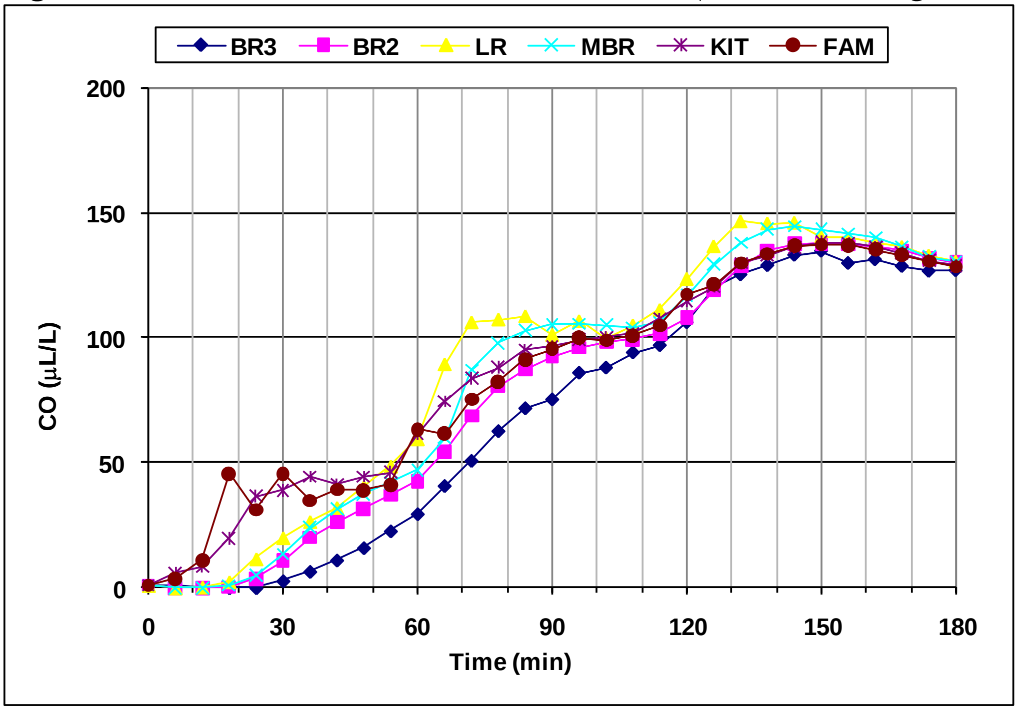
Figures 5a, 5b, and 5c show the results for Test N, which was a two hour test of Gen SO1 with the same test house configuration as used in Test B unmod Gen X and four and Test O of mod GenX (Configuration 1). This test was terminated earlier than planned after a fuse blew on the load bank after 114 min of operation, dropping half the load. The generator was turned off 138 min after it was started. A natural decay period of 45 min was included after the generator was stopped, followed by mechanical venting.

Figure 5a CO and O_2 concentrations in the garage and measured load for Test N (Gen SO1, Configuration 1)



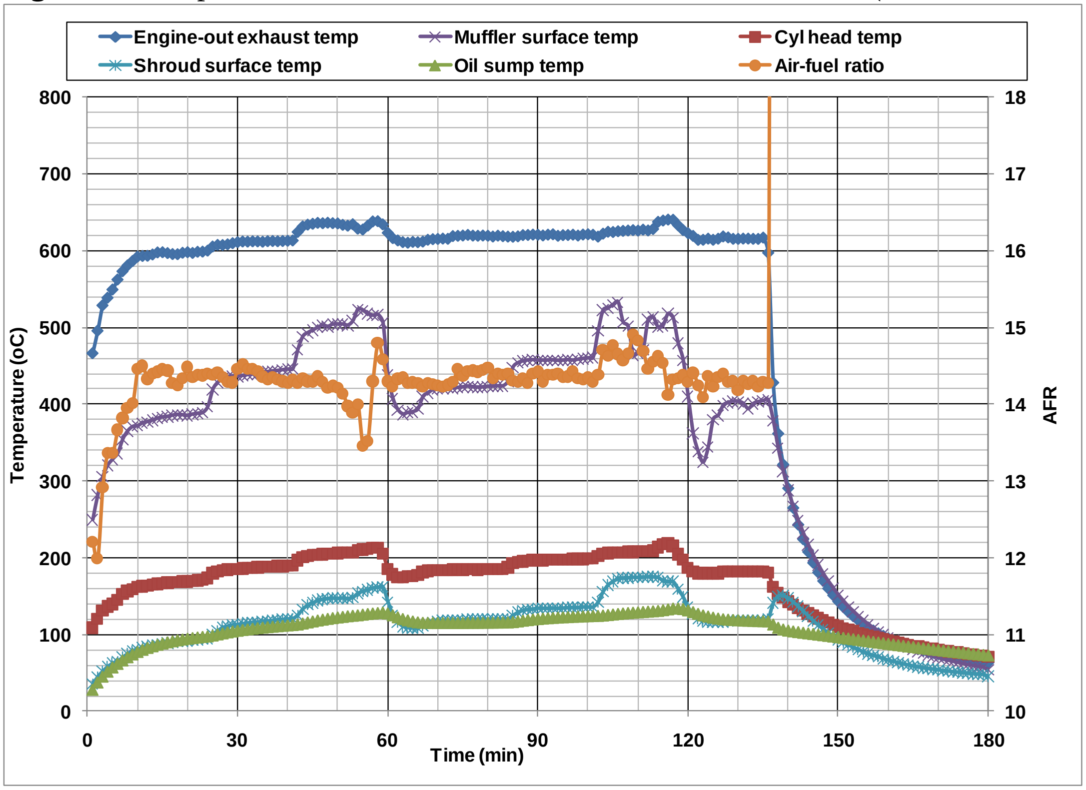
As shown in Figure 5a, there was an initial increase of CO to almost 220 µL/L in the first 12 min after the generator was started. This rise is due to the rich operation upon cold engine start until the oil warms and the ECU transitions to the calibrated AFR fuel control. This initial increase is observed at the start of each of the tests with Gen SO1. The garage CO concentration reached a peak of around 300 µL/L and the garage O_2 concentration dropped by 1.6 % to 19.4 % before the generator was stopped. The garage CO concentration after two hours is about 98 % lower than the concentration at two hours with unmod Gen X in Test B, which was about 13,000 µL/L. In the first load cycle, as the oxygen dropped, the delivered electrical output was less than the load bank setting for the highest load in the load cycle, 5500 W. This difference increased in the subsequent load cycle as the oxygen level decreased. Comparing the performance of mod Gen X (Figure 4a) and Gen SO1 (Figure 5a) shows that, under similar conditions (Configuration 1), Gen SO1 resulted in significantly lower CO concentrations at the 2 h mark.

Figure 5b CO concentrations in the house for Test N (Gen SO1, Configuration 1)



As shown in Figure 5b, the concentration throughout the house was about 130 µL/L when the generator was stopped after 114 min. There is a relatively even distribution among the rooms in spite of the HVAC fan being off. For the following 45 min in which the exhaust was allowed to naturally decay, the CO continued to infiltrate from the garage into to the house, slightly increasing the house concentration to about 140 µL/L before the concentration began dropping. By comparison, unmod Gen X in Test B produced a peak concentration of over 3500 µL/L in the family room after 2 h.

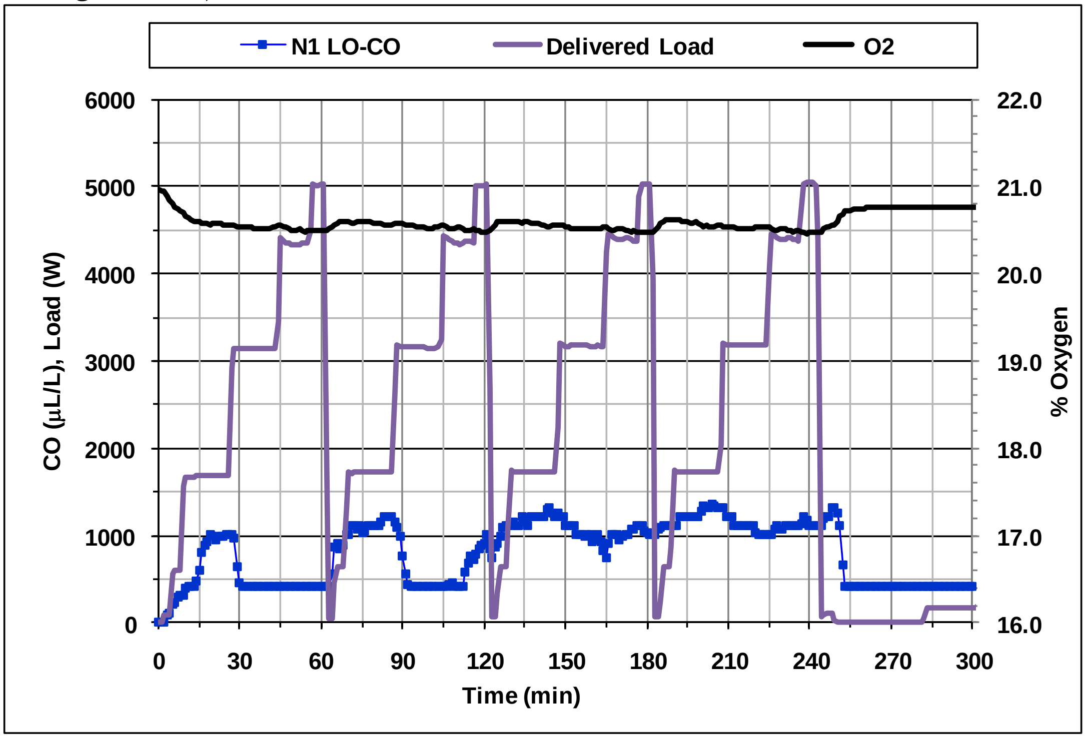
Figure 5c Temperatures and AFR measured on Gen SO1 in Test N (Gen SO1, Configuration 1)



The AFR and temperatures measured on Gen SO1 during Test N are shown in Figure 5c. With the exception of two periods of AFR excursion after the engine warmed up (i.e., after approximately 10 min), the engine operated at the calibrated AFR as the oxygen level dropped. The spike in AFR at the end of the test corresponds to when the engine was turned off.

Figures 6a and 6b show the results for Test F, which was a four hour test of unmod Gen X with Configuration 2 (garage bay door open, garage access door to house closed, and the house central HVAC fan off). After the generator was stopped, the garage concentration was allowed to naturally decay for one hour before the garage and house were mechanically vented.

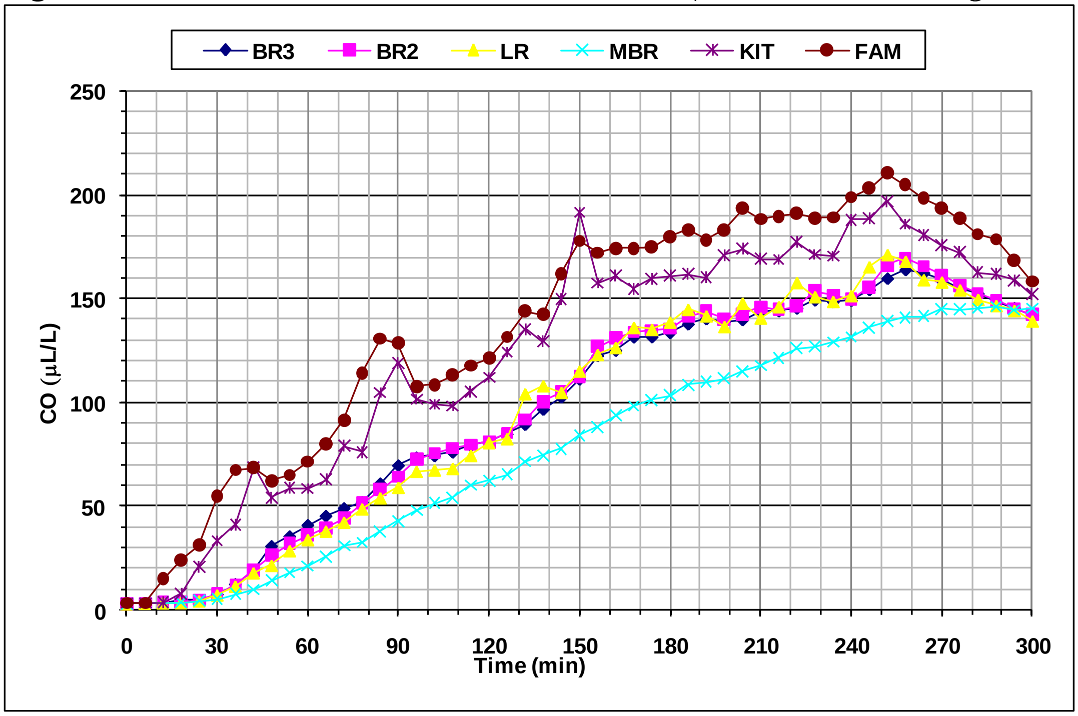
Figure 6a CO and O_2 concentrations in the garage and measured load for Test F (unmod Gen X, Configuration 2)



The garage CO concentration peaked during each load cycle during the 1500 W load bank setting. The peak concentration rose slightly in each load cycle, reaching a maximum concentration near 1500 µL/L in the fourth load cycle. For this test, the garage was not instrumented with a low concentration CO analyzer, and the instrument uncertainty is large relative to measured concentrations below 500 µL/L.

During the course of this test, with the garage bay door open, the oxygen level dipped only slightly, down by 0.5 % to 20.5 %, the delivered electrical output was consistent during each cycle, largely meeting the load bank setting with the exception of the 5500 W setting.

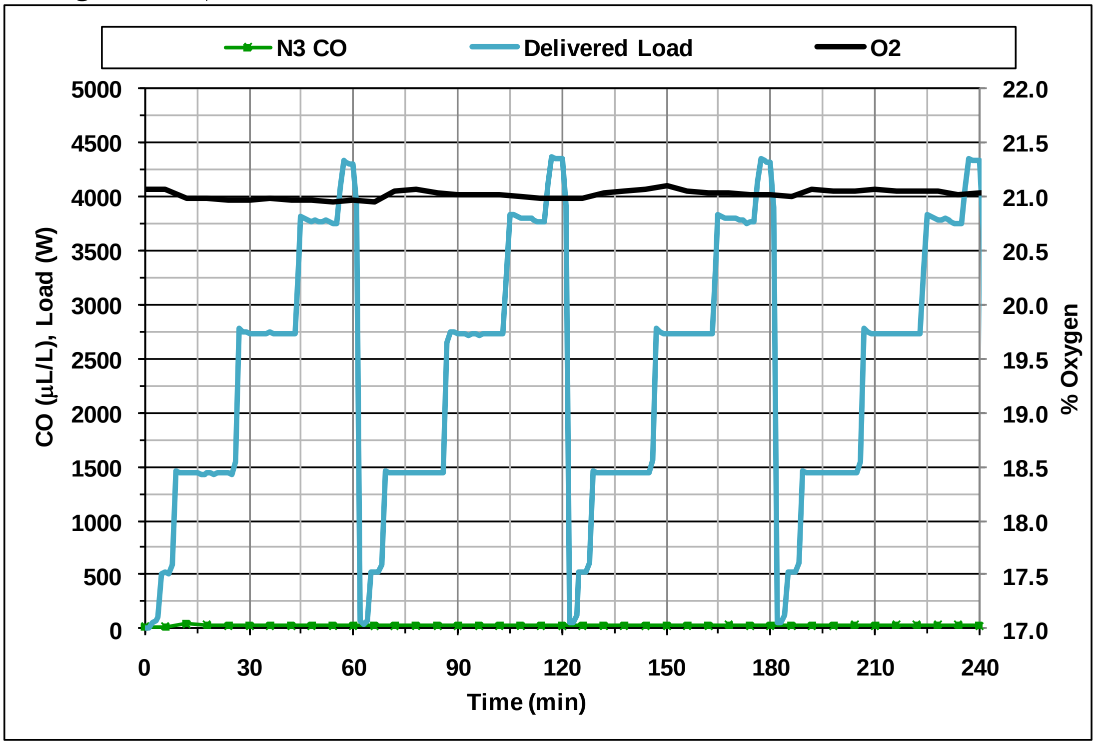
Figure 6b CO concentrations in the house for Test F (unmod Gen X, Configuration 2)



As shown in Figure 6b, the maximum house CO concentration was measured in the family room at just over 200 µL/L about 15 min after the generator was stopped after a 4 h runtime. The master bedroom had the lowest peak concentration among all the rooms, reaching just over 150 µL/L about 30 min after the generator was stopped.

