

**Measured Carbon Monoxide Concentrations from Stock and Reduced- Emission
Prototype Portable Generators Operated in an Attached Garage**

SJ Emmerich, L Wang, and AK Persily

Abstract

There is concern about the hazard of acute residential CO exposures from portable gasoline powered generators which can result in death or serious adverse health effects in exposed individuals. To address this hazard, the U.S. Consumer Product Safety Commission has developed low CO emission prototype generators by adapting off-the-shelf emission control technologies onto commercially-available generators. A series of tests were conducted to characterize the indoor CO concentrations resulting from portable generators operating in the attached garage of a research house under seven different test house/garage configurations. The tested generators include both unmodified and modified low CO emission prototypes. It was found that CO concentrations varied widely, with peak house CO concentrations ranging from under 10 ppm to over 10,000 ppm. The highest concentrations in the house resulted from operation of the unmodified generator in the garage with the garage bay door closed and the house access door open. The lowest concentrations resulted from operation of a modified low CO-emission prototype in the garage with the bay door open and the house access door closed. These tests documented reductions of up to 98 % in CO concentrations due to emissions from two low CO-emission portable generators compared to a stock generator.

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 which can result in death or serious and/or lasting adverse health effects in exposed individuals. As of April 2013, CPSC databases contain records of at least 739 deaths (involving 552 incidents) from CO poisoning caused by consumer use of a generator in the period of 1999 through 2012 (Hnatov 2013). There were additional 61 CO poisoning deaths (involving 45 incidents) associated with consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 800 CO poisoning deaths (involving 597 incidents) associated with generators for the same 14-year period. 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 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 to form carboxyhemoglobin (COHb), which causes the anoxia.

In order to understand the CO exposures associated with such incidents and their potential reduction, the CO emissions of these generators need to be better characterized. In an initial study, CPSC measured the CO emission rates from stock generators in a small, laboratory test chamber (Brown 2006). Using those data, CPSC performed preliminary indoor air quality (IAQ) modeling and estimated that a 92 % reduction in the CO emission rate would be necessary relative to these measurements to result in a significant delay and reduced severity of the CO exposure in areas of a home remote from the generator location (Inkster 2006). CPSC subsequently worked with the University of Alabama (UA) to develop low CO-emission prototype generators by adapting off-the-shelf emission control technologies onto commercially-available portable generators.

This paper presents measured data from a series of tests of both unmodified and low CO emission prototype generators operated in the garage attached to NIST's IAQ research house, a test facility designed for conducting residential IAQ studies. This is the first study testing the actual performance of generators in a full-size house and under real weather conditions. The reported data is beneficial to understanding and drawing public attentions to the potential hazards of CO emissions from "stock" generators and to evaluating the applicability of lowering the emissions by using off-the-shelf emission control technologies on generators under a real-world test setup.

METHODS AND EQUIPMENT

Instrumentation

Gas concentrations were measured with two multi-gas engine exhaust analyzers, which combine non-dispersive infrared (NDIR) and electrochemical sensor technologies. These

analyzers measured CO on two channels covering different ranges of 0 % to 1 % and 0 % to 10 %, CO₂ from 0 % to 20 %, hydrocarbons (as hexane) from 0 % to 2 %, and O₂ from 0 % to 25 % with a reported accuracy of 1 % of full scale for all five channels. An electrochemical sensor CO analyzer, referred to as N3 in this paper, measured CO over a range of 0 ppm_v to 2000 ppm_v and with a reported accuracy of 1 % of full scale. Two additional NDIR CO analyzers were used, both with ranges of 0 ppm_v to 1000 ppm_v and reported accuracies of 1 % of full scale. Finally, a separate portable O₂ analyzer was also used. Repeated calibrations during the test periods found that the measurement uncertainties were consistent with the manufacturers' reported accuracies. 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.

Test House

The test house used in this study was a manufactured house located on the NIST campus, which was erected in 2002 (Nabinger and Persily 2008). An aerial view and floorplan of the house are shown in Figures 1 and 2. The house includes three bedrooms (MBR, BR2, and BR3), a living room (LR), a family room (FAM), a kitchen (KIT), and an attached garage. The house has a floor area of 140 m² and a volume of 340 m³. The attached garage has a floor area of 36.5 m², a volume of 90 m³ and was built as an addition to the house in 2007. 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.

Measurements of gas concentrations were made at various points throughout the house using sample lines suspended 1.5 m above the floor 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 six individual living space locations were measured for one minute each in a repeating six minute cycle. The garage sample locations were measured separately, as well as a mixed sample from all the garage locations, the latter of which is reported here. Indoor air temperature and humidity

were measured with sensors in each room of the house and on two opposite walls of the garage.

Generators and Loading

Two generators were selected with electrical power output ratings in the size range most commonly involved in fatal consumer incidents, which is 5.0 kW to 6.5 kW (Hnatov 2013). The first generator was powered by a carbureted 11 horsepower single-cylinder gasoline engine and has an advertised full-load rating of 5.0 kW. This generator was tested in both an unmodified condition (referred to as “unmod Gen X”) and as a modified low-CO emission prototype (referred to as “mod Gen X”). The unmodified generator operates at air-fuel ratios (AFR) in the range of 10 to 13 depending on the load, which is common for small air-cooled carbureted engines. The modifications included adding an engine management system (EMS) with associated sensors and actuators for electronic fuel injection (replacing the carburetor) and a muffler with a small catalyst. UA calibrated the engine control unit (ECU) microcomputer to operate at 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 a metallic substrate coated with platinum palladium, and rhodium and primarily targets reduction of oxides of nitrogen (NO_x) and has relatively low catalytic activity because the EMS significantly reduces the available oxidation constituents in the exhaust stream.

