TECHNOLOGY DEMONSTRATION OF A PROTOTYPE LOW CARBON MONOXIDE EMISSION PORTABLE GENERATOR

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The U.S. Consumer Product Safety Commission (CPSC) databases contained, as of April 2012, reports of at least 755 carbon monoxide (CO) poisoning deaths involving generators for the 13-year period of 1999 through 2011. Deaths occurred when generators were operated in indoor locations, as well as outdoor locations where the exhaust infiltrated indoors. In 2006, in response to staff's recommendation that a strategy of reducing the generator engine's CO emission rate is the most reliable means to reduce the CO hazard associated with this product, the Commission voted to approve an advance notice of proposed rulemaking (ANPR) and directed staff to investigate potential technologies to reduce the hazard.[1]

CPSC staff's preferred approach to addressing any hazard is to attempt to eliminate or reduce the hazard at the source. Therefore, staff created a technology development and demonstration program to see if a portable generator powered by an engine with a substantially reduced CO emission rate could be developed to reduce the risk of fatal and severe CO poisoning when used in an indoor location that is frequently reported in generator-related consumer fatalities, despite warnings against use in this location. This strategy will not only help to reduce the hazard for those who, either knowingly or unknowingly expose themselves to the risk of CO poisoning by operating a generator in an indoor location, but it will also help to protect those who are making a conscious effort to use the product properly in an outdoor location. Staff's goal is not to reduce the CO emission rate to make generators safe to run indoors so that occupants can remain in the exposure without serious health consequences, but rather, to reduce it enough, such that symptom onset is delayed, and the rate of progression of worsening symptoms is significantly reduced. Staff believes this would give occupants a realistic chance to recognize that their symptoms are indicative of a developing hazardous situation, even if they are not aware of the cause, as well as a longer period of awareness which will provide them an opportunity to remove themselves from the exposure before being incapacitated. The high CO emission rate of current generators can result in situations where the exposed person experiences extremely quick onset of confusion, loss of muscular coordination, loss of consciousness, and death with little or no time in experiencing the milder CO poisoning symptoms. Without adequate warning provided by milder symptoms, victims have very little, if any, time to recognize that an imminent life-threatening environmental hazard is occurring and to seek safety or take other actions that could help their situation after the initiation of the exposure.

The demonstration program occurred in two separate series of efforts. The first part involved development of a prototype low CO emission portable generator and demonstration of its performance with respect to durability and compliance with the U.S. Environmental Protection Agency's (EPA) small engine exhaust emissions standards at the end of the engine's rated useful life. The second part involved demonstration of the prototype generator's performance with respect to predicted health impacts on hypothetical occupants when empirically tested in a common fatal residential scenario.

[1] 16 CFR Chapter 11, *Portable Generators; Advance Notice of Proposed Rulemaking; Request for Comments and Information*, Federal Register, 71 FR 74472, December 12, 2006.

The objectives for the development of the prototype generator were to reduce the engine's CO emission rate to the lowest possible level without negatively impacting power output, engine durability, maintainability, fuel economy, and risk of fire and burn, while continuing to meet the EPA's small spark-ignited (SI) nonhandheld engine exhaust emissions standard for hydrocarbons and nitrogen oxides (HC+NOx) to which the engine was originally certified. Staff specified a target CO emission rate of 30 grams per kilowatt-hour (g/kW-hr), which is 95 percent below the EPA's small SI nonhandheld engine exhaust emission CO standard of 610 g/kW-hr.

For the prototype, closed-loop electronic fuel injection (EFI) with stoichiometric fuel control and a three-way catalyst were adapted onto the engine of a commercially available portable generator with an advertised continuous electrical power output rating of 5.0 kW. This portable generator was powered by a small, air-cooled, single-cylinder, carbureted, Class II SI engine with a rated power of 8.2 kW and certified to the EPA's Phase 2 standards for HC+NOx and CO. The EFI/catalyst emission control strategy was adapted onto the engine without making any other improvements to the engine. Before being modified into the prototype configuration, the emission rate of the original, unmodified engine, while installed in the generator, was measured. The prototype generator was then subjected to a durability program in which the generator was loaded with a resistive 6-mode hourly cyclic load profile, from no load to a 5.5 kW load applied through the alternator's 240-volt receptacle, for a total of 500 hours, which is the rated useful life of the engine. An unmodified baseline unit was subjected to the same initial emissions test and durability program in order to compare performance of the prototype relative to an identical model, original equipment as-manufactured (OEM) carbureted unit. Comparative findings from the 500-hour durability testing of the baseline and prototype generators include the following:

- After 500 hours of operation, the prototype demonstrated an approximate 30 percent reduction of HC+NOx and 93 percent reduction of CO, compared to the unmodified baseline unit.
- The prototype engine cylinder head temperature remained below the engine manufacturer's limit, and the exhaust manifold gas temperatures were within the catalyst manufacturer's recommended operating range.
- The integrity of the adapted emission control components was maintained throughout the durability test program, demonstrating the ability to reduce emissions while not shortening the expected life of the engine or generator.
- The prototype reduced the average fuel consumption by approximately 20 percent, compared to the unmodified baseline unit.
- The prototype's muffler surface temperatures across all 6 modes ranged from 50° Celsius (C) to 83° C hotter than the muffler on the unmodified baseline unit. Factors contributing to the increased temperature on the prototype muffler surface may have been the muffler configuration, as the prototype muffler configuration differed from that of the unmodified, original muffler. The temperature of the prototype's muffler shroud, which was added to reduce the risk of fire and burns, was 110° C or less when the engine was operated over the range of deliverable power and was significantly lower than the muffler surface temperature range (266 to 434° C) measured on the surface of the unmodified baseline unit's unshrouded muffler.

After the durability program was completed, staff contracted with an independent laboratory to conduct end-of-life emission testing of the prototype generator engine in accordance with the EPA's small SI engine test procedures. This was performed to ascertain whether, at the end of the engine's rated useful life, the prototype engine's emissions would meet: (1) the EPA's Phase 2 requirements for HC+NOx, which the unmodified OEM version of the engine was originally labeled as being certified to; and (2) staff's target for the exhaust CO emission rate. The results showed the following:

- The prototype configuration using EFI and catalyst muffler had a HC+NOx emission rate of 6.7 g/kW-hr, which is approximately 45 percent below the EPA Phase 2 standard and approximately 16 percent below the more recent Phase 3 standard (adopted in 2008). For the prototype configuration of EFI, but without the catalyst, the HC+NOx emission rate was 13.0 g/kW-hr, which exceeds both the Phase 2 and 3 standards. These results indicate that the catalyst is required for the prototype to comply with both the OEM engine's applicable EPA Phase 2 and the now-current Phase 3 HC+NOx emissions standards for Class II engines.
- The prototype configuration of EFI and catalyst muffler had a CO emission rate of 6.0 g/kW-hr, well below staff's 30 g/kW-hr target, achieving CO emissions reduction of more than 95 percent, when compared to the published CO emission certification data for the unmodified engine, and 99 percent below the EPA's Phase 2 and Phase 3 CO standard of 610 g/kW-hr.
- The prototype generator's cylinder head temperature remained below the engine manufacturer's recommended limit, and the prototype generator's exhaust gas manifold temperature at all modes remained within the catalyst manufacturer's recommended operating range.
- The prototype engine delivered a maximum power of 7.9 kW, which is within 0.3 kW of the advertised rated power for the unmodified OEM, carbureted engine.

In a parallel effort, as the second part of the demonstration program, a similar generator was tested in its OEM configuration and prototype configuration, in variations of a common fatal consumer scenario of a generator operating in the attached garage of a single-family home. In these tests, conducted in a test house facility designed for indoor air quality studies at the National Institute of Standards and Technology (NIST), the CO accumulation in the garage and CO infiltration from the garage into the home was measured. The test results showed that the prototype generator equipped with the catalyst muffler achieved a 97 percent reduction in CO, compared to the unmodified OEM carbureted version of the same engine, based on the peak CO concentrations achieved in the garage after equivalent durations of generator operation. Health effects modeling was performed on the empirical CO time course profiles to estimate the respective times when hypothetical occupants would be expected to experience and be aware of obvious adverse CO poisoning symptoms and when they would be expected to be incapacitated by the CO exposure. The time interval between these predicted times was derived for all tests in order to provide a comparative estimate of the window of opportunity for occupants to escape a developing CO hazard.