Figures 7a, 7b, and 7c show the results for Test R, which was a four hour test of mod Gen X with the same test house configuration as used in Test F of unmod Gen X (Configuration 2). Mechanical venting was initiated right after the generator was stopped.

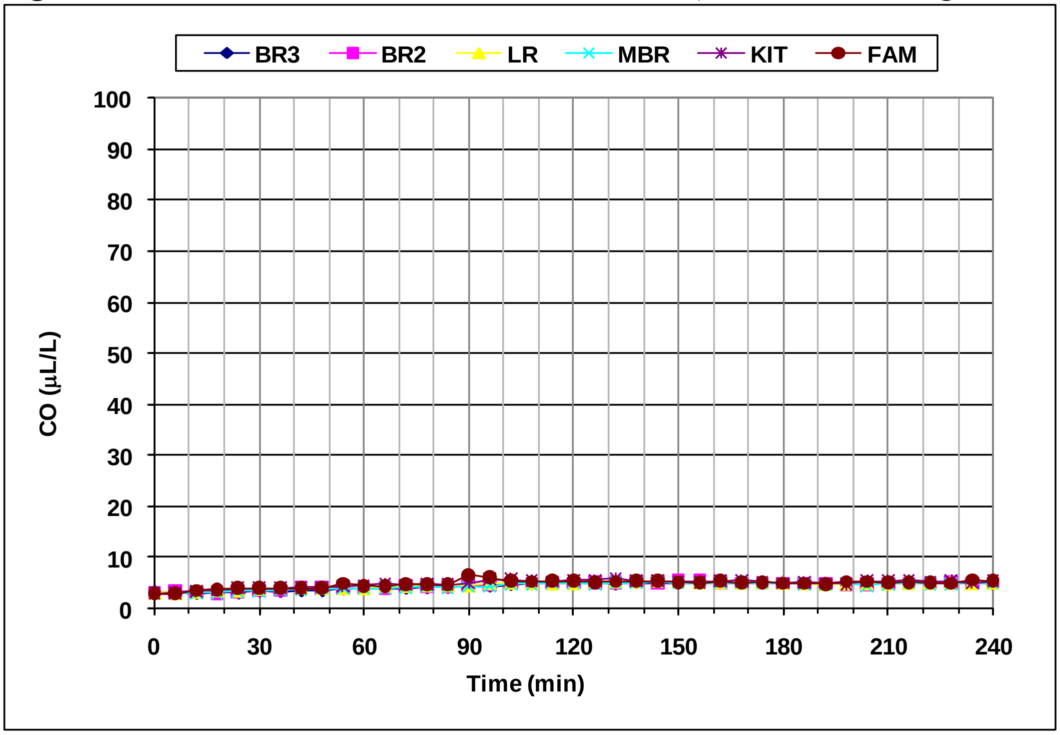
Figure 7a CO and O_2 concentrations in the garage and measured load for Test R (mod Gen X, Configuration 2)



As seen in Figure 7a, the garage CO concentration was nominally steady at 30 µL/L (though the uncertainty of the instrument is large relative to this level) and the oxygen stayed nominally at ambient throughout the test. This is about a 98 % reduction in CO compared to the nearly 1500 µL/L measured with unmod Gen X in Test F.

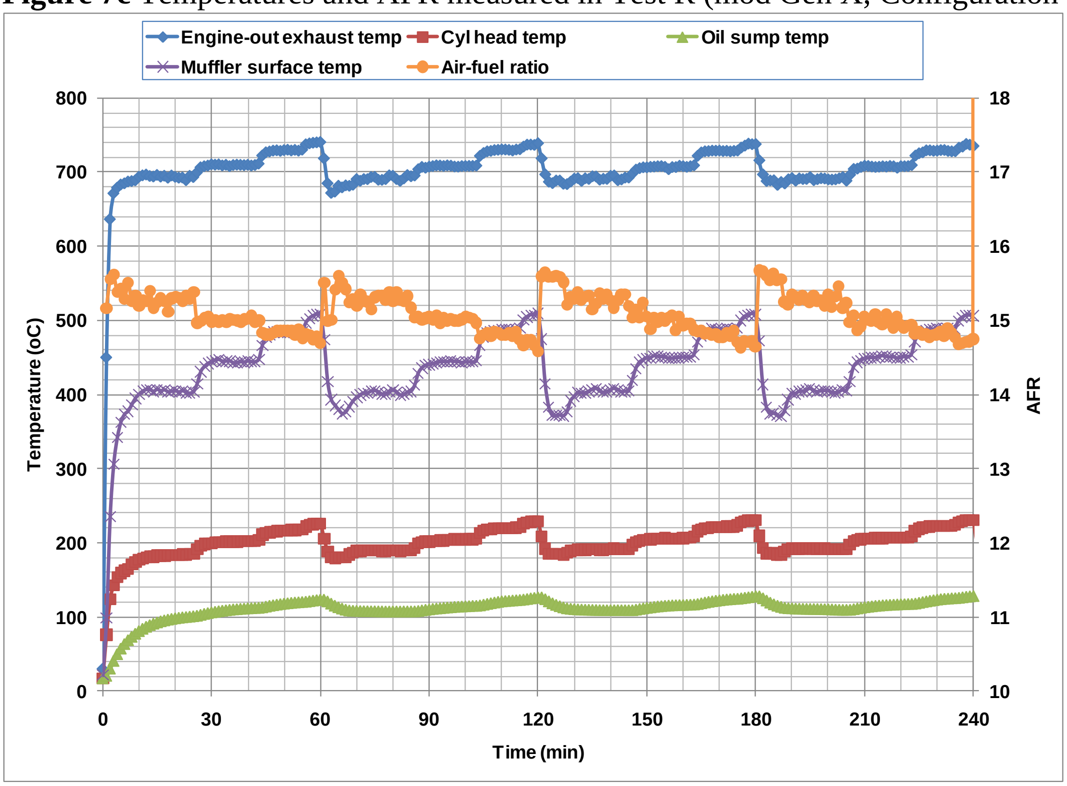
The delivered electrical output was less than the load bank settings for the three highest loads in the load cycle, which occurred with no significant oxygen depletion. After this test, the unit was thoroughly inspected, including the wiring between the generator head and the 240-volt receptacle (in UA's development of the prototype, they observed on several occasions that these wires and associated connector melted), but no anomalies were found.

Figure 7b CO concentrations in the house for Test R (mod Gen X, Configuration 2)



The CO concentration throughout the house was nominally steady at 5 µL/L (though the instrument uncertainty is large relative to this concentration) in all rooms throughout the test. By comparison, unmod Gen X in Test F produced a maximum CO concentration in the family room at just over 200 µL/L. a reduction of around 98 %.

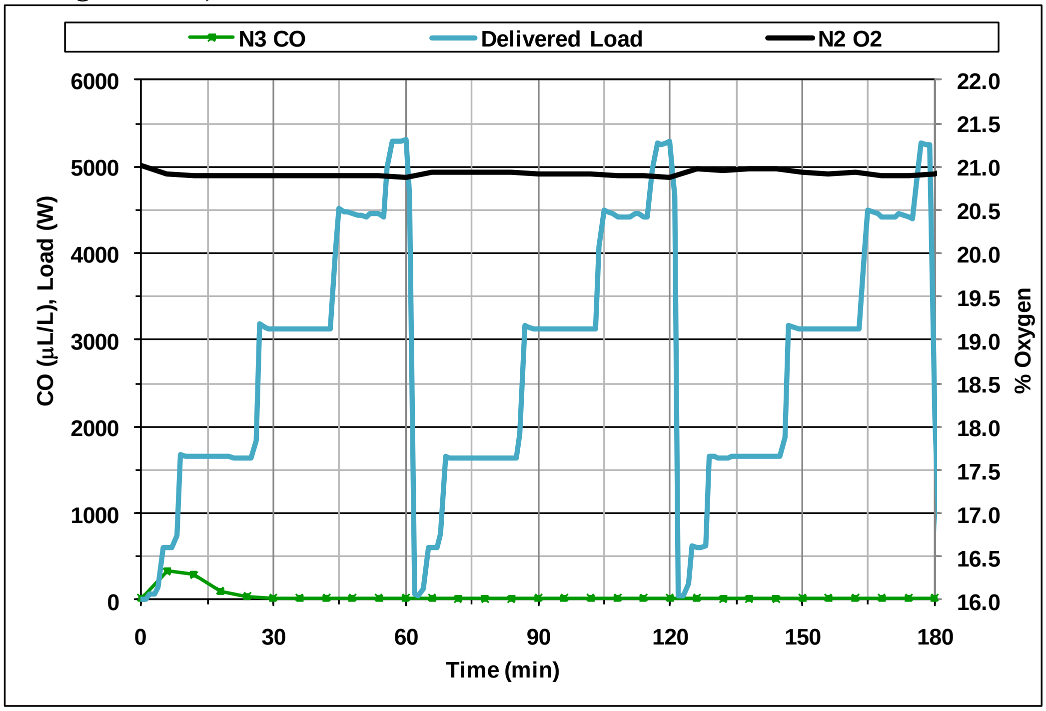
Figure 7c Temperatures and AFR measured in Test R (mod Gen X, Configuration 2)



The AFR and temperatures measured on modGen X during Test R are shown in Figure 7c. During each load cycle, the engine primarily ran lean, with the AFR ranging from about 14.5 to 15.6. The spike in AFR at the end of the test corresponds to when the engine was turned off.

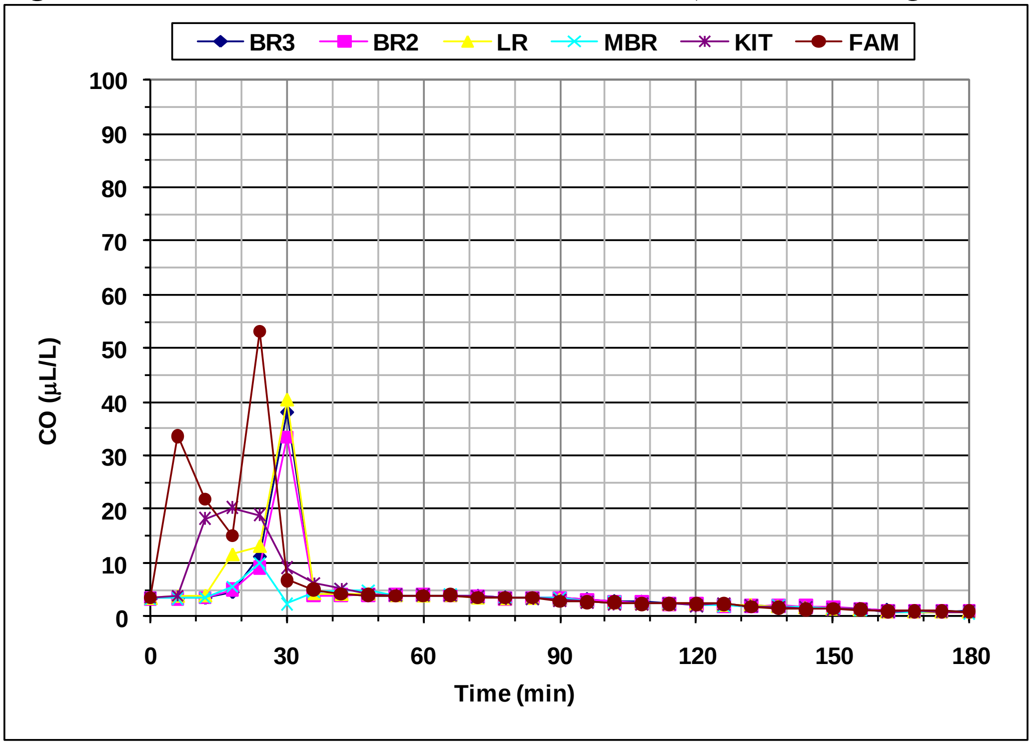
Figures 8a, 8b, and 8c show the results for Test T, which was a three hour test of Gen SO1 with the same test house configuration as used in Test F and Test R of unmod Gen X (Configuration 2). The generator was stopped when a circuit breaker on the 240-volt receptacle tripped. Mechanical venting was initiated right after the generator was stopped.

Figure 8a CO and O_2 concentrations in the garage and measured load for Test T (Gen SO1, Configuration 2)



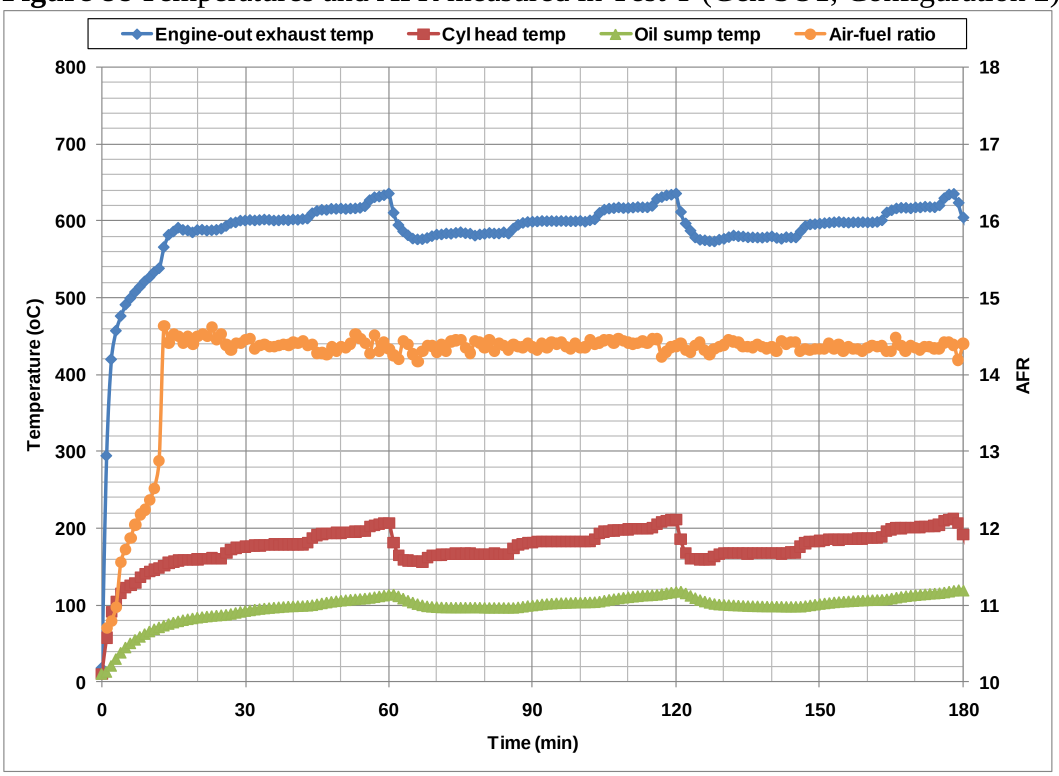
As shown in Figure 8a, there was an initial spike of CO in the garage of over 300 µL/L when the engine was started and as the oil warmed before operation transitioned to the calibrated AFR. The CO concentration then dropped and maintained a nominal level of about 20 µL/L (though the uncertainty of the instrument is large relative to this level) throughout the test. With the garage bay door open, the garage oxygen level stayed nominally at ambient. With the exception of the early peak, this CO concentration is over a 98 % reduction compared to the peak garage CO measured with unmod Gen X in Test F. Throughout the test, the delivered electrical output was consistent during each cycle, largely meeting the load bank setting with the exception of the 5500 W setting. Comparing the performance of mod Gen X (Figure 7a) and Gen SO1 (Figure 8a) shows that, for Configuration 2, both generators resulted in similar low CO concentrations after an initial spike in Test T.