The second generator (referred to as “Gen SO1”), a model similar to Gen X, had the same engine but an alternator with an output rating of 7 kW. It was tested after UA modified it using the same fuel control strategy and largely the same emission control hardware that was used in mod Gen X. One difference noted during the testing is that its manufacturer included programming to maintain rich AFR operation until the oil temperature rose above 60 °C, resulting in an initial spike of CO when the engine was started cold. 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 detailed description of the prototype configuration of both mod Gen X and Gen SO1 is provided in the UA’s report to CPSC (CPSC 2012).

Generators mod GenX and Gen SO1 were outfitted with thermocouples and a Lambda sensor to measure AFR with reported accuracy of 0.2 for $12 < \text{AFR} < 18$. The Lambda sensor and thermocouple for measuring engine exhaust temperature were mounted through ports on the exhaust manifold pipe between the engine and muffler. Other thermocouples measured cylinder head temperature and engine oil temperature. Results of AFR (which typically were between 14 and 16 with short spikes below that range during transient events such as load changes) and generator temperatures are not included in this paper but are presented in Emmerich et al. (2013). The generators were operated using reformulated gasoline with 10 % ethanol. 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.

A portable alternating current (AC) resistive load bank was used to draw electrical power from the generator. Some tests involved a constant load while others followed a cyclic load profile (see Table 1). This profile is similar to the one used by UA during the durability and emission testing of the prototype generators. The delivered power was measured and recorded during all tests.

Testing Configurations

Testing was conducted under seven different test house configurations including two different garage bay door positions (fully closed or open 0.6 m) which would primarily impact concentrations in the garage, two connecting door settings between the garage and the family room (fully closed or open 5 cm) which would primarily impact transport from garage to the living space, and two house central HVAC fan settings (on or off) which would primarily impact mixing within the house. All internal house doors were open throughout all tests. Table 2 includes a summary of the tests conducted including average measured wind speed and outdoor temperature.

RESULTS

Figures 3 through 12 show the measurement results for 10 of the tests listed in Table 2, including CO concentration in the house and garage, O₂ concentration in the garage, and the electric load supplied by the generator. The tests with the HVAC fan on are not shown or discussed in detail in this paper because, in general, a portable electric generator would not be used to power the central HVAC system. In all tests, the generator was cold started at time 0 and was manually shut off using a wireless switch that interrupted the engine's ignition. The data in the figures are plotted up until the time mechanical venting was initiated, which typically occurred immediately after generator shut-off. In some tests, when circumstances permitted, the CO concentrations were allowed to decay after the generator was stopped and before mechanical venting was initiated.

House Configuration 1

Figures 3a and 3b show the results for Test B, which was a three-hour test of unmod Gen X in House Configuration 1 (garage bay door closed, garage door to house open, and HVAC fan off). The hourly cyclic load profile in Table 1 was repeated three times until the generator was stopped, and the garage was mechanically vented.

Figure 3a shows the concentration of CO in the garage reached a peak of over 19,500 ppm and the O₂ in the garage dropped 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, which were applied when the oxygen was already below 19 %. As the oxygen continued to drop in the subsequent cycles, the delivered power for these loads decreased further. Figure 3b shows the CO concentration in six rooms of the test house (see Figure 2 for room locations). The CO reached a peak of over 6500 ppm in the family room, with peak concentrations in the other rooms ranging from about 3500 ppm to 6000 ppm. Note that Figure 3(a) shows the CO concentrations measured in two ranges: a higher range (N1 HI-CO) and a lower range (N1 LO-CO), the latter of which levels out after the maximum range was exceeded as shown in the figure. This case quickly resulted in lethal levels of CO as a CO

concentration of 1600 ppm may cause death in less than 2 hours and a concentration of 12800 may cause death in less than 3 minutes (Goldstein 2008).

Figures 4a and 4b show the results for Test O of mod Gen X with the same test house configuration (Configuration 1) as in Test B of unmod Gen X. As shown in Figure 4a, the garage CO concentration reached a peak of nearly 3000 ppm while the garage O₂ concentration dropped to 19.5 % after completing the fourth cycle of the load profile. At three hours into this test, the garage CO concentration was approximately 1400 ppm. Under fairly similar ambient conditions, this CO concentration is a 93 % reduction compared to that measured at the corresponding time with unmod Gen X in Test B. 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. While the electrical output stayed near constant for the four cycles, the CO levels increased progressively and the O₂ decreased slightly with each additional cycle. As seen in Figure 4b, the peak CO concentration throughout the house was about 800 ppm, 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 higher concentration in the family room, over 6500 ppm, relative to the other rooms.

Figures 5a and 5b show the results for Test N of Gen SO1 with the same Configuration 1 used in Test B of unmod Gen X and Test O of mod GenX. This test was terminated after a fuse blew on the load bank, dropping half the load. A decay period of 45 min was included, followed by mechanical venting. As shown in Figure 5a, there was an initial increase of CO to almost 220 ppm in the first 12 min after the generator was started. This rise is due to the rich operation upon cold engine start prior to the oil warming and the ECU transitioning to the calibrated AFR fuel control; it was observed at the start of each of the tests with Gen SO1. The garage CO concentration reached a peak of around 300 ppm, and the garage O₂ concentration dropped 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. In the first load cycle, as the O₂ dropped, the delivered electrical output was less than the load bank setting for the highest

load in the load cycle. This difference increased in the subsequent load cycle as the O₂ level decreased. Comparing the performance of mod Gen X (Figure 4a) and Gen SO1 (Figure 5a) shows that, under similar conditions, Gen SO1 resulted in significantly lower CO concentrations at the 2 hr mark.