The health effects modeling was performed using a physiologically based, mechanistic model that is the most widely accepted approach for predicting an exposed population's formation of carboxyhemoglobin (COHb, which reflects the percentage share of the body's total hemoglobin pool that is occupied by CO, serves as a useful, though inexact, approximation of acute CO uptake by the body, and of acute symptom severity). Using the physiological parameters for an average adult, healthy male performing light-to-moderate indoor activities as inputs to the model, COHb levels of 20 percent and 40 percent were used to define the times when obvious symptom recognition and incapacitation, respectively, were reached. The modeling results of all the tests predicted that, relative to the unmodified unit, the reduced CO emission rate of the prototype significantly delays the onset and progression of CO poisoning symptoms for hypothetical occupants located in all spaces of the home. By significantly reducing the engine's CO emission rate, the prototype increases the exposure time needed to cause incapacitation in even the most extreme circumstances of an occupant co-located with the generator in the garage. With the garage bay door closed, for all four tests with the OEM unit (in which the engine operated from 2 to 4 hours), the estimated time for a hypothetical garage occupant to progress from obvious symptom recognition to death was consistently about 13 to 14 minutes, and that person would likely be conscious for only 7 to 8 of these minutes. In the two corresponding tests of the prototype equipped with the catalyst muffler (in which the engine operated for 138 minutes and 6 hours in the two tests, respectively), only the longer test resulted in death being the *possible* outcome for a garage occupant. In this test, the estimated time in the garage from obvious symptom recognition to possible death was significantly longer at 152 minutes, with the exposed individual likely being conscious for 96 of these minutes. This example shows that the prototype equipped with the catalyst provided a twelve-fold increase in the time interval that occupants co-located with the generator have for recognizing that a hazardous situation is developing after the onset of obvious symptoms, providing them a greater opportunity to escape the CO exposure before becoming incapacitated. The increased opportunity to escape applies to individuals already inside the garage and individuals, who for any reason, entered the garage while the prototype was operating, or in the first few hours after it stopped operating. The tests show that the time interval for hypothetical occupants in the living spaces of the house is extended even further, relative to the garage location. Staff recognizes that this does not guarantee safety because, even with slowed progression of symptoms, this will depend on individual behavioral responses; however, staff believes that the additional response time ultimately can result in many lives saved.

In their feasibility assessment for the Phase 3 regulations that were adopted in 2008, the EPA states that for small SI nonhandheld engines, it is technically feasible to apply the emission control strategy of EFI with fuel control closer to stoichiometry and three-way catalyst to the entire small SI Class II engine inventory.[2,3] CPSC staff's technology demonstration program, which used EFI with fuel control *at* stoichiometry and a three-way catalyst adapted onto a Class II SI engine, shows that significant CO reduction that will reduce the risk of fatal and severe CO poisoning was achieved after operating in the generator for the rated useful life of the engine.

It is important to note that in 2005, in response to market demand, the marine industry found consensus to voluntarily adopt a stringent CO emission standard of 5 g/kW-hr to apply only to small, water-cooled SI engines used to power marine generators. The marine industry did this specifically to address acute CO exposures that were identified as causing deaths and injuries on

[2] 40 CFR Parts 90, 60, et.al., *Control of Emissions from Nonroad Spark-Ignition Engines and Equipment; Final Rule*, Federal Register, 73 FR 59034, October 8, 2008.

[3] U.S. EPA, *Control of Emissions from Marine SI and Small SI Engines, Vessels, and Equipment - Final Regulatory Impact Analysis*, EPA420-R-08-014, September 2008.

and around recreational boats. The EPA set precedent in deciding to adopt this CO level in their Phase 3 regulation as a unique standard that applies specifically to these engines "to prevent backsliding in CO emissions that could occur if new manufacturers were to attempt to enter the market with less expensive, high-CO designs." [2] Further, the EPA did not consider adopting a less stringent standard in their analysis of regulatory alternatives because it "could enable market penetration of new engine offerings which potentially endanger public health." [3] The CPSC's incident data, which only includes fatalities and does not include any injuries, clearly shows that CO emissions from small, air-cooled SI engines providing power to generators can endanger consumers' health. CPSC staff strongly encourages industry consensus, similar to that accomplished within the marine industry, to achieve a reduced CO emission rate on engines used in generators that is expected to reduce the risk of fatal and severe CO poisoning associated with consumer use of this product.