Figure 8b CO concentrations in the house for Test T (Gen SO1, Configuration 2)



As shown in Figure 8b, an initial spike of CO exceeding 50 µL/L was measured in the family room about 25 min after the generator was started, but 5 min after that it dropped below 10 µL/L and continued to drop for the remainder of the test. By comparison, unmod Gen X in Test F produced a maximum CO concentration in the family room at just over 200 µL/L.

Figure 8c Temperatures and AFR measured in Test T (Gen SO1, Configuration 2)



The AFR and temperatures measured on Gen SO1 during Test T are shown in Figure 8c. The engine operated at the calibrated AFR after the engine oil temperature warmed to about 70 °C (158 °F).

After this series of tests was conducted, due to limitations in the test program that would not support continued testing of both prototypes, a decision was made to continue the testing with the newer prototype Gen SO1 for drawing comparisons between performance of the prototype and stock generator.

Figures 9a, 9b, and 9c show the results for Test I, which was a four hour test of unmod Gen X in Configuration 3 (garage bay door closed, garage access door to house open two inches, and the house central HVAC fan on). These conditions are similar to the three hour Test B with unmod Gen X except for the HVAC fan status. Since the operation of HVAC fan primarily affects the airflow between rooms in the house and is not expected to significantly impact the airflow between the house and garage, this allows a comparison to be made for the resulting garage CO and oxygen levels between Tests I and B. After the generator was stopped, the exhaust naturally decayed for one hour before the garage and house were mechanically vented.

Figure 9a CO and O_2 concentrations in the garage and measured load for Test I **(**unmod Gen X, Configuration 3)

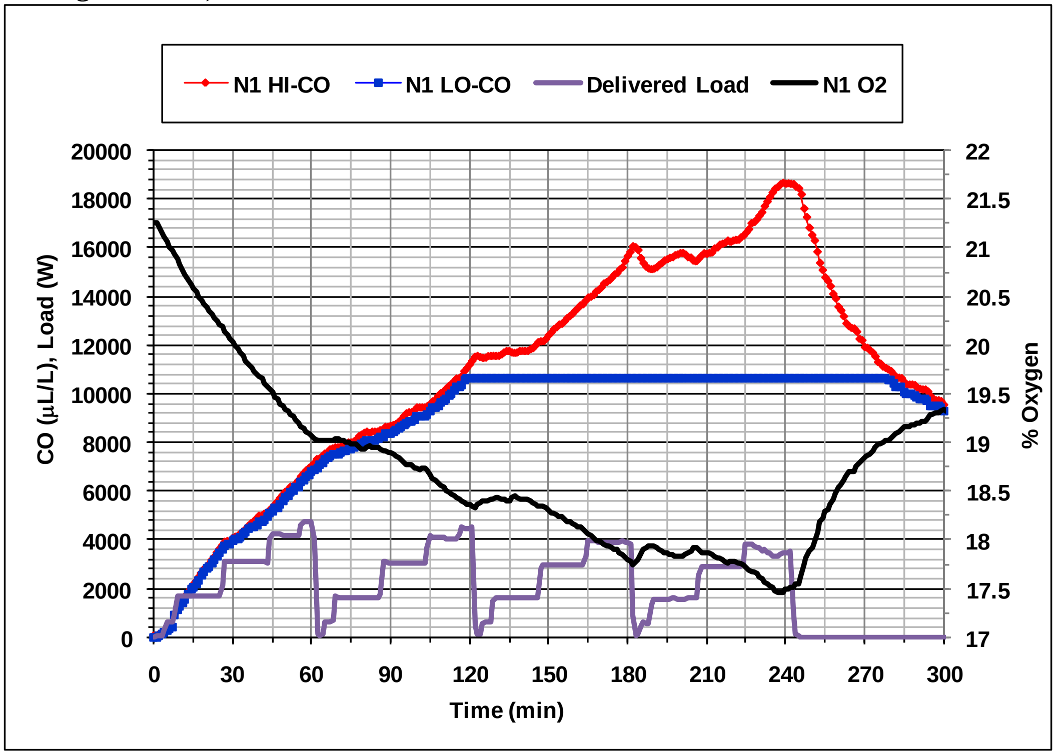


Figure 9a shows that the concentration of CO in the garage reached a peak of about 18,600 µL/L and the concentration of O_2 in the garage dropped by 3.7 % to 17.5 % when the generator was stopped. It also shows that in the first load cycle the delivered electrical output was less than the load bank settings for the two highest loads in the load cycle, 4500 W and 5500 W, which were applied as the oxygen was approaching 19 %. As the oxygen continued to drop in the subsequent load cycles, the delivered power for these load points decreased further. These results are fairly similar to those in Test B.

Figure 9b CO (ppm range) concentrations in the house for Test I **(**unmod Gen X, Configuration 3)

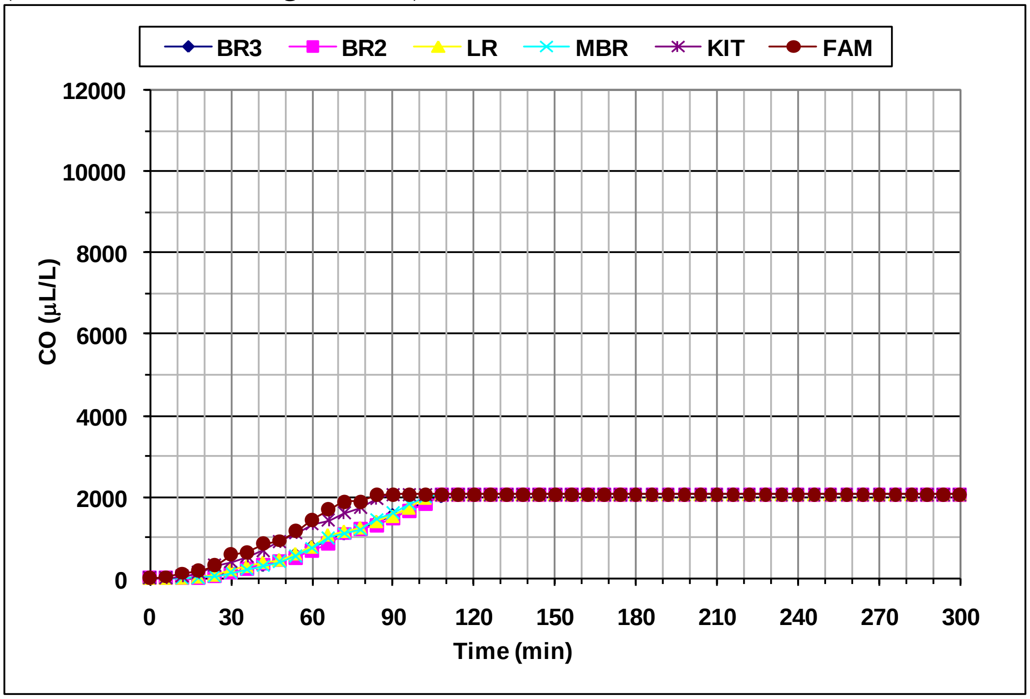
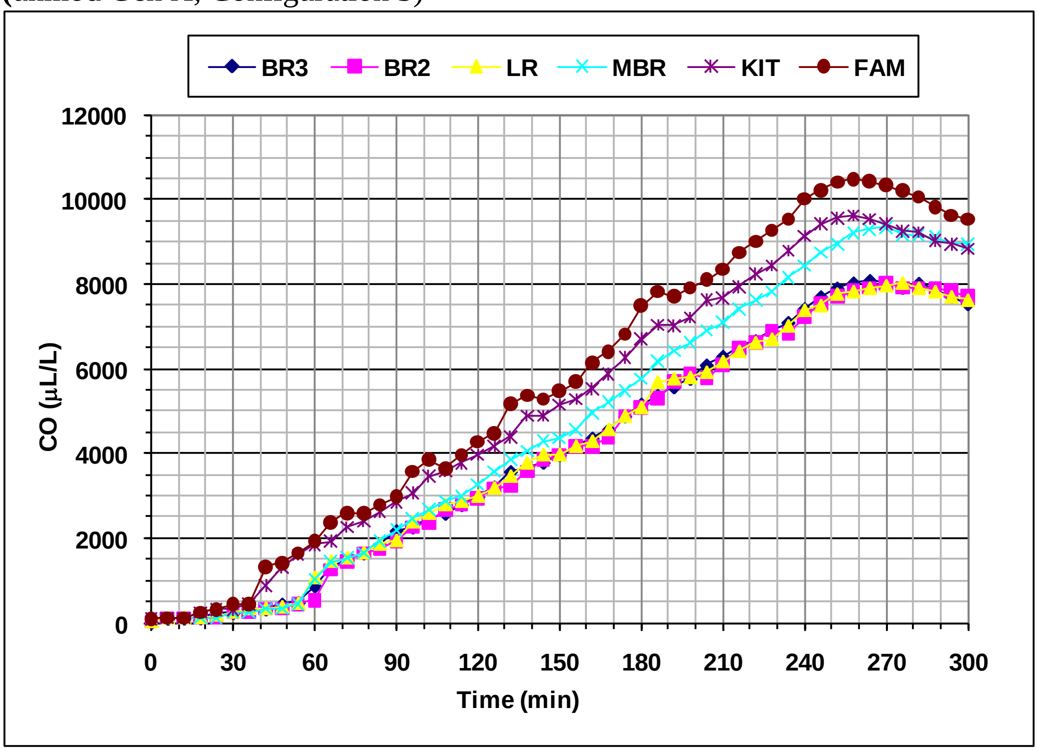


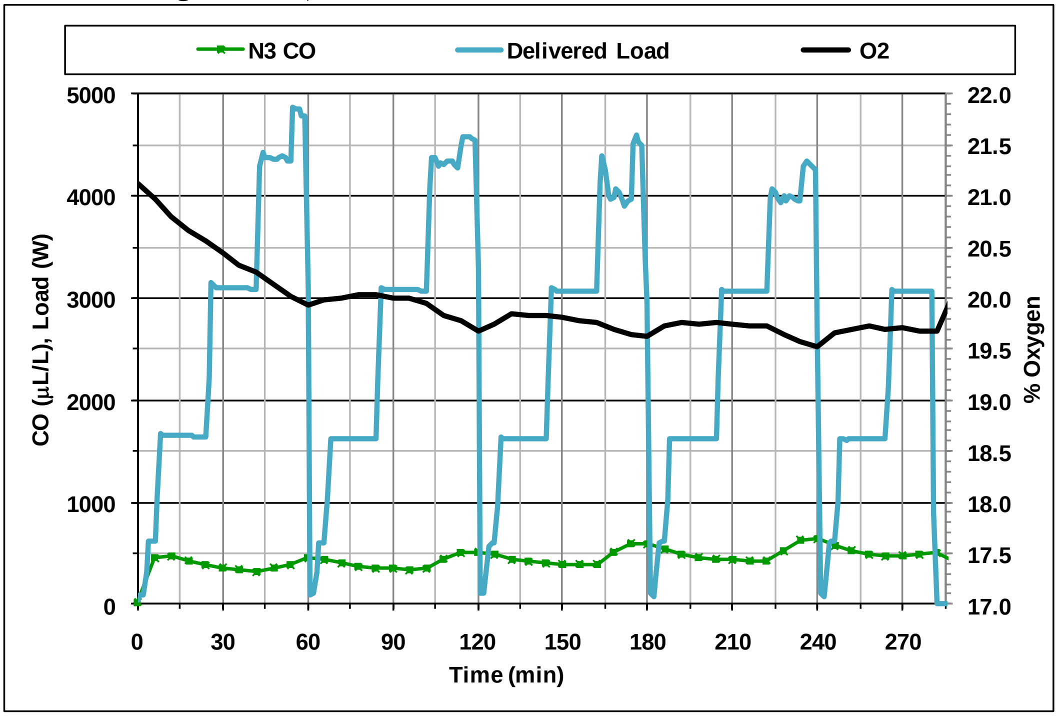
Figure 9c CO (high range) concentrations in the house for Test I **(**unmod Gen X, Configuration 3)



Figures 9b and 9c show the CO concentration in the rooms of the test house, as measured in the 'ppm range' (where the CO concentration plot plateaus at the instrument's 2000 μL/L limit) and with 'high range' CO instruments, respectively. The CO reached a peak concentration of around 10,500 μL/L in the family room, with peak concentrations in the other rooms ranging from about 8,200 μL/L to 10,000 μL/L. With the HVAC fan on in this test, there is a relatively more uniform distribution of CO compared to Test B in which the HVAC fan was off.

Figures 10a, 10b, and 10c show the results for Test Z, which was a 4.75 h test of Gen SO1 with the noncat muffler (Configuration 3). The test ended when the generator ran out of fuel. (Note: this run time does not indicate a limit on potential run-time as the tank was not full at the beginning of the test.) The test house configuration conditions are the same as that in the 4 h Test I with unmod Gen X. They are also the same as that used in the 2 h Test N with Gen SO1 except that the HVAC fan was off in Test N and Gen SO1 had the catalyst-installed muffler (referred to as catmuffler). Since the operation of the HVAC fan primarily affects the airflow between rooms in the house and is not expected to significantly impact the airflow between the house and garage, the effect of the catalytic and non-catalytic muffler on the resulting garage CO and oxygen levels between Tests Z and N (Configuration 3 and 1, respectively) up to the 2 h point can be seen. After the generator was stopped, the garage and house were mechanically vented.