Figure 5b shows the house concentration was about 130 ppm 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 decay period, CO continued to infiltrate from the garage into the house, slightly increasing the house concentration to about 140 ppm before the concentration began dropping.

House Configuration 2

Figures 6a and 6b show the results for Test F of unmod Gen X with Configuration 2 (bay door open, garage access door to house closed, and HVAC fan off). After the generator was stopped, a one-hour decay occurred before mechanical venting. The garage CO concentration peaked during each load cycle during the 1500 W load. The peak rose slightly for each load cycle, reaching a maximum somewhat under 1500 ppm in the fourth cycle. During this test, with the bay door open, the garage O₂ level decreased only slightly to 20.5 %, and 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 shows the maximum house CO concentration measured in the family room at just over 200 ppm about 15 min after the generator was stopped after a 4 hr runtime. The master bedroom had the lowest peak concentration among all the rooms, reaching just over 150 ppm about 30 min after the generator was stopped. This case shows that when the access door of garage to the house is closed, the CO concentrations in the house can be significantly reduced but not eliminated.

Figures 7 shows the results for Test R of mod Gen X with the same test house configuration as used in Test F of unmod Gen X (Configuration 2). As seen in Figure 7a, the garage CO concentration was nominally steady at 30 ppm, and the O₂ stayed

nominally at ambient throughout the test. This is about a 98 % reduction in CO compared to unmod Gen X in Test F. The CO concentration throughout the house was nominally steady at 5 ppm in all rooms throughout test R. By comparison, unmod Gen X in Test F produced a maximum CO concentration in the family room at just over 200 ppm, corresponding to a reduction of around 98 % in Test R. The delivered electrical output was significantly less than the load bank settings for the three highest loads in the cycle, which occurred with no significant O₂ depletion. After this test, the unit was thoroughly inspected, including the wiring between the generator head and the 240-volt receptacle, but no anomalies were found.

Figures 8a and 8b show the results for Test T of Gen SO1 with the same configuration (Configuration 2) as used in Test F and Test R of unmod Gen X and mod GenX respectively. The generator was stopped when a circuit breaker tripped. As shown in Figure 8a, there was an initial spike of CO in the garage of over 300 ppm. The garage CO concentration then dropped and maintained a level of about 20 ppm. With the bay door open, the garage O₂ 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.

Figure 8b shows an initial spike of CO exceeding 50 ppm in the family room about 25 min after the generator was started, but 5 min later it dropped below 10 ppm 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 ppm.

House Configuration 5

Figures 9a and 9b show the results for Test D of unmod Gen X in Configuration 5 (bay door closed, garage door to house closed, and HVAC fan off). These conditions are the same as the two and a quarter hour Test J with unmod Gen X except in that test the HVAC fan was on. Figure 9a shows the concentration of CO in the garage reached a

peak of almost 23,000 ppm, and the garage O₂ had dropped 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 cycle, 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 cycle pattern in Test J. Figure 9b shows the CO reached a peak concentration of almost 1660 ppm in the family room with peaks in the other rooms ranging from 600 ppm to 1400 ppm. This is comparable to the 1670 ppm peak measured in the family room at the 2 hr point in Test J.

Figures 10a and 10b show the results for Test AH of Gen SO1 with the noncat muffler and the same Configuration (5) as used in the Test D with unmod Gen X. These conditions are also the same as those used in Test W with Gen SO1 except that in Test W Gen SO1 had the catmuffler and the HVAC fan was on. After the generator was stopped, the garage concentrations decayed naturally for 45 min before being mechanically vented.

As shown in Figure 10a, the CO concentration in the garage initially rose to 670 ppm upon startup, then continued to climb until it reached a peak of 2300 ppm and O₂ lowered 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. Figure 10a 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 cycle. During the subsequent load cycles the delivered power degraded even further as the garage O₂ approached and then dropped below 18 %. 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 garage CO concentration at that point in time suggests the prototype's catalyst is provided about a 50 % reduction in the CO emissions compared with that provided by the EMS alone. Figure 10b shows the house CO reached a peak concentration of about 470 ppm with even distribution among the rooms even though the HVAC fan was off. At 2 hr into this test,

the CO in the house was about 180 ppm. By comparison, after 2 hr of operation unmod Gen X in Test D produced peak CO of almost 1660 ppm in the family room.

House Configuration 7

Figures 11a and 11b show the results for Test K of unmod Gen X in Configuration 7 (bay door and garage door to house open, and HVAC fan off). For this test, the load cycle was applied in reverse order to that shown in Table 1. The house conditions for this test are similar to Test G with unmod Gen X except in that test the HVAC fan was on.

Figure 11a shows the CO in the garage peaked at about 680 ppm. With the bay door open, the garage oxygen level decreased 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 11b shows the CO reached a peak concentration of 320 ppm in the family room, with peak concentrations in the other rooms just below that value.

Figures 12a and 12b show the results for Test V of Gen SO1 with the noncat muffler and the same test house configuration (7) as used in Test K with unmod Gen X. The load cycle for this test was also applied in reverse order to match Test K. The test house conditions for this test are also the same as that used in the Test U with Gen SO1, except that in Test U Gen SO1 had the catmuffler and the house central HVAC fan was on. About 15 min of data were not recorded 1 h into the test due to a software issue.

As shown in Figure 12a, after an initial spike to nominally 430 ppm of CO in the garage shortly after the generator was started, it dropped to a level near 50 ppm before rising to about 80 ppm during a partial third load cycle. 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. With the garage bay door open, the garage O₂ level stayed nominally at ambient. Through most of the test, the delivered electrical output met the load bank settings.