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MEMORANDUM

DATE: August 6, 2012

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FROM	:	Janet Buyer, Project Manager Division of Combustion and Fire Sciences, Directorate for Engineering Sciences
SUBJECT	:	Technology Demonstration of a Prototype Low Carbon Monoxide Emission Portable Generator

1. Introduction

This memorandum and the attached staff and contractor reports document U.S. Consumer Product Safety Commission (CPSC) staff's technology demonstration program of a prototype low carbon monoxide (CO) emission portable generator. This memorandum includes the following:

- the background on the CPSC's Portable Generator Project, including epidemiology data on fatal CO incidents associated with generators reported to the CPSC and explanations of staff's rationale for pursuing the strategy of reduced CO emissions to address the hazard;
- a summary of the development, durability testing, and end-of-life emission testing of the prototype low CO emission portable generator;

- a summary of empirical test results comparing the performance of prototype and unmodified commercially available generators in variations of a common fatal consumer scenario; and
- a summary of the ability of the prototype to reduce the risk of fatal and severe CO poisoning, based on health effects modeling of the empirical test results.

2. Background

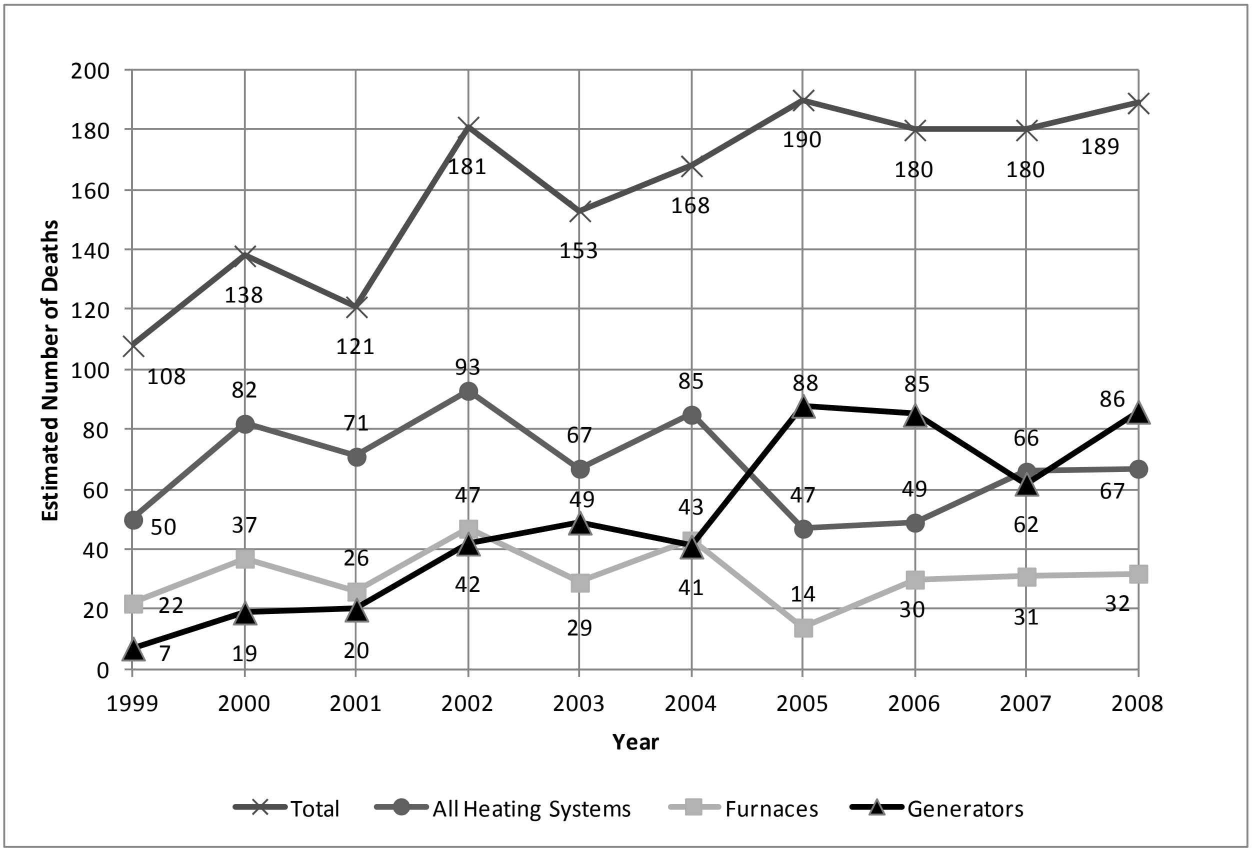
2.1. CPSC Staff Annual Estimates and Counts of CO Deaths Associated with Generators