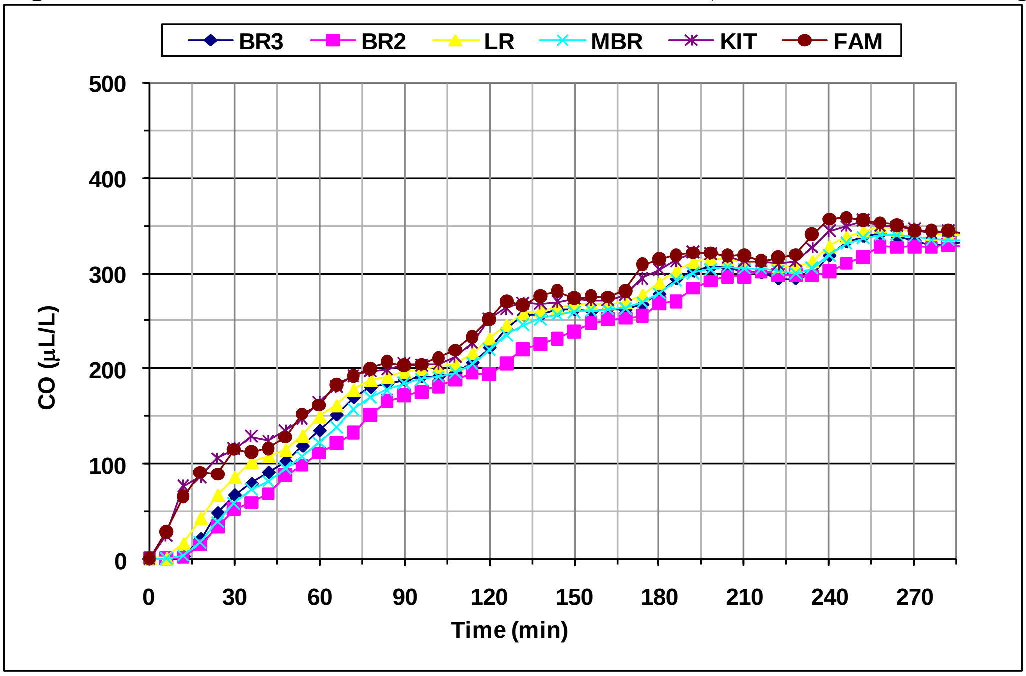
Figure 10a CO and O_2 concentrations in the garage and measured load for Test Z **(**Gen SO1 noncat, Configuration 3)



As shown in Figure 10a, the CO concentration in the garage initially rose to about 470 μL/L upon start, then lowered after the engine warmed up. It further increased and decreased cyclically with each successive load cycle. By the end of the fourth load cycle, it had reached a nominal peak of 630 μL/L and the oxygen dropped 1.6 % to 19.5%. This peak CO concentration is a 97 % reduction compared to that measured with unmod Gen X in Test I in which the garage CO reached about 18,600 μL/L at the end of the fourth load cycle.

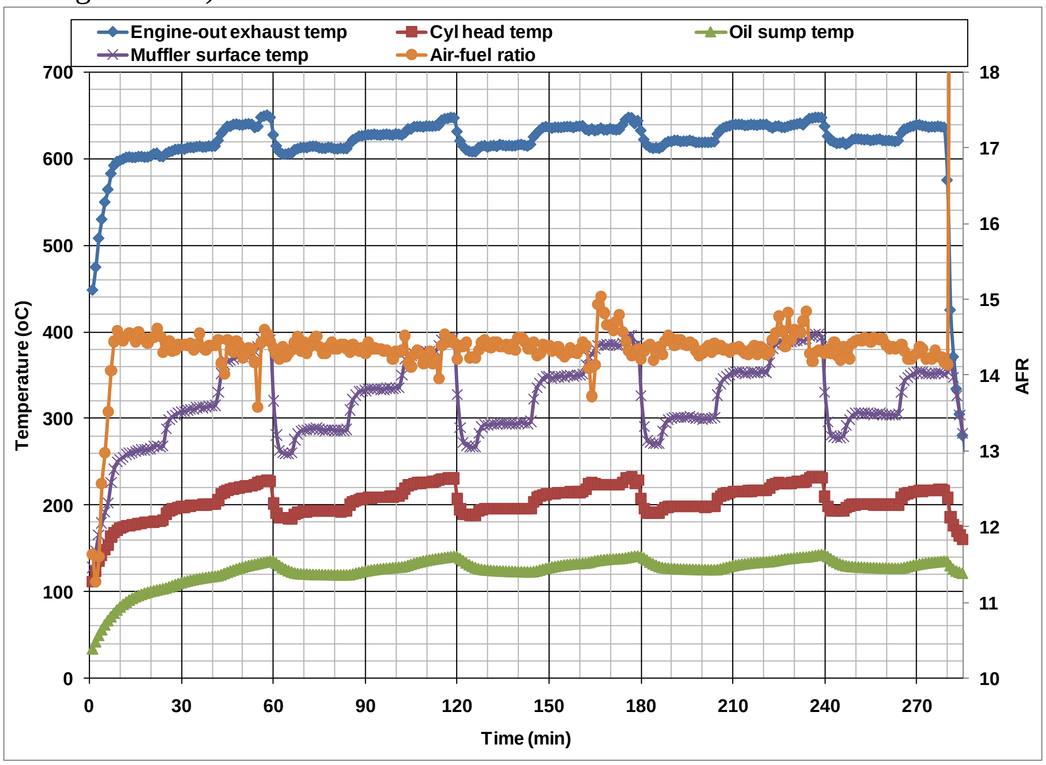
Figure 10a also shows that the delivered electrical output was progressively less than the load bank settings for the two highest loads in the load cycle as the oxygen dropped throughout the test.

Figure 10b CO concentrations in the house for Test Z **(**Gen SO1 noncat, Configuration 3)



As shown in Figure 10b, the CO concentration reached a peak of nominally 360 µL/L at 4 h in the family room. There is a relatively even distribution (with all the rooms reaching at least 300 µL/L) as would be expected with the HVAC fan on. By comparison, unmod Gen X in Test I produced a peak CO concentration of around 10,600 µL/L in the family room with peak concentrations in the other rooms ranging from about 8,200 µL/L to 10,000 µL/L.

Figure 10c Temperatures and AFR measured on Gen SO1 in Test Z **(**Gen SO1 noncat, Configuration 3)

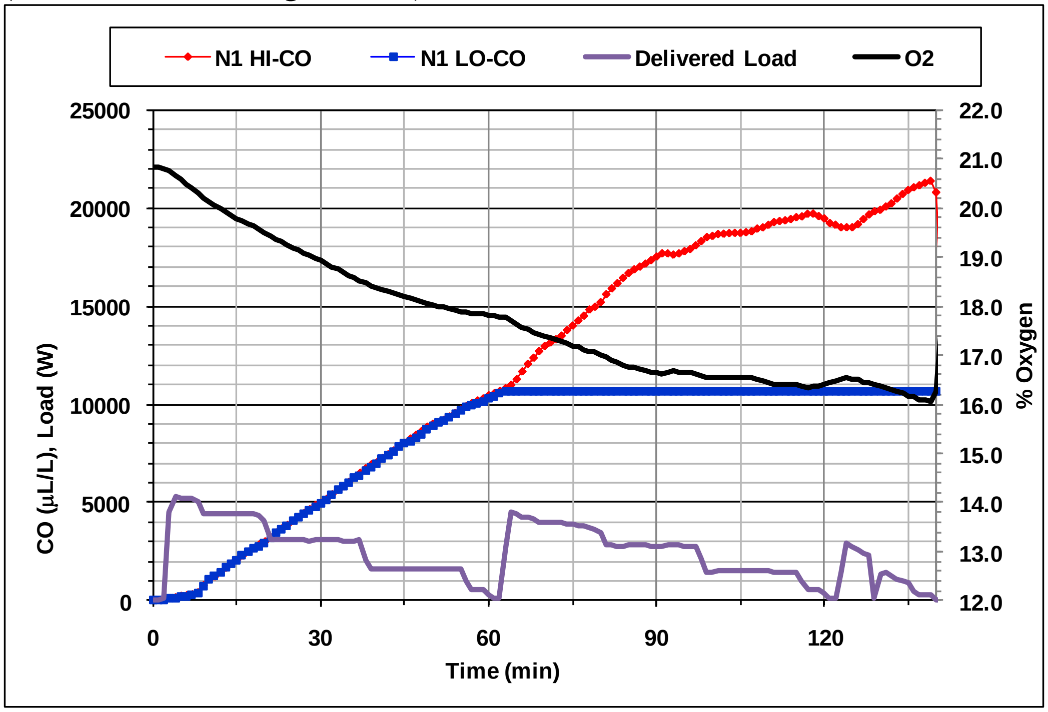


The AFR and temperatures measured on Gen SO1 during Test Z are shown in Figure 10c. With the exception of a few short periods of AFR excursion after the engine warmed up, the engine operated at the calibrated AFR. The spike in AFR at the end of the test corresponds to when the engine was turned off.

Since engine operation was, by and large, comparable between Test Z and Test N, which were with Gen SO1 and the catmuffler, the garage CO concentrations at the same time in each test can be compared to get an indication of the catalyst's performance in further lowering the CO emissions. At 2 h into Test Z, the garage CO concentration was 500 μL/L and the oxygen was 19.7 %. By comparison, at the end of the 2 h Test N, the garage CO concentration reached a peak of around 300 μL/L and the garage O_2 concentration dropped to 19.4 %. Therefore, the resulting CO concentrations were approximately 40 % lower for Test Z with the catalyst than for Test N with the EMS alone. An unknown portion of the difference may be due to differences in ambient or other test conditions.

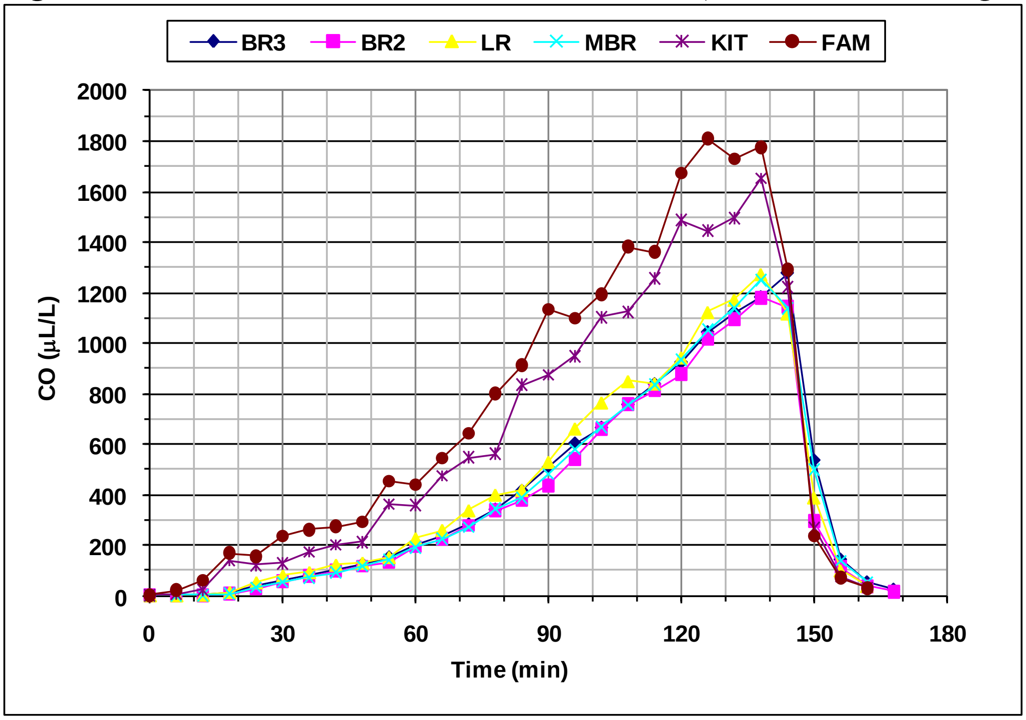
Figures 11a and 11b show the results for the two and a quarter hour test of unmod Gen X, Test J, in Configuration 4 (garage bay door closed, garage access door to house closed, and the house central HVAC fan on). After the generator was stopped, the garage was mechanically vented. For this test, the load cycle was applied in reverse order to that shown in Table 1.

Figure 11a CO (high range) and O_2 concentrations in the garage and measured load for Test J (unmod Gen X, Configuration 4)



As shown in Figure 11a, at the time the generator was stopped, the garage CO concentration reached a peak of over 21,300 µL/L and the oxygen dropped by 4.7 % to about 16 %. It also shows that in the first load cycle, the delivered electrical output matched the load bank settings with the exception of the 5500 W setting. However, during the third load cycle, as the oxygen level dropped significantly, the generator's ability to meet the load was severely compromised and the test was ended due to poor generator operation.

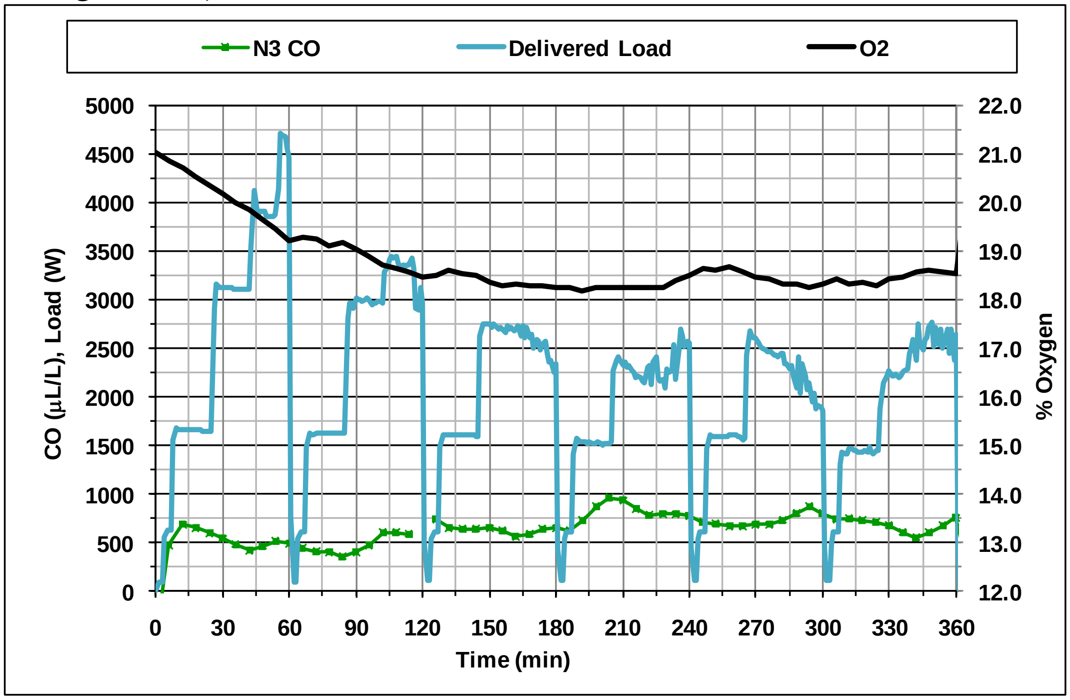
Figure 11b CO concentrations in the house for Test J **(**unmod Gen X, Configuration 4)



As shown in Figure 11b, the CO reached a peak concentration of about 1,800 µL/L in the family room with peak concentrations in the other rooms ranging from about 1,250 µL/L to 1,650 µL/L.

Figures 12a, 12b, and 12c show the results for a six hour test of Gen SO1, Test W, with the same test house configuration as used in Test J of unmod Gen X (Configuration 4). The load cycle was applied with the same profile as that in Table 1, with the load going from low to high. After the generator was stopped, the garage was mechanically vented.