As shown in Figure 12b, the CO concentration in the family room initially spiked to 135 ppm and then dropped to a uniform concentration throughout the house of around 50 ppm. Engine performance in this test was similar to that in Test U with Gen SO1 and

the catmuffler. A comparison of the 50 ppm garage CO concentration in this test with the 20 ppm 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.

Summary of Garage Tests

A summary of the test results is provided in Table 3. These tests document reductions of 85 % to 98 % in CO concentrations due to reduced emissions from two modified, prototype portable generators compared to an unmodified 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.

CONCLUSION

The U.S. NIST conducted a series of tests to characterize the indoor time course profiles of CO concentrations resulting from portable generators. The tests included both unmodified and modified prototype generators operated in the garage attached to a test house. Testing was conducted under seven different test house/garage door and HVAC fan configurations to evaluate their impacts on the buildup of CO in the garage and its transport into the house. CO concentrations varied widely with peak house CO concentrations ranging from under 10 ppm to over 10,000 ppm. Note that a CO concentration of 1600 ppm may cause death in less than 2 hours and a concentration of 12800 may cause death in less than 3 minutes. It was found that the highest concentrations resulted from operation of the unmodified generator in the garage with the bay door closed and the house access door open. The lowest concentrations resulted from operation of a reduced-emission prototype in the garage with the bay door open and the house access door closed.

These garage tests showed reductions of 85 % to 98 % in CO concentrations for the two modified, prototype low CO-emission portable generators compared to an unmodified generator. Note that these results apply to the specific units tested and that other units, modifications and test conditions may produce different results. NIST also conducted

tests with the generators operating in a one-zone shed to derive their CO emission and O₂ consumption rates, to be used as inputs to a model validation effort as well as for simulations conducted to examine the potential performance of the low CO-emission prototype under a wider range of operating conditions (Emmerich et al. 2013). Those single-zone tests also showed reductions of CO emissions of over 90 % depending on the specific emission controls for the two modified low CO emission prototype generators.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Consumer Product Safety Commission (CPSC) under interagency agreement CPSC-I-06-0012.

REFERENCES

ASHRAE. 2009. *Handbook of Fundamentals Chapter 16*, ASHRAE.

Brown, C. J. 2006. *Engine-drive Tools, Phase 1 Test Report for Portable Electric Generators*, U.S. Consumer Product Safety Commission.

CPSC. 2006. *Portable Generators: Legal Memorandum and staff briefing package for advance notice of proposed rulemaking (ANPR)*; U.S. Consumer Product Safety Commission.

CPSC. 2012. *Technology Demonstration of a Prototype Low Carbon Monoxide Emission Portable Generator*, U.S. Consumer Product Safety Commission.

Emmerich, S.J., Persily, AK, and Wang, L. 2013. Modeling and Measuring the Effects of Portable Gasoline Powered Generator Exhaust on Indoor Carbon Monoxide Level. NIST Technical Note 1781.

Goldstein, M., 2008. Carbon monoxide poisoning. *Journal of Emergency Nursing*, 34(6).

Hnatov, M. V. 2013. Incidents, Deaths, and In-Depth Investigations Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 1999-2012; U.S. Consumer Product Safety Commission.

Inkster, S.E. 2006. An estimation of how reductions in the carbon monoxide (CO) emission rate of portable, gasoline-powered generators could impact the chance of surviving an acute CO exposure resulting from operation of a portable gasoline-powered generator in a basement. U.S. Consumer Product Safety Commission. (Available as Tab P of CPSC 2006).

Nabinger, S.J. and Persily, A.K. 2008. *Airtightness, Ventilation and Energy Consumption in a Manufactured House: Pre-Retrofit Results*. NISTIR 7478, U.S. National Institute of Standards and Technology.

Wang, L., and Emmerich, S.J. 2010. In situ Experimental Study of Carbon Monoxide Generation by Gasoline-Powered Electric Generator in an Enclosed Space. *Journal of the Air & Waste Management Association*, Vol 60(12).

Wang, L., Emmerich, S.J., Persily A.K. and C-C Lin. 2012. Carbon Monoxide Generation, Dispersion and Exposure from Indoor Operation of Gasoline-powered Electric Generators under Actual Weather Conditions. *Building and Environment* 56.

TABLES

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

Table 2 Tests Conducted in Attached Garage

Test ID	Generator	House Config	Garage bay door	Garage to house door	HVAC fan	Wind speed (m/s)	Outdoor temp (°C)
B	unmod GenX	1	Closed	Open	OFF	6.5	20.1
O	Mod GenX	1	Closed	Open	OFF	6.5	22.0
N	SO1	1	Closed	Open	OFF	6.3	19.9
F	unmod GenX	2	Open	Closed	OFF	7.7	22.8
R	Mod GenX	2	Open	Closed	OFF	6.7	19.9
T	SO1	2	Open	Closed	OFF	6.9	13.4
I	unmod GenX	3	Closed	Open	ON	7.4	22.8
Z	SO1 noncat	3	Closed	Open	ON	6.7	28.3
J	unmod GenX	4	Closed	Closed	ON	9.6	18.2
W	SO1	4	Closed	Closed	ON	9.5	17.8
D	unmod GenX	5	Closed	Closed	OFF	8.2	12.2
AH	SO1 noncat	5	Closed	Closed	OFF	6.5	15.6
G	unmod GenX	6	Open	Open	ON	7.0	25.1
U	SO1	6	Open	Open	ON	7.8	20.4
K	unmod GenX	7	Open	Open	OFF	7.0	13.8
V	SO1noncat	7	Open	Open	OFF	6.5	15.8

Table 3 Summary of Garage Test Results

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

Note: % reduction in peak garage CO concentration excludes initial spike.