For many years, the U.S. Consumer Product Safety Commission (CPSC) annually established a strategic goal of reducing the rate of estimated non-fire-related CO poisoning deaths associated with consumer products. In 1999, staff became concerned that portable generators in particular, would create an emerging hazard of CO poisoning for consumers when fears of widespread power outages associated with "Y2K" were rampant and this product became more widely available to consumers. The CO from a portable generator is emitted by its internal combustion engine, which burns fuel to produce rotational energy, which, in turn, is used to generate electricity. The engine may be fueled by gasoline, diesel fuel, natural gas, or liquid propane, and just like any other combustion appliance, produces CO when the fuel is not completely combusted. In 2002, the Commission initiated the Portable Generator Project to look specifically at the CO poisoning hazard associated with this product because the CPSC's estimated number of CO deaths associated with generators appeared to be increasing annually. Figure 1 shows the total yearly in-scope [A] estimated CO deaths for each of the years 1999 through 2008, which are associated with all consumer products and provides specific estimates for CO deaths that involved generators as well as the product category of heating systems and its subset of furnaces, the latter being the product type that historically has been responsible for most CO poisoning deaths.[B,1] The observed increase in generator-related CO deaths in recent years appears significant. In particular, Figure 1 show that, since 2005, generators have overtaken furnaces, and more importantly, that in three of the last 4 years, generators have replaced the entire product category of heating systems to become the consumer product responsible for the largest estimated number of annual non-fire-related CO deaths. For the most current 3 years, 2006 through 2008, generators account for 42 percent of the estimated CO deaths compared to 33 percent for all heating systems and 17 percent for furnaces in particular. Staff does not have current consumer sales or ownership data of generators and heating systems to compare their normalized estimated CO fatality rates or determine if the rate of generator-related estimated CO fatalities is increasing. However, staff reasons that, based on past numbers of units in use [10,18] and the different usage patterns (*i.e.*, daily use of heating systems during the heating season versus more occasional use of generators), the relative risk of CO poisoning caused by generators is significantly greater.

[A] Incidents considered in-scope are those that are unintentional and non-work-related. Additionally, the generators involved must be standalone products not intended for integrated use, such as RV or boat generators designed specifically for those purposes. Only in-scope incidents are referred to and included in the data provided here.

[B] Superscripted numbers refer to references listed in Section 6 of this memorandum. Superscripted letters refer to footnotes.

Figure 1. 1999-2008 Annual Estimates for Non-Fire CO Poisoning Fatalities Associated with Consumer Products and Those Specifically Related to Heating Systems and Generators