Figure 12a CO and O_2 concentrations in the garage and measured load for Test W **(**Gen SO1, Configuration 4)

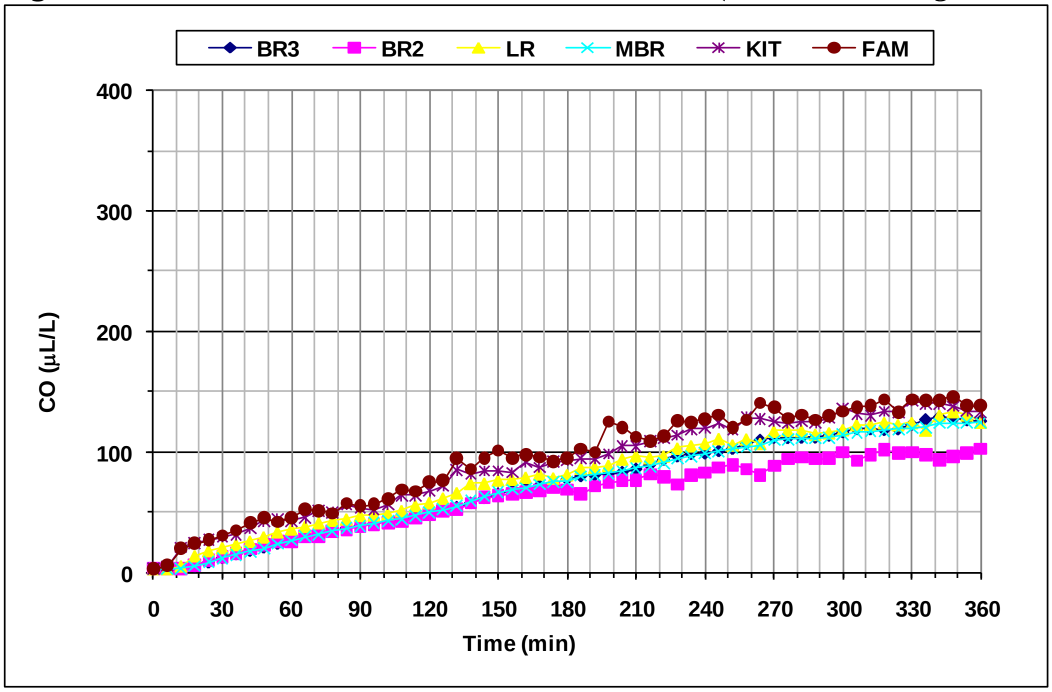


As shown in Figure 12a, the CO concentration in the garage initially rose to 680 µL/L, and then decreased after the engine warmed up. In the fourth load cycle, it reached a peak of about 960 µL/L and the oxygen lowered by 2.8 % to 18.2 %.

At two and one quarter hours into this test, the garage CO concentration was nominally 640 µL/L. Although the tests were not entirely comparable due to the opposite loading pattern, this CO concentration is a 97 % reduction compared to that measured with unmod Gen X in Test J in which the garage CO was over 21,300 µL/L at the same time during the test.

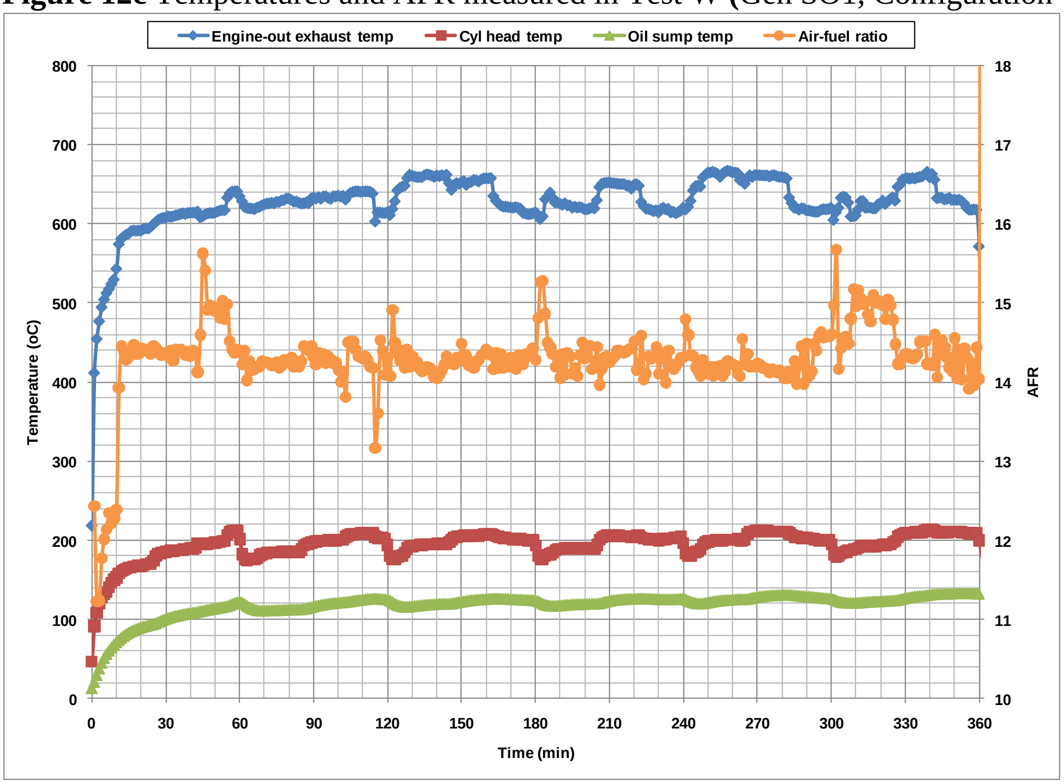
In the first load cycle, the delivered electrical output exceeded the load bank settings except for the two highest loads. In the subsequent load cycles, as the oxygen level dropped, the delivered power was less than the load bank settings for the three highest loads in the cycle.

Figure 12b CO concentrations in the house for Test W **(**Gen SO1, Configuration 4)



As shown in Figure 12b, the CO reached a peak concentration of about 145 µL/L in the family room with peak concentrations in the other rooms relatively evenly distributed just below that, down to 100 µL/L. By comparison, unmod Gen X in Test J produced a peak CO concentration of over 1,800 µL/L in the family room after 2 h of operation.

Figure 12c Temperatures and AFR measured in Test W **(**Gen SO1, Configuration 4)



The AFR and temperatures measured on Gen SO1 during Test W are shown in Figure 12c. After the engine warmed up, the engine operated at the calibrated AFR for the next 30 min. There were then occasional periods of lean as well as rich operation, with most of them occurring during the transition between the load cycles when the load bank was switched from 5500 W to no load. The spike in AFR at the end of the test corresponds to when the engine was turned off.

Figures 13a and 13b show the results for the two hour test of unmod Gen X, Test D, in Configuration 5 (garage bay door closed, garage access door to house closed, and the house central HVAC fan off). These conditions are the same as the two and a quarter hour Test J with unmod Gen X except that in that test the HVAC fan was on. Since the operation of the HVAC fan primarily affects the airflow between rooms in the house and is not expected to significantly impact the airflow between the house and garage, especially with the house door closed, this allows some degree of comparison to be made for the resulting garage CO and oxygen levels between Tests D and J. After the generator was stopped, the garage was mechanically vented.

Figure 13a CO (high range) and O_2 concentrations in the garage and measured load for Test D **(**unmod Gen X, Configuration 5)

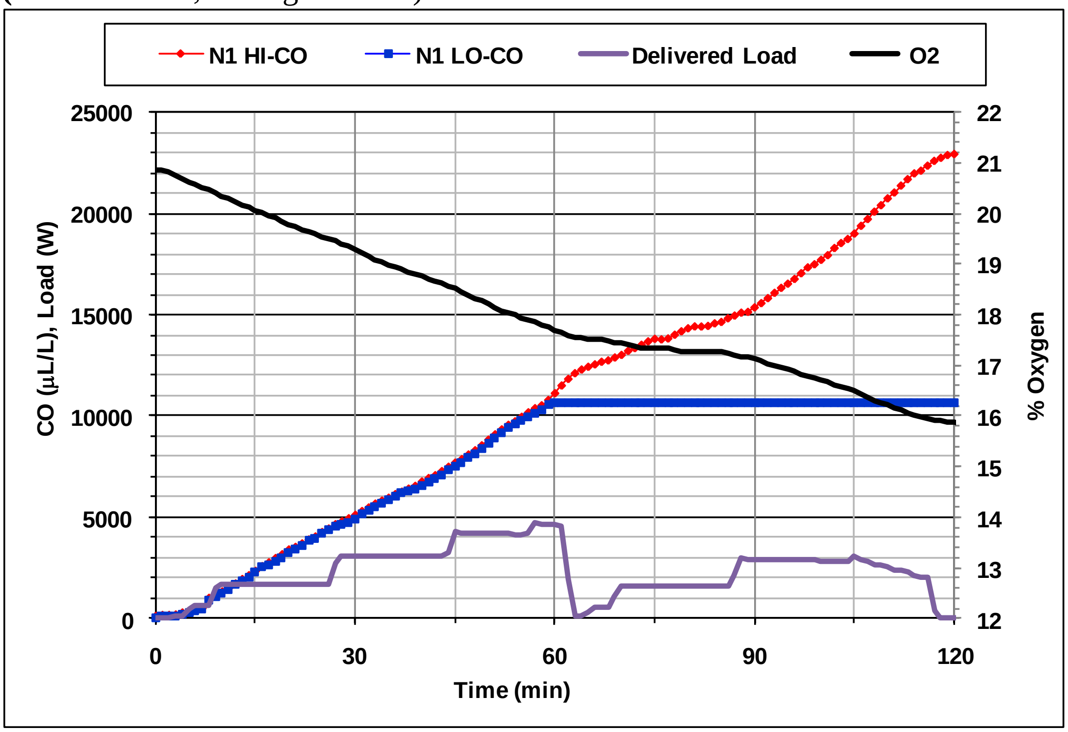


Figure 13a shows the concentration of CO in the garage reached a peak of almost 23,000 µL/L and the concentration of O_2 in the garage dropped by 5.0 % to below 16 % when the generator was stopped. It also shows that in the first load cycle the delivered electrical output was less than the load bank settings for the two highest loads in the load cycle, 4500 W and 5500 W, which were applied as the oxygen was approaching 18 %. As the oxygen continued to drop in the subsequent load cycle, the delivered power for these load points decreased further. The results are similar to those in Test J despite the reversal of the load cycled pattern in Test J.

Figure 13b CO concentrations in the house for Test D **(**unmod Gen X, Configuration 5)

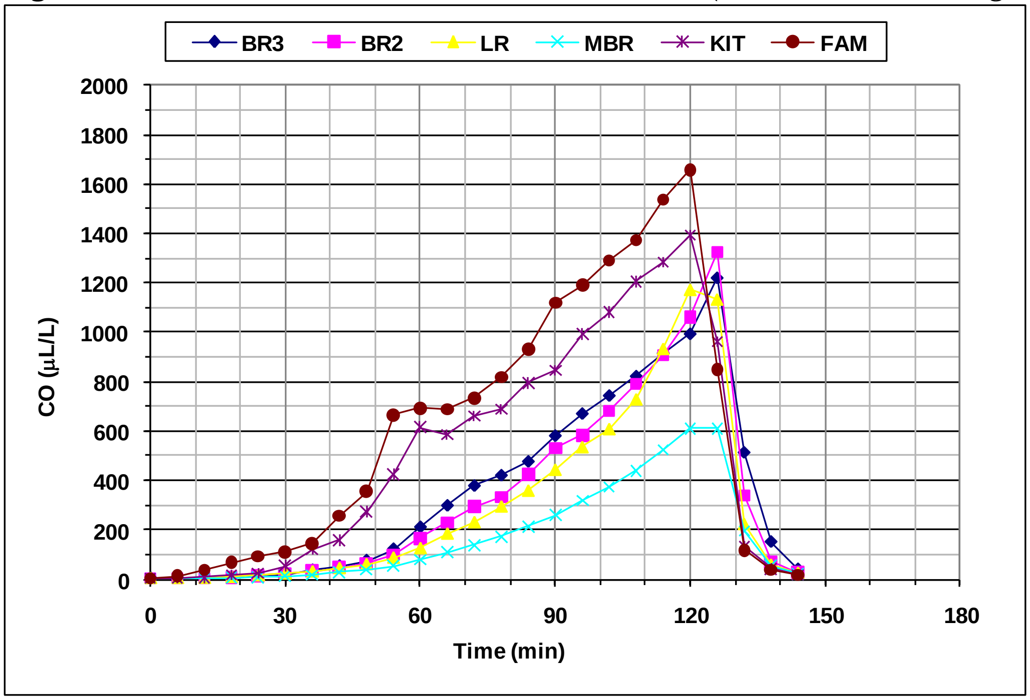
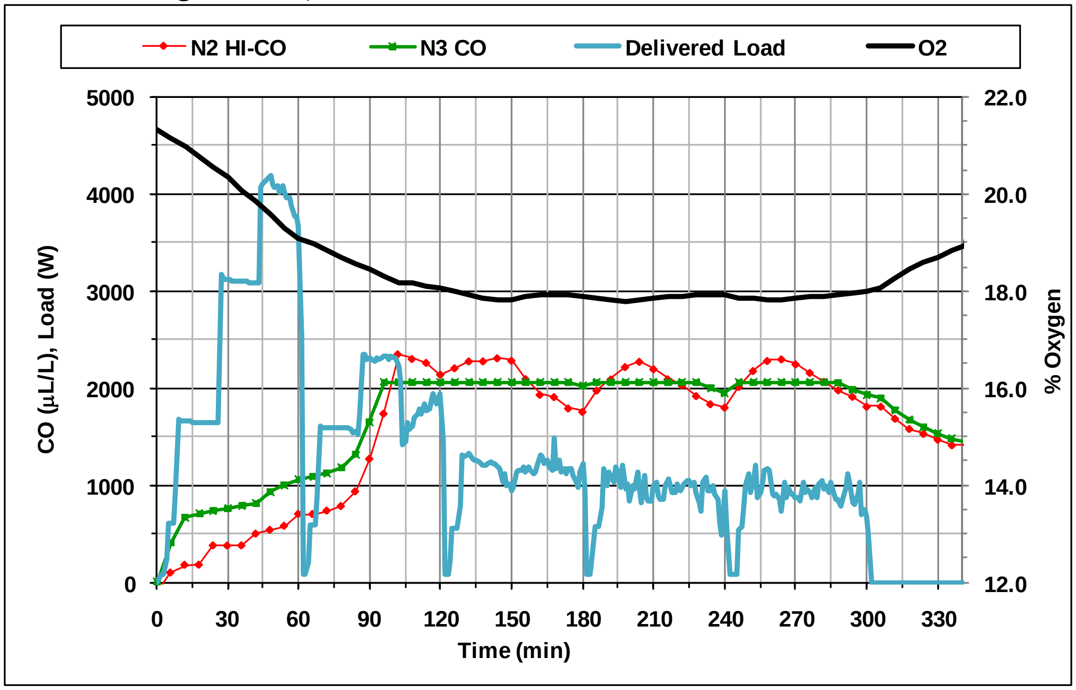


Figure 13b shows the CO reached a peak concentration of almost 1660 µL/L in the family room with peak concentrations in the other rooms ranging from about 600 µL/L to 1400 µL/L. This is a comparable peak CO concentration to the 1670 µL/L measured in the family room at the 2 h point in Test J. When comparing the other room time course profiles with those at the 2 h point in Test J, it can be observed that the mixing due to the operation of the HVAC fan made the most difference in the master bedroom. This effect is not consistent during all tests as other factors affecting mixing (such as temperatures) differ from test to test.