FIGURES



Figure 1 Aerial view of NIST manufactured test house

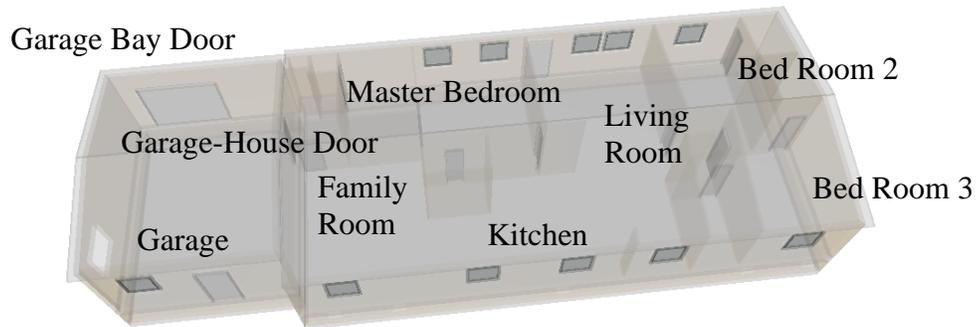
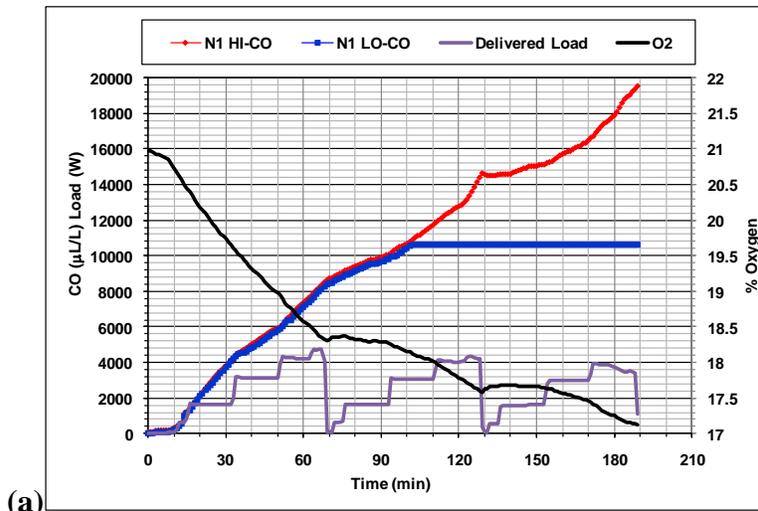
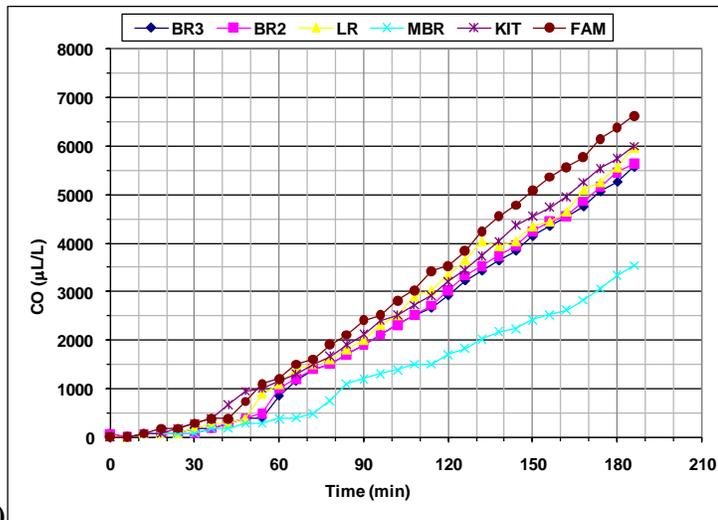


Figure 2 3D layout view of NIST manufactured test house

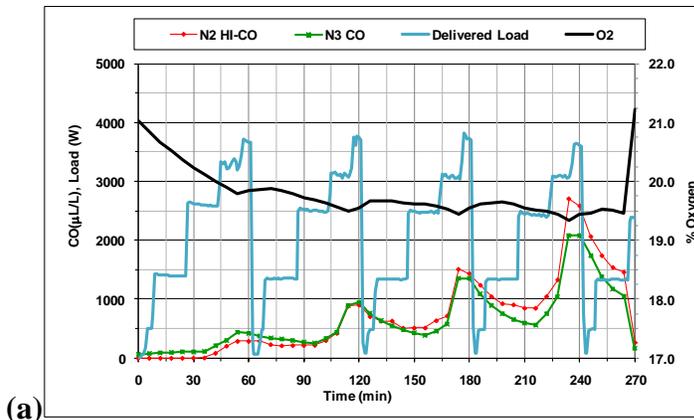


(a)

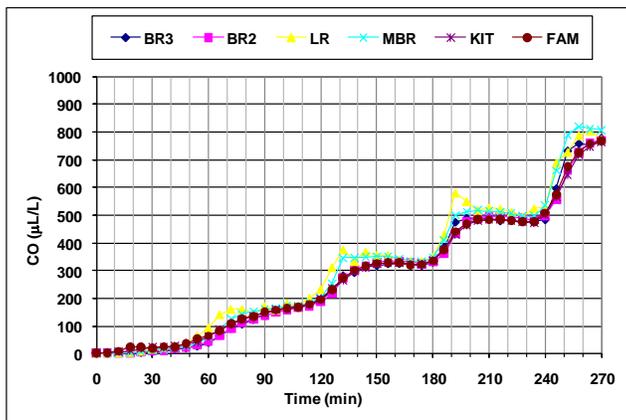


(b)

Figure 3 (a) CO and O₂ concentrations in the garage and measured load for Test B; **(b)** CO concentrations in the house for Test B (unmod Gen X, Configuration 1)

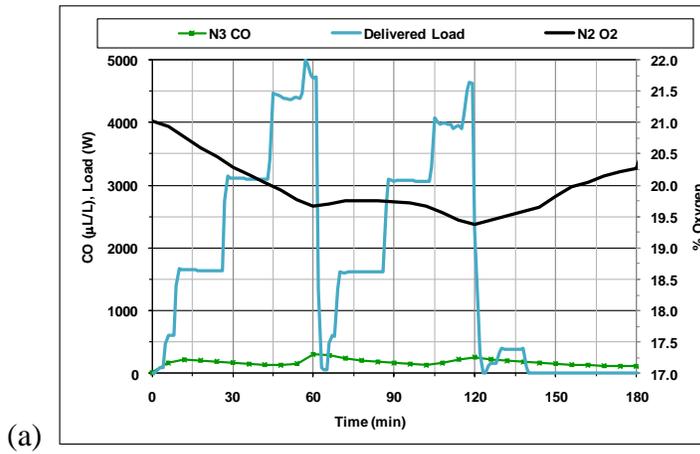


(a)

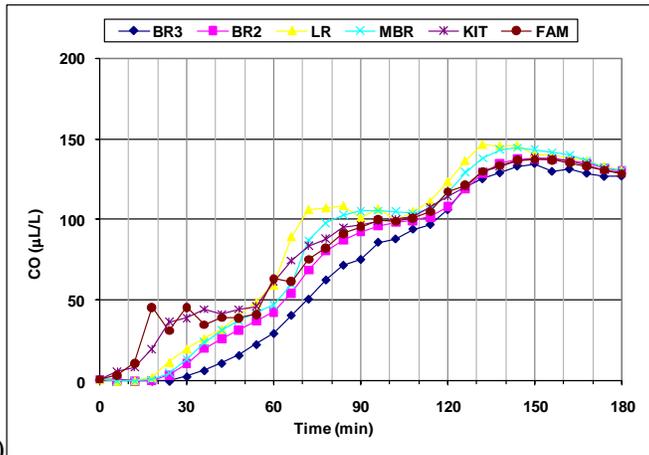


(b)

Figure 4 (a) CO and O₂ concentrations in the garage and measured load for Test O; **(b)** CO concentrations in the house for Test O (mod Gen X, Configuration 1)

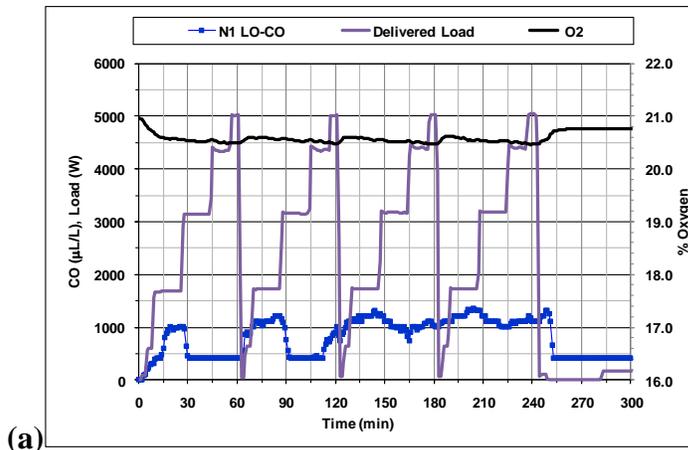


(a)

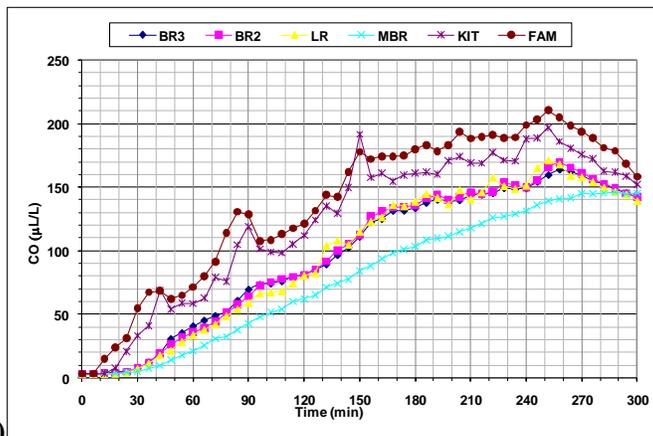


(b)

Figure 5 (a) CO and O₂ concentrations in the garage and measured load for Test N; (b) CO concentrations in the house for Test N (Gen SO1, Configuration 1)



(a)



(b)

Figure 6 (a) CO and O₂ concentrations in the garage and measured load for Test F; (b) CO concentrations in the house for Test F (unmod Gen X, Configuration 2)