Figures 14a, 14b, and 14c show the results for Test AH, which was a five hour test of Gen SO1 with the noncat muffler and the same conditions of the test house as used in the 2 h Test D with unmod Gen X (Configuration 5). These conditions are also the same as that used in the 6 h Test W with Gen SO1 except that in Test W Gen SO1 had the catmuffler and the HVAC fan was on. Since the operation of the HVAC fan primarily affects the airflow between rooms in the house and has less affect on the airflow between the house and garage, especially with the house door closed, this allows some degree of comparison to be made for the resulting garage CO and oxygen levels between Tests AH and W. After the generator was stopped, the exhaust decayed naturally for 45 min and then the garage and house were mechanically vented.

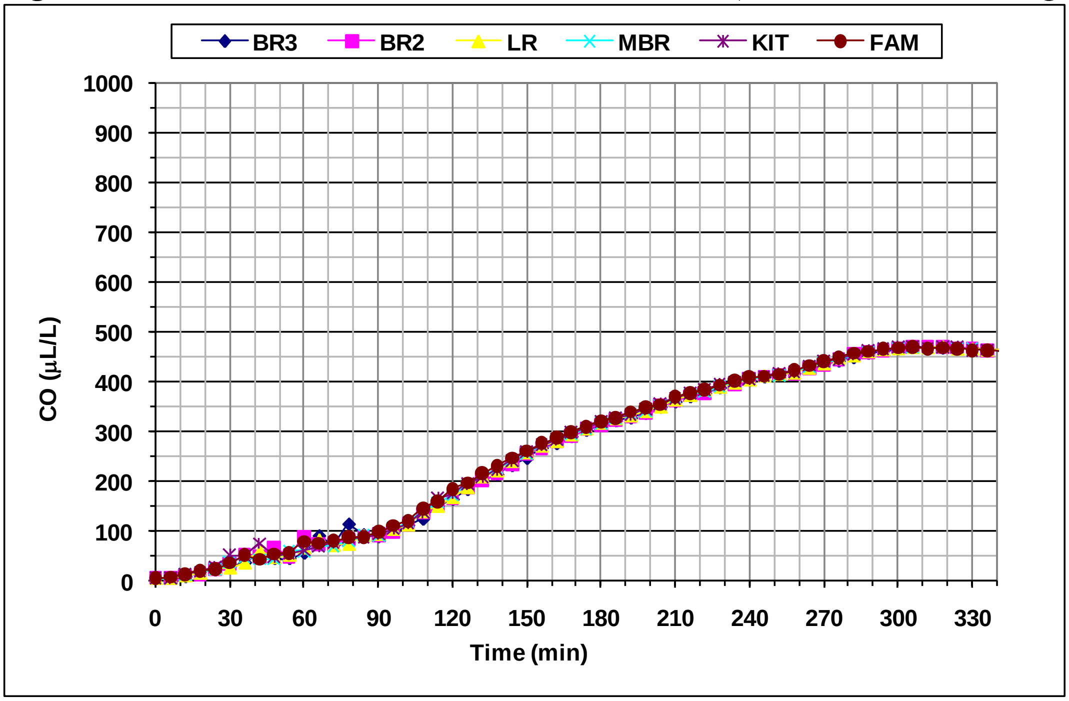
Figure 14a CO and O_2 concentrations in the garage and measured load for Test AH **(**Gen SO1 noncat, Configuration 5)



As shown in Figure 14a, the CO concentration in the garage initially rose to nominally 670 µL/L upon start, then continued to climb until it reached a nominal peak of 2300 µL/L and oxygen lowered 3.5 % to 17.8 % in the garage during the second load cycle. This CO concentration is a 90 % reduction compared to that measured with unmod Gen X in Test D in which the CO in the garage at the end of the second load cycle was almost 23,000 µL/L.

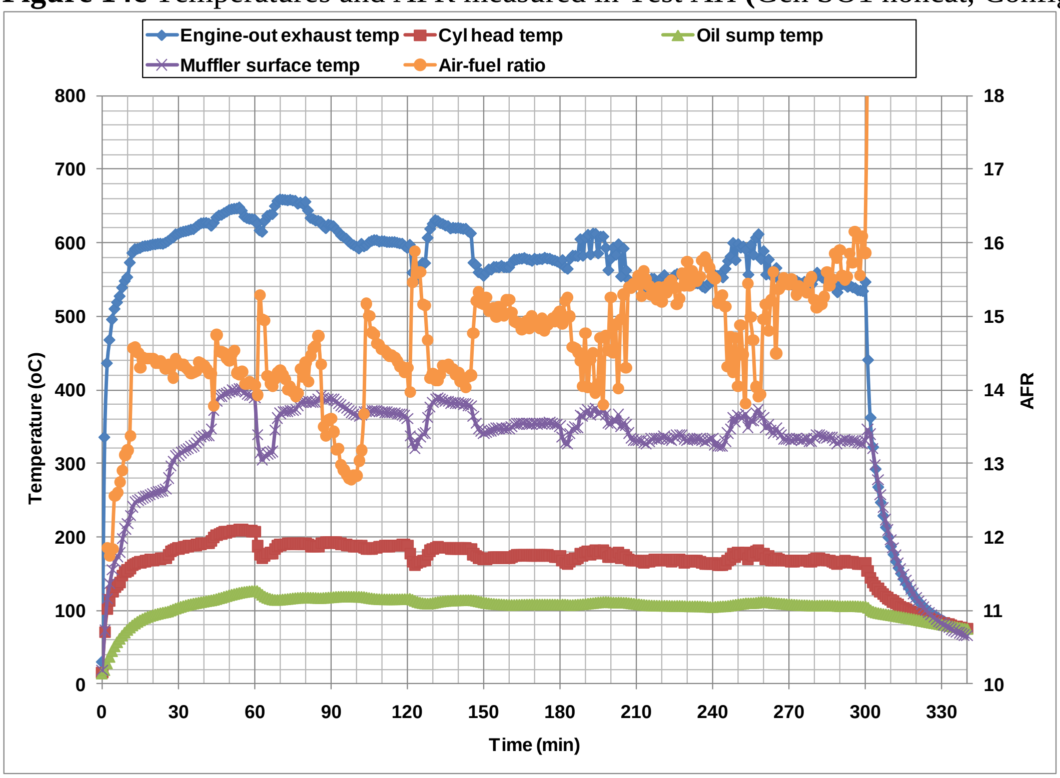
Figure 14a also shows that in the first load cycle the delivered electrical output was less than the load bank settings for the two highest loads in the load cycle. During the subsequent load cycles the delivered power degraded even further as the garage oxygen approached and then dropped below 18 %.

Figure 14b CO concentrations in the house for Test AH **(**Gen SO1 noncat, Configuration 5)



As shown in Figure 14b, the CO reached a peak concentration of about 470 µL/L throughout the house, with even distribution among the rooms even though the HVAC fan was off. At 2 h into this test, the CO in the house was about 180 µL/L. By comparison, in 2 h unmod Gen X in Test D produced a peak CO concentration of almost 1660 µL/L in the family room with peak concentrations in the other rooms ranging from about 600 µL/L to 1400 µL/L.

Figure 14c Temperatures and AFR measured in Test AH **(**Gen SO1 noncat, Configuration 5)

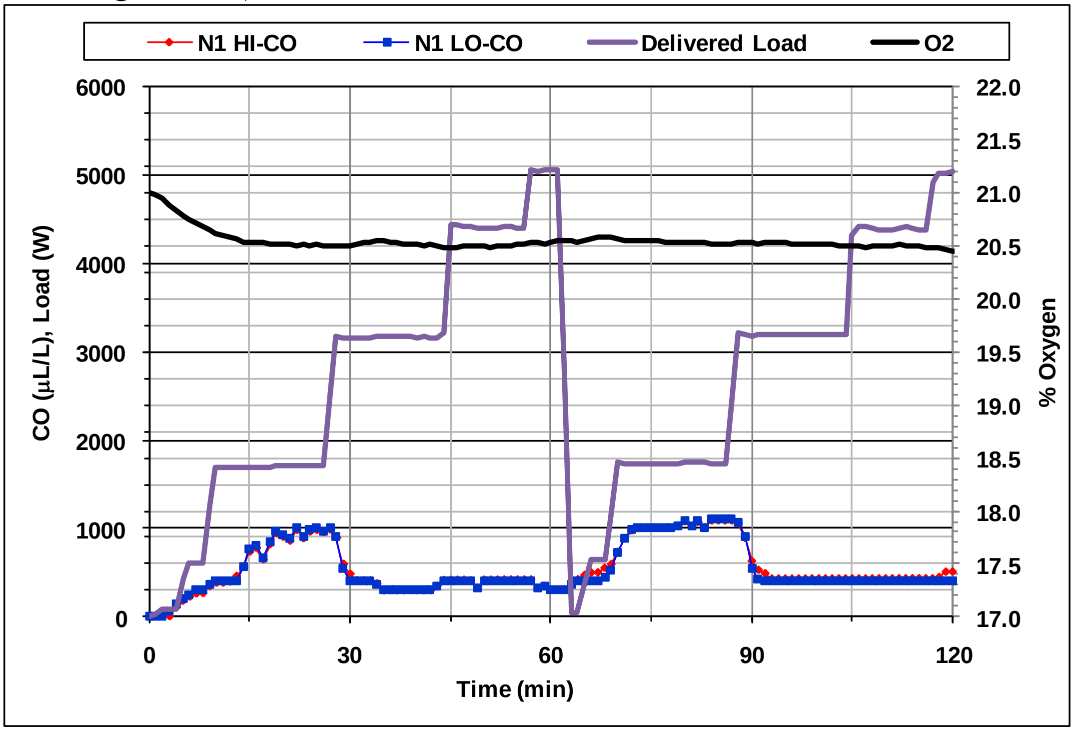


The AFR and temperatures measured on noncat Gen SO1 during Test AH are shown in Figure 14c. After the engine warmed up, it operated at the calibrated AFR for the next 30 min, but then had periods of off-design operation throughout the remainder of the test. The spike in AFR at the end of the test corresponds to when the engine was turned off.

Since engine performance during the first 40 min in Test AH was similar to that in Test W with Gen SO1 and the catmuffler, a comparison of each test's garage CO concentration at that point in time suggests the prototype's catalyst is providing about a 50 % reduction of the CO emissions compared with that provided by the EMS alone. At 40 min, the garage CO concentrations were about 410 μL/L and 820 μL/L in Tests W and AH, respectively. This reduction is somewhat larger than the 40 % reduction observed when comparing the garage CO concentrations in Tests Z and N.

Figures 15a and 15b show the results for Test G, a 2 h test of unmod Gen X in Configuration 6 (garage bay door open, garage access door to house open two inches, and the house central HVAC fan on). After the generator was stopped, the garage was mechanically vented.

Figure 15a CO and O_2 concentrations in the garage and measured load for Test G **(**unmod Gen X, Configuration 6)



As shown in Figure 15a, the CO in the garage peaked at around 1100 μL/L in the second load cycle (though the instrument uncertainty is large relative to the concentrations). With the garage bay door open, the oxygen level dipped by 0.5 % to about 20.5 %. Throughout the test, the delivered electrical output met or exceeded the load bank settings.

Figure 15b CO (ppm range) concentrations in the house for Test G **(**unmod Gen X, Configuration 6)

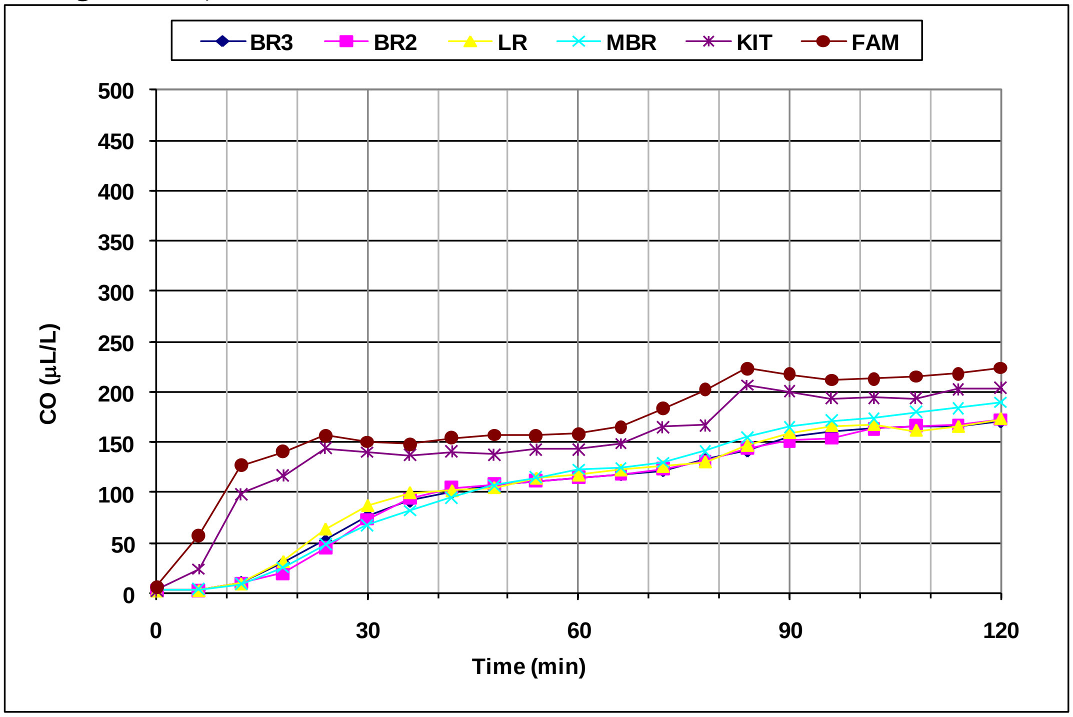
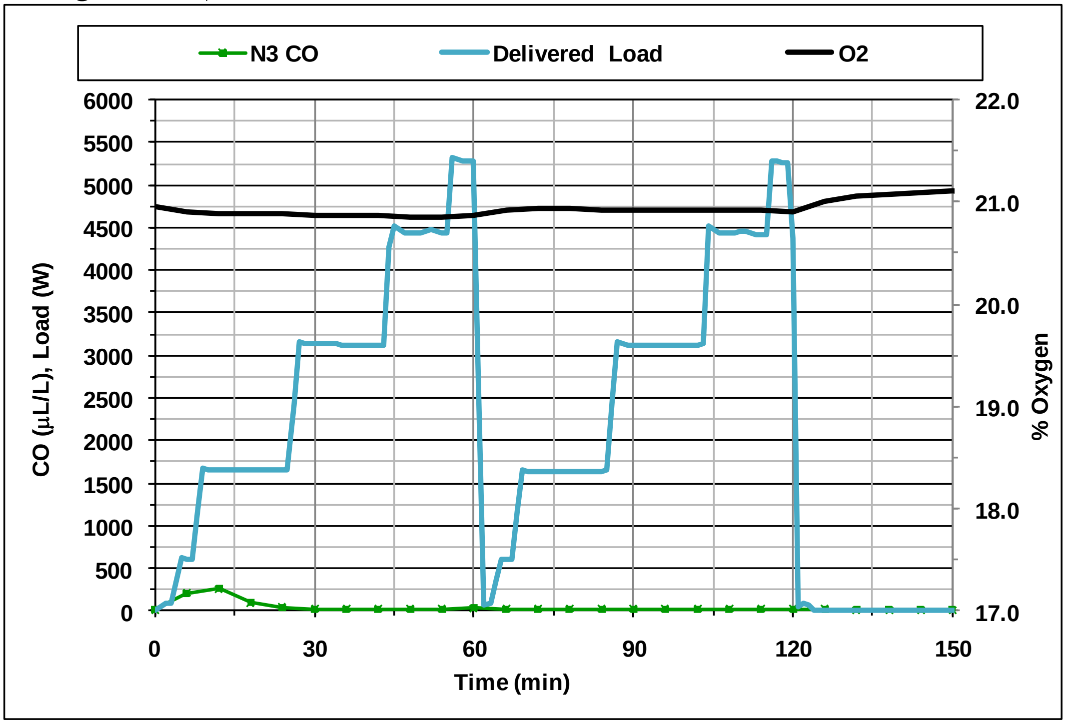


Figure 15b shows the CO reached a peak concentration of about 220 µL/L in the family room with slightly lower peak concentrations in the other rooms of around 190 µL/L to 200 µL/L.