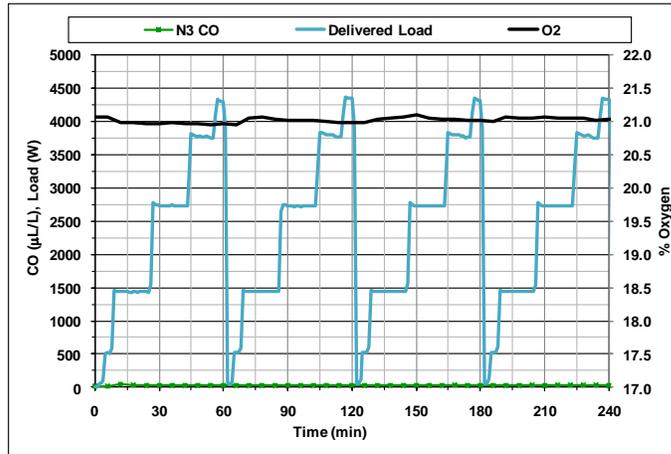
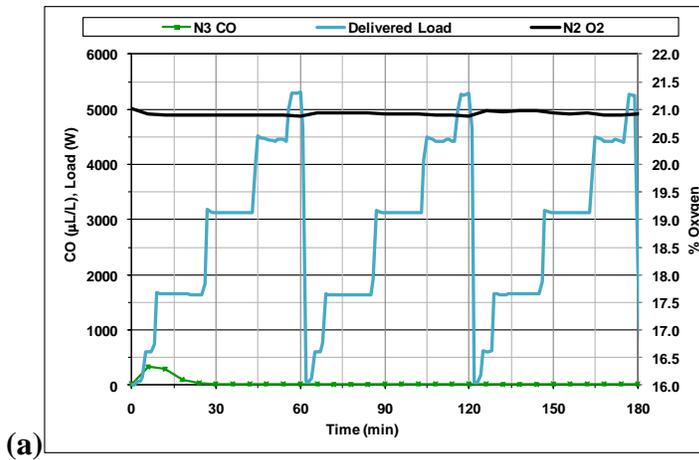
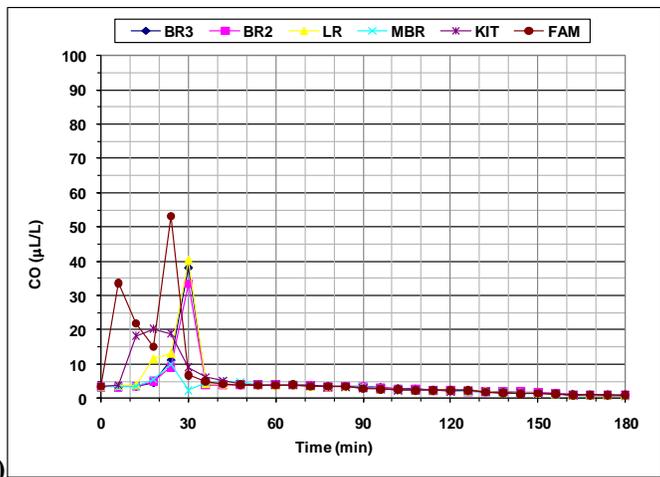


Figure 7 CO and O₂ concentrations in the garage and measured load for Test R (mod Gen X, Configuration 2)

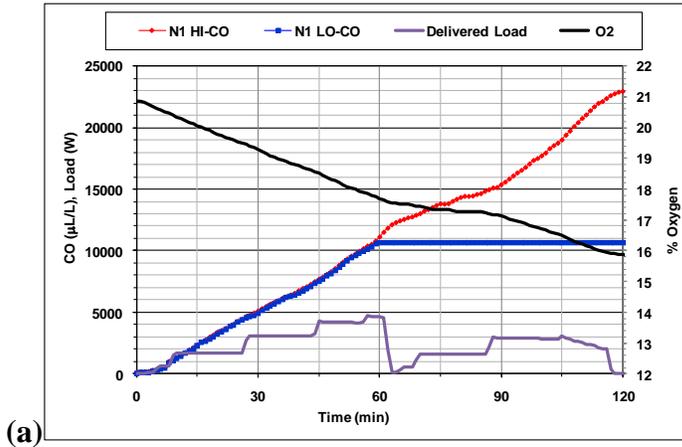


(a)

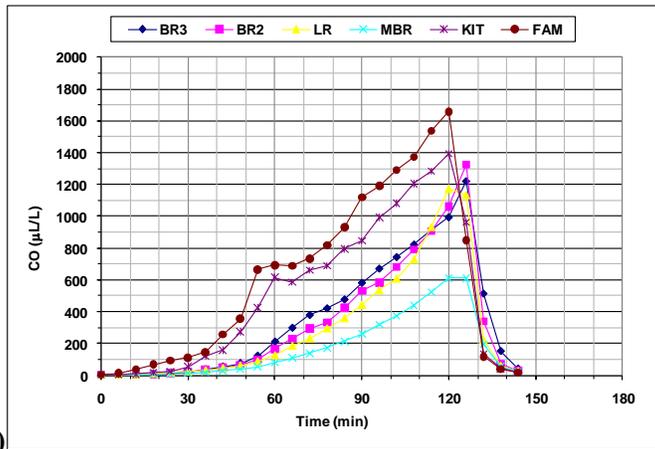


(b)

Figure 8 (a) CO and O₂ concentrations in the garage and measured load for Test T; (b) CO concentrations in the house for Test T (Gen SO1, Configuration 2)



(a)



(b)

Figure 9 (a) CO and O₂ concentrations in the garage and measured load for Test D; (b) CO concentrations in the house for Test D (unmod Gen X, Configuration 5)