Figures 16a, 16b, and 16c show the results for Test U, which was a 2 h test of Gen SO1 with the same conditions of the test house as used in the 2 h Test G with unmod Gen X (Configuration 6). After the generator was stopped, the exhaust decayed naturally for 30 min and then the garage and house were mechanically vented.

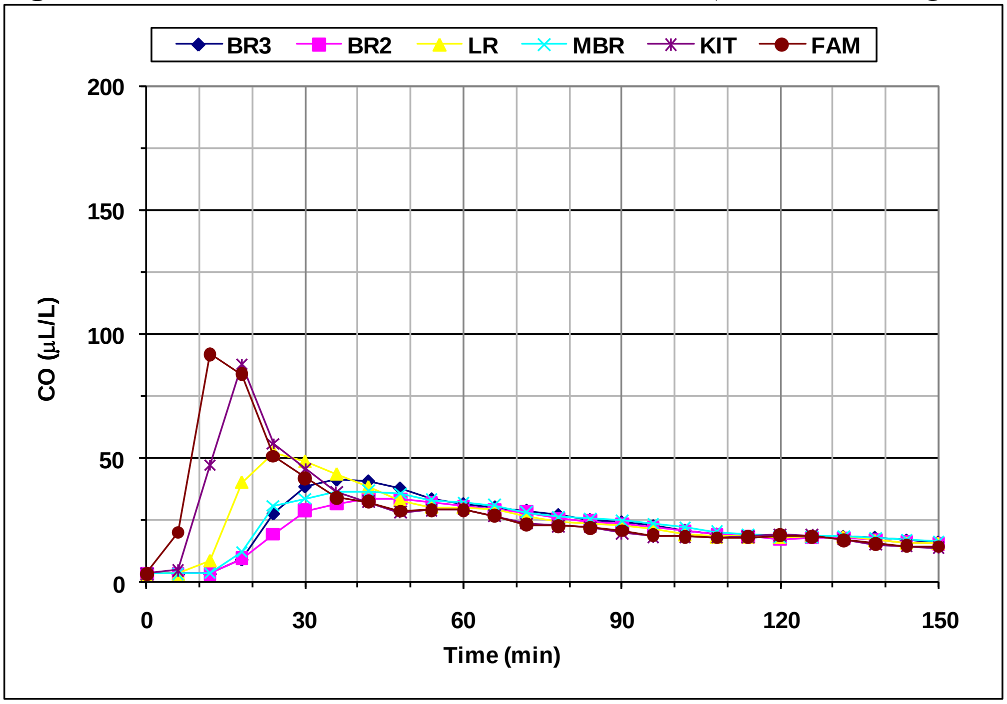
Figure 16a CO and O_2 concentrations in the garage and measured load for Test U **(**Gen SO1, Configuration 6)



As shown in Figure 16a, after an initial spike to nominally 260 µL/L of CO in the garage shortly after the generator was started, it dropped and maintained a level below 30 µL/L throughout the test. After the initial spike, this CO concentration reflects about a 97 % reduction compared to that measured with unmod Gen X in Test G in which the CO in the garage was around 300 µL/L to 1100 µL/L for portions of the second load cycle. With the garage bay door open, the oxygen level stayed nominally at ambient.

Throughout the test, the delivered electrical output met or exceeded the load bank settings with the exception of the highest load setting.

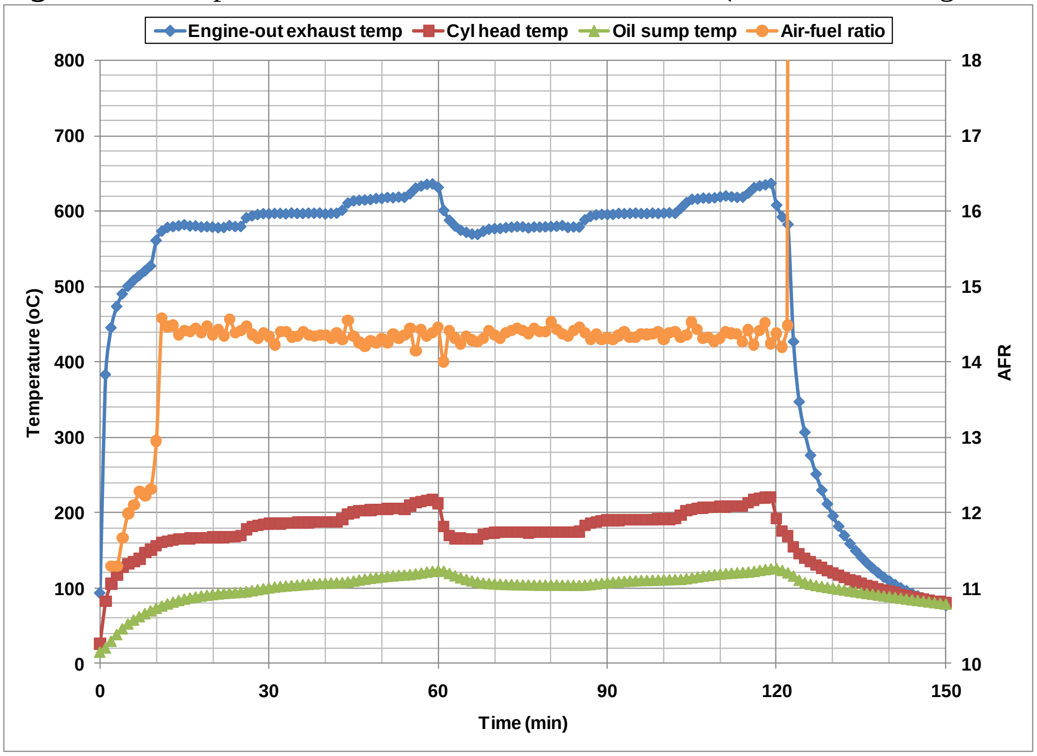
Figure 16b CO concentrations in the house for Test U **(**Gen SO1, Configuration 6)



As shown in Figure 16b, the CO concentration in the family room initially spiked to about 90 µL/L and then dropped to an even distribution in all rooms of the house around 30 µL/L with a continual decline to below 20 µL/L before mechanical venting was initiated.

By comparison, unmod Gen X in Test G produced a nominal peak CO concentration of 220 µL/L in the family room with a minimum peak concentration in the other rooms just below 190 µL/L.

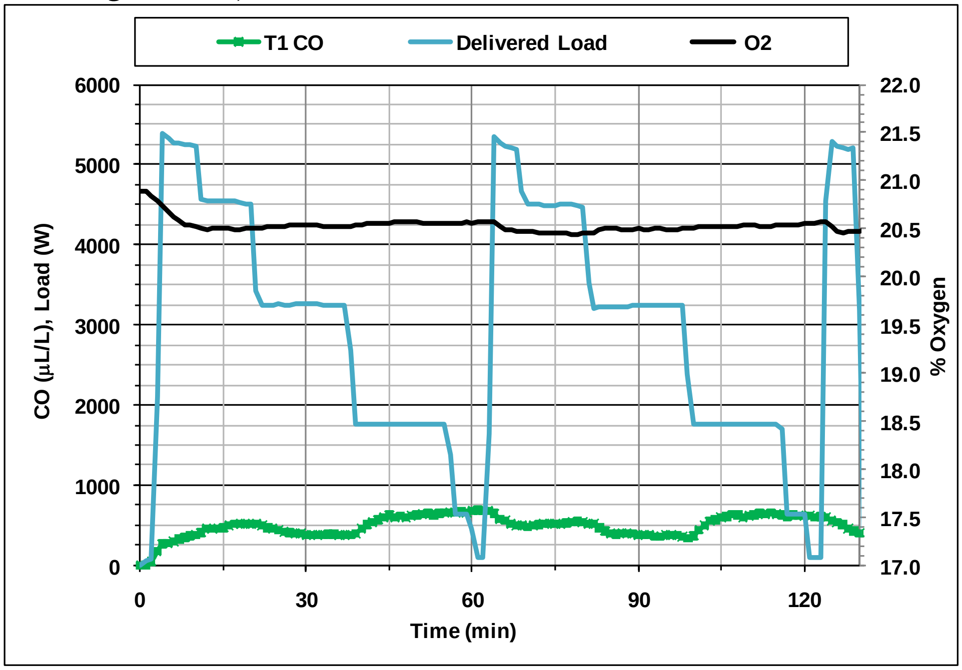
Figure 16c Temperatures and AFR measured in Test U **(**Gen SO1, Configuration 6)



The AFR and temperatures measured on Gen SO1 during Test U are shown in Figure 16c. The engine operated at the calibrated AFR after the engine oil temperature warmed to nominally 70 $^{\circ}$C. The spike in AFR at the end of the test corresponds to when the engine was turned off.

Figures 17a and 17b show the results for Test K, which was a 2 h 10 min test of unmod Gen X in Configuration 7 (garage bay door and garage access door to house open, and the house central HVAC fan off). For this test, the load cycle was applied in reverse order to that shown in Table 1. The test house conditions for this test are similar to the 2 h Test G with unmod Gen X except that in that test the HVAC fan was on. Since the operation of the HVAC fan primarily affects the airflow between rooms in the house but has less affect on the airflow between the house and garage, this allows some degree of comparison to be made for the resulting garage CO and oxygen levels between Tests K and G. After the generator was manually stopped, the garage and house were mechanically vented.

Figure 17a CO and O_2 concentrations in the garage and measured load for Test K (unmod Gen X Configuration 7)



As shown in Figure 17a, the CO in the garage peaked at about 680 µL/L. This compares to the 1100 µL/L reported in Test G with unmod Gen X that was measured with a high range CO analyzer. With the garage bay door open, the garage oxygen level dipped to about 20.4 %.

Throughout the test, the delivered electrical output exceeded the load bank settings with the exception of the highest load setting.

Figure 17b CO concentrations in the house for Test K (unmod Gen X Configuration 7)

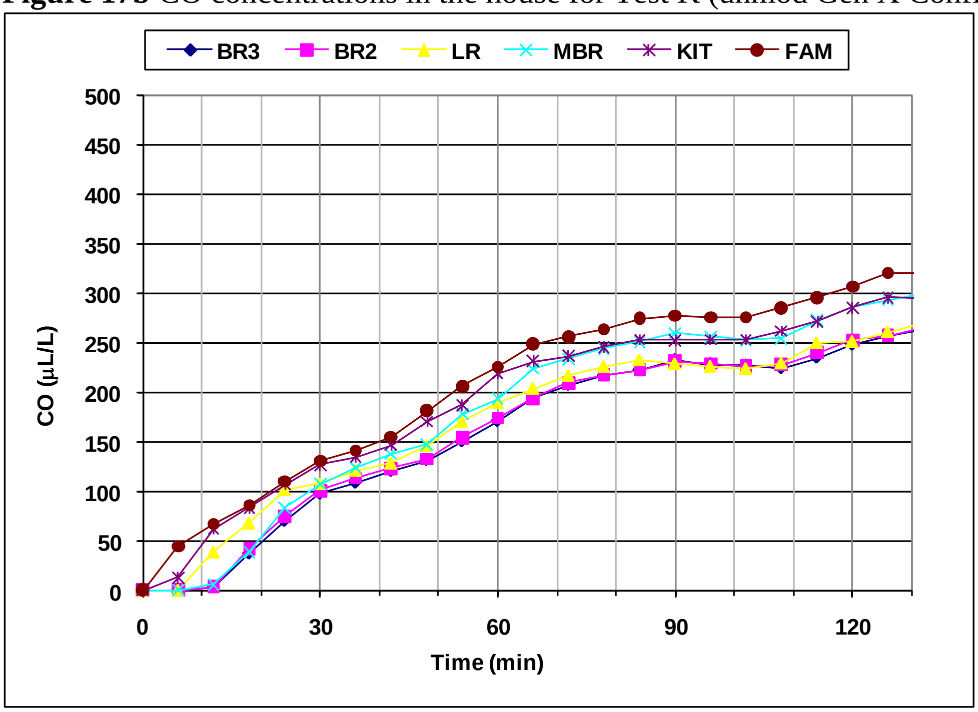
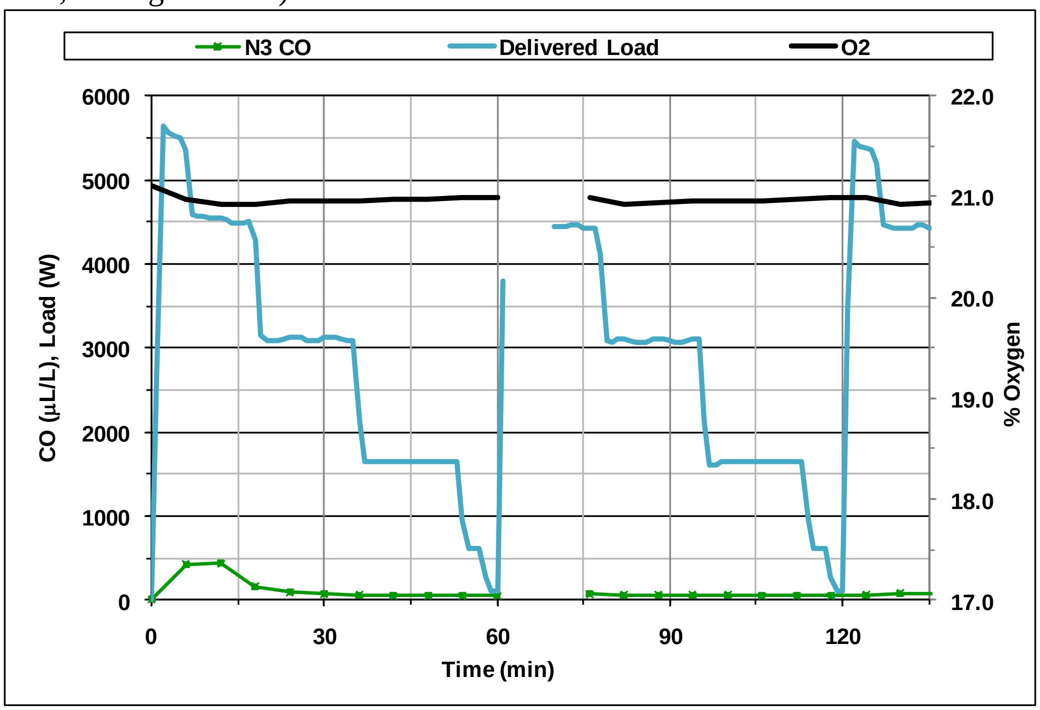


Figure 17b shows the CO reached a peak concentration of 320 μL/L in the family room with peak concentrations in the other rooms just below that value, down to nominally 260 ppm_y when mechanical venting was initiated.

Figures 18a, 18b, and 18c show the results for Test V, which was a 2 h 15 min test of Gen SO1 with the noncat muffler and the same test house configuration as used in the 2 h Test K with unmod Gen X (Configuration 7). To match the reverse order load profile used Test K, the load cycle for this test was also applied in reverse order to that shown in Table 1. The test house conditions for this test are also the same as that used in the 2 h Test U with Gen SO1 except that in Test U Gen SO1 had the catmuffler and the house central HVAC fan was on. After the generator was stopped, the garage and house were mechanically vented. Due to a software error, about 15 min of data were not recorded approximately 1 h into the test.

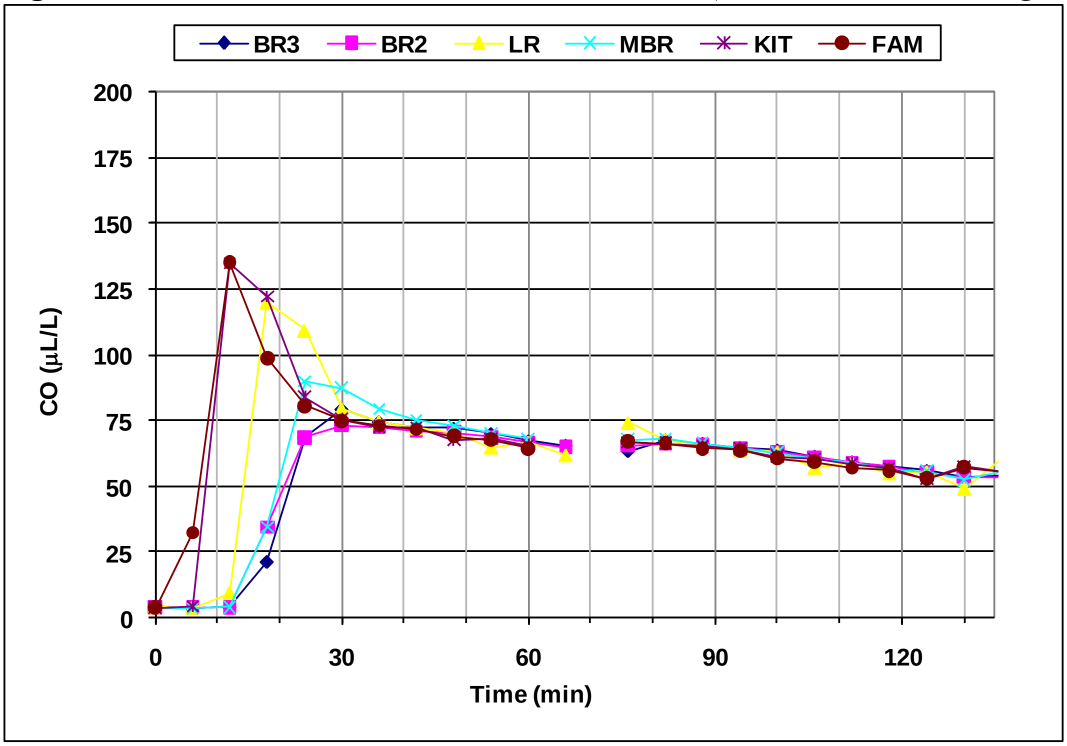
Figure 18a CO and O_2 concentrations in the garage and measured load for Test V (noncat Gen SO1, Configuration 7)



As shown in Figure 18a, after an initial spike to nominally 430 μL/L of CO in the garage shortly after the generator was started, it dropped to a level near 50 μL/L before rising to about 80 μL/L during the brief 3rd load cycle. Note that the missing data included the high load portion of the 2nd load cycle and a peak during this time cannot be ruled out. Excluding the initial peak of Test V, this is a reduction of 85 % to 88 % compared to that measured with unmod Gen X in Test K in which the CO in the garage ranged from 350 μL/L to 650 μL/L.

With the garage bay door open, the garage oxygen level stayed nominally at ambient. Throughout the test, the delivered electrical output met or exceeded the load bank settings with the exception of a slight drop at the highest setting during the 3rd load cycle.

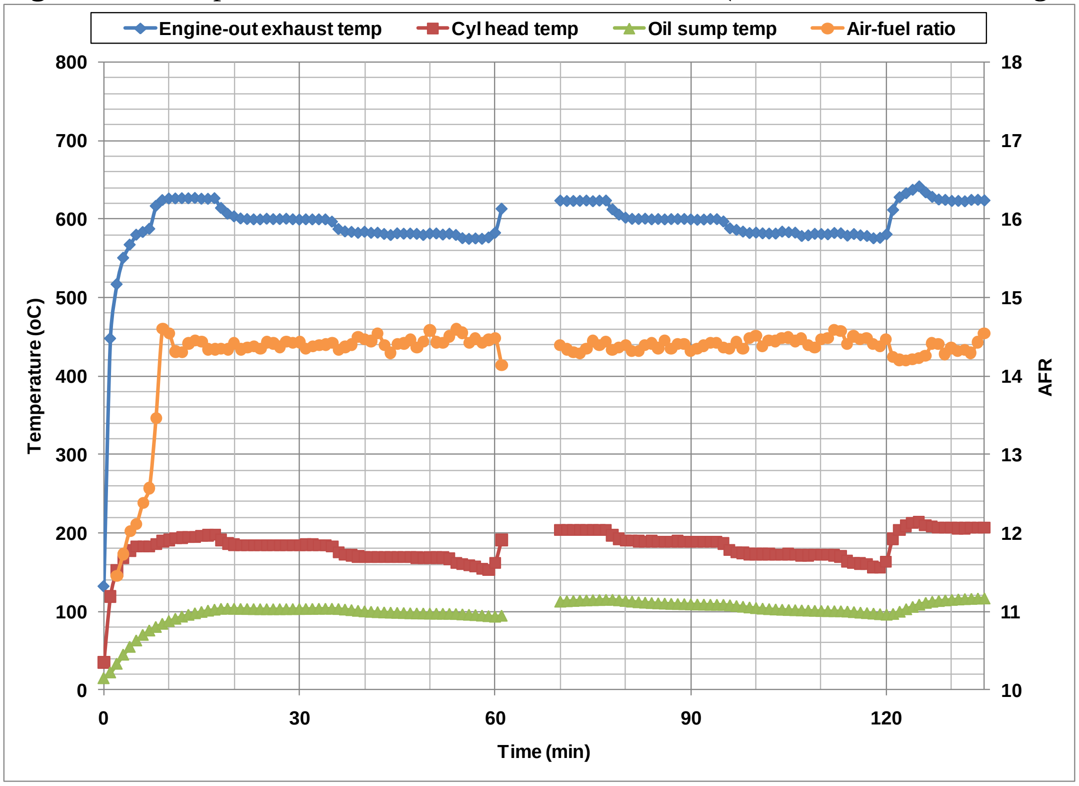
Figure 18b CO concentrations in the house for Test V (noncat Gen SO1, Configuration 7)



As shown in Figure 18b, the CO concentration in the family room initially spiked to 135 µL/L and then dropped to a uniform distribution throughout the house at around 75 µL/L, with a continual decline to 50 µL/L when mechanical venting was initiated. With the exception of the first 25 min of the test, the distribution was very uniform despite the HVAC fan being off.

By comparison, unmod Gen X in Test K produced a less uniform house distribution, with a peak CO concentration of nominally 320 µL/L in the family room and concentrations in the other rooms just below that, down to 260 µL/L.

Figure 18c Temperatures and AFR measured in Test V (noncat Gen SO1, Configuration 7)



The AFR and temperatures measured on Gen SO1 during Test V are shown in Figure 18c. The engine operated at the calibrated AFR after the engine oil temperature warmed to about 70 °C.

Since engine performance in this test was similar that in Test U with Gen SO1 and the catmuffler (with the caveats that the loads were applied in opposite order and some data was missed in Test V), a comparison of the 50 μL/L garage CO concentration in this test with the 20 μL/L in Test U indicates the prototype's catalyst is providing about up to a 60 % reduction in CO emissions from that provided by the EMS alone. This somewhat larger difference than found when comparing Tests Z to N and Tests AH to W could be due to changes in infiltration rates or other factors.

SUMMARY

This interim report presents data from a series of tests NIST completed in which portable gasoline-powered electric generators were operated in the attached garage of the NIST manufactured test house. The data includes CO generation and O_2 depletion in the garage, CO migration into the test house and engine operation parameters. A summary of the test results is provided in Table 3. These tests document reductions of 85 % to 98 % in CO concentrations due to emissions from 2 different modified, prototype low CO-emission portable generators compared to a "stock" generator. The second prototype (Gen SO1) resulted in lower CO concentrations during similar tests with the garage bay door closed while both prototypes resulted in low CO concentrations during tests with the garage bay door open. Note that these results apply to the specific units tested and that other units, modifications, etc. may produce different results.

Table 3 Summary of results

Generator	Test ID	Garage bay door, house door, HVAC	Test Duration (h)	Peak Garage CO Concentration (μL/L)	% Reduction in peak garage CO relative to unmod GenX	Peak CO concentration in house (μL/L)
unmod GenX	B	Closed, open, off	3	19,500 (12,800 at 2 h)	NA	6500
modGenX	O	Closed, open, off	4.5	3000 (1,400 at 3 h)	93	800
SO1	N	Closed, open, off	2	300	98	140
unmod GenX	F	Open, closed, off	4	1,500	NA	200
modGenX	R	Open, closed, off	4	30	98	5
SO1	T	Open, closed, off	3	300 (20 after initial spike)	98	50
unmod GenX	I	Closed, open, on	4	18,600	NA	10,600
SO1 with noncat muffler	Z	Closed, open, on	4.75	630	97	360
unmod GenX	J	Closed, closed, on	2.25	21,300	NA	1,800
SO1	W	Closed, closed, on	6	960 (640 at 2.25 h)	97	145
unmod GenX	D	Closed, closed, off	2	23,000	NA	1660
SO1 with noncat muffler	AH	Closed, closed, off	5	2,300	90	470
unmod GenX	G	Open, open, on	2	1,100	NA	220
SO1	U	Open, open, on	2	260 (< 30 after initial spike)	97	90
unmod GenX	K	Open, open, off	>2	680	NA	320
SO1 with noncat muffler	V	Open, open, off	>2	430 (50 to 80 after initial spike)	85 to 88	135

Notes: Unmod Gen X is an unmodified (stock) generator with a carbureted engine.
Mod Gen X is a modified (prototype) generator with electronic fuel injection, an engine control unit and a catalytic converter.
Gen SO1 is a modified (prototype) generator with electronic fuel injection, an engine control unit (different than mod Gen X), and a catalytic converter (no catalytic converter used in 'noncat' configuration).
% reduction in peak garage CO concentration excludes initial spike.

ACKNOWLEDGEMENTS
This effort was funded by the U.S. CPSC under Interagency Agreement CPSC-I-06-0012. Janet Buyer, Don Switzer, Sandy Inkster, Susan Bathalon, Han Lim and other CPSC staff provided significant planning and execution support for this effort.

DISCLAIMERS
Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

REFERENCES
Brown, C. J. 2006. Engine-drive tools, phase 1 test report for portable electric generators; U.S. Consumer Product Safety Commission: Bethesda, MD; p 52.

Hnatov, M. V. 2010. *Incidents, deaths, and in-depth investigations associated with non-fire Carbon Monoxide from engine-driven generators and other engine-driven tools, 1999-2009*; U.S. Consumer Product Safety Commission: Bethesda, MD.

Hnatov, MV. 2011. *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2007 Annual Estimates,* U.S. Consumer Product Safety Commission, Bethesda, MD.

Nabinger, SJ and AK Persily. 2008. *Airtightness, Ventilation and Energy Consumption in a Manufactured House: Pre-Retrofit Results*. NISTIR 7478.

Appendix A Summary of Instrument Calibrations

This table summarizes the calibrations of the CO and O_2 analyzers covering the testing periods included in this report. The table includes the date of the calibrations, the standard error for each instrument channel for each calibration, and the average standard error and the average standard error relative to the full scale for each device based on all of the calibrations. Not all analyzer channels were calibrated on each date due to instrument failure or other issues. Table 2 in the report describes which instrument was used for each test. For comparison, the manufacturer's stated accuracy for all of these analyzers is 1 % of full scale.

	Nova2	**Nova1**	**Nova2**	**Nova2**	**Nova1**	**Nova1**	**Nova3**	**TE**	**RM**
Date	**O_2**	**O_2**	**hi CO**	**lo CO**	**hi CO**	**lo CO**	**CO**	**CO**	**CO**
	std error	std error	std error	std error	std error	std error	std error	std error	std error
3/17/2008	0.0105	0.0191	0.0160	0.0036	0.0096	0.0056	NA	NA	
4/17/2008	0.0203	0.0243	NA	NA	NA	0.0094	26.3	NA	
4/21/2008	0.482	0.0290	0.0107	0.0033	0.0033	0.0072	23.4	NA	NA
4/29/2008	0.0317	0.0299	0.0090	0.0035	0.0026	0.0031	18.1	NA	NA
5/5/2008	0.0210	0.0344	0.0052	0.0035	0.0028	0.0056	18.1	NA	NA
5/13/2008	0.0255	0.0794	0.0397	0.0229	0.0074	0.0094	10.8	23.0	NA
5/21/2008	0.0192	0.0305	0.0026	0.0059	0.0062	0.0094	26.0	18.0	NA
6/2/2008	0.0551	0.0225	0.0108	0.0074	0.0065	0.0035	NA	NA	NA
6/10/2008	0.0140	0.0298	0.0086	0.0108	0.0081	0.0155	44.4	NA	NA
3/17/2010	0.239	NA	0.0090	NA	0.0070	0.0045	14.4	NA	NA
4/9/2010	0.0543	NA	0.0029	0.0065	0.0091	0.0067	13.8	NA	0.387
4/28/2010	0.0625	NA	0.0056	0.0004	0.0028	0.0003	11.0	NA	NA
5/12/2010	0.0798	NA	0.0088	0.0253	0.0028	0.0057	6.87	NA	3.22
5/27/2010	0.0745	NA	0.0144	0.0215	0.0076	0.0225	11.6	NA	4.62
7/1/2010	0.0443	NA	0.0086	0.0123	0.0447	0.0056	15.9	NA	6.36
Average of all calibrations	0.0822	0.0332	0.0108	0.0098	0.0086	0.0076	18.5	20.5	3.65
Percent of full scale	0.33	0.13	0.36	1.08	0.29	0.85	1.03	2.27	0.41