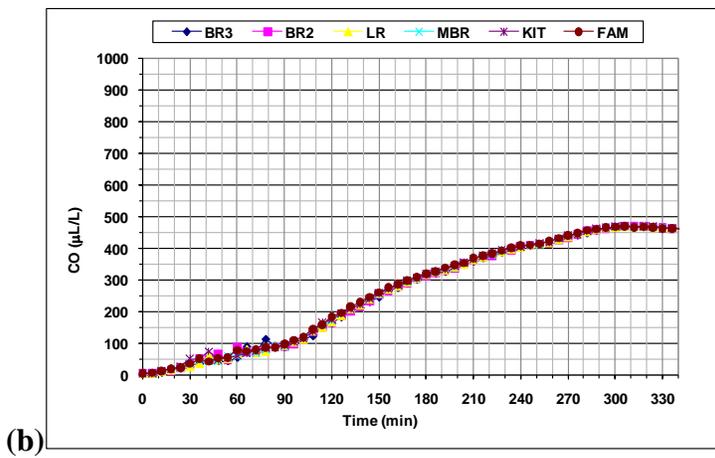
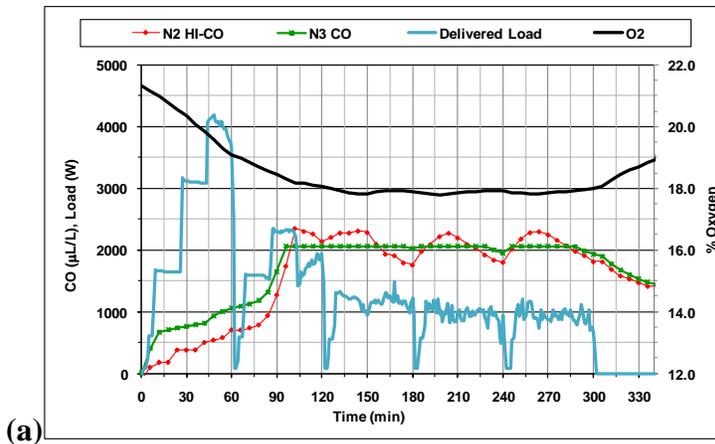
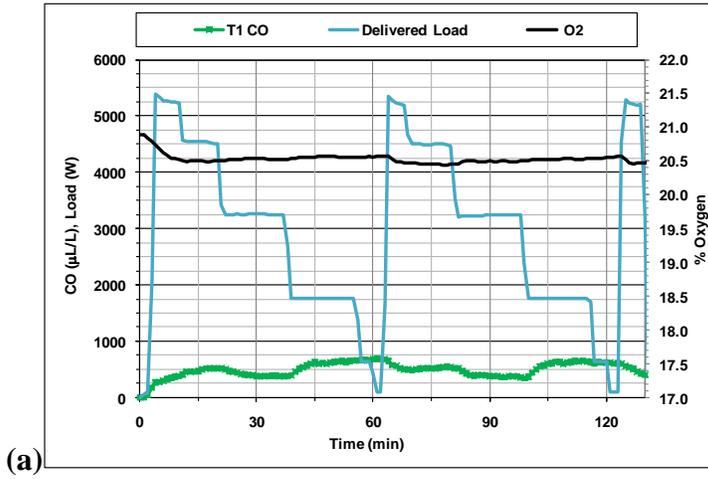
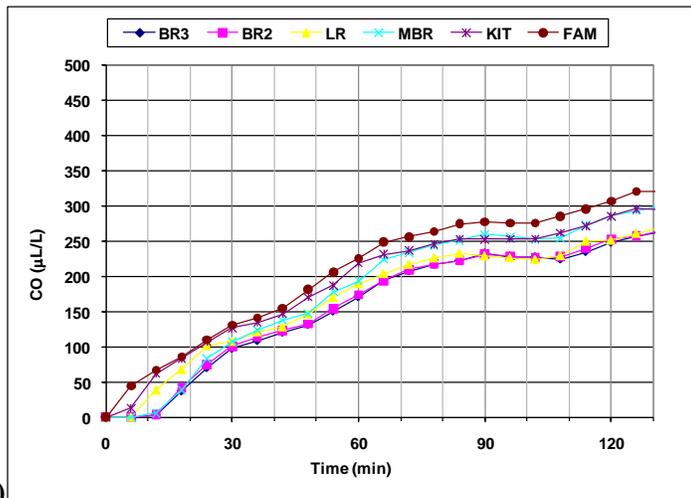


Figure 10 (a) CO and O₂ concentrations in the garage and measured load for Test AH;

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



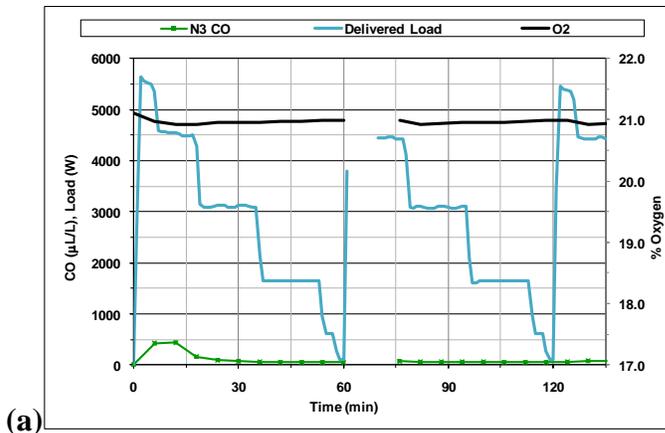
(a)



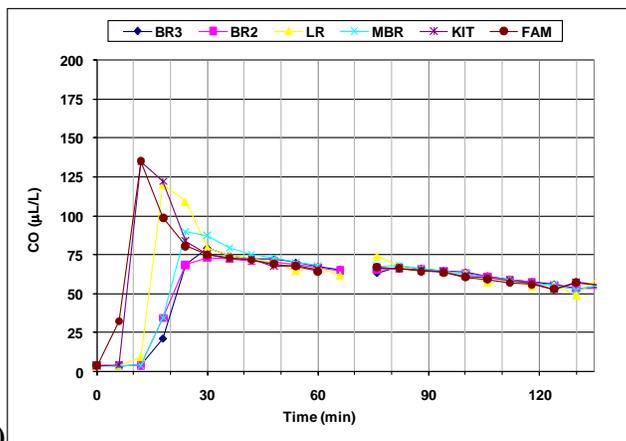
(b)

Figure 11a CO and O₂ concentrations in the garage and measured load for Test K; **(b)**

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



(a)



(b)

Figure 12 (a) CO and O₂ concentrations in the garage and measured load for Test V; **(b)**

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