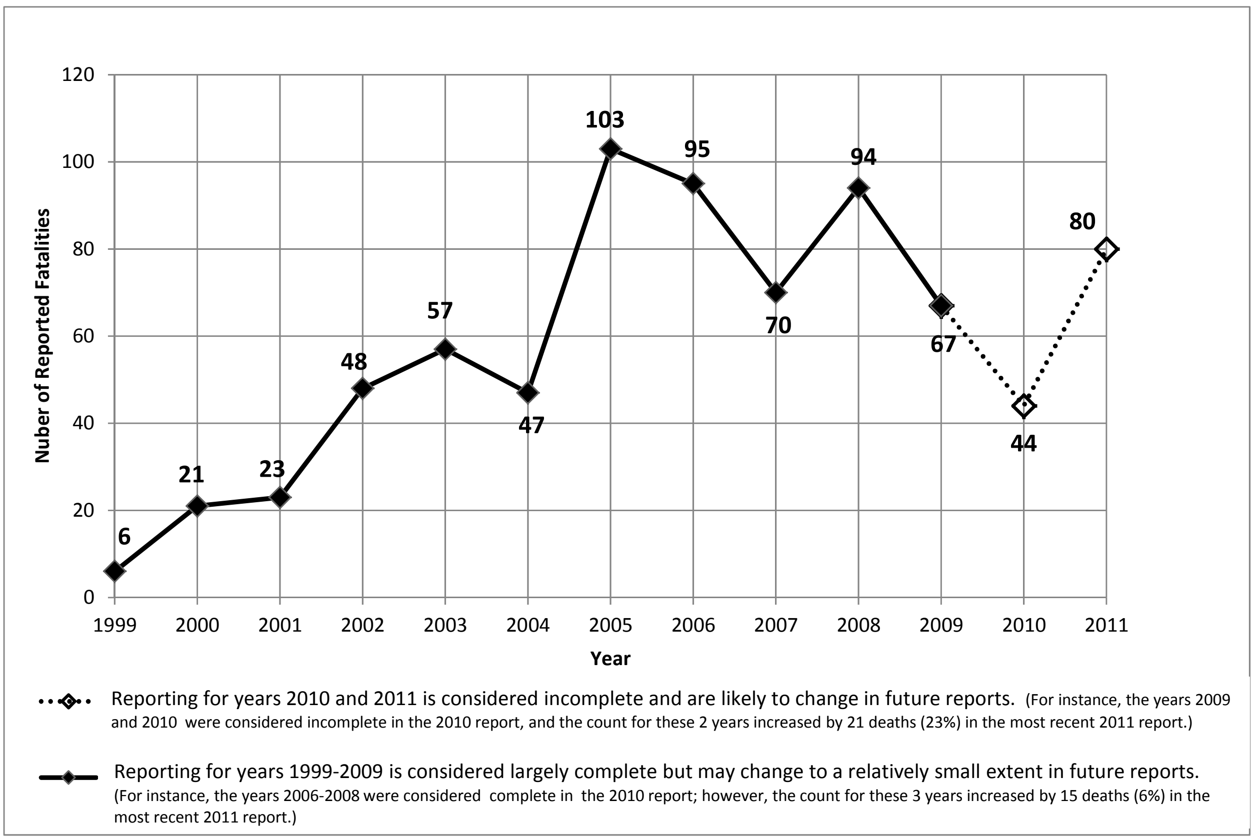


Note: This figure excludes deaths involving multiple CO-producing consumer products.
Source: Hnatov, Matthew, *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2008 Annual Estimates*, U.S. Consumer Product Safety Commission, Bethesda, MD, December 2011.

In addition to making national estimates of CO deaths for all relevant combustion-type consumer products, CPSC staff counts the number of CO deaths specifically associated with generators that are reported in the CPSC databases. The main reason for providing the count is to provide a more current perspective of generator-related deaths because the most recent estimate usually lags 3 years behind the current year. This is because the primary source of data for making estimates is death certificates, and there is often a 2- to 3-year delay before they are received at the CPSC. The source documents that are used for the more current death count include not only death certificates, but also other reports that typically are much more recent, such as news articles and Medical Examiners and Coroners Alert Project (MECAP) reports. Incidents involving a generator-related CO death received through these other sources allow staff to investigate the circumstances surrounding the incident in a relatively timely fashion to help gain better insight on the hazard patterns. Generator-related CO poisoning deaths are considered an especially urgent issue, and CPSC staff investigates nearly all of the in-scope, generator-related CO deaths in its databases. CPSC staff takes painstaking effort to check all the source documents of generator-related CO deaths reported to the CPSC to ensure that each death is counted only once.

As of April 20, 2012, the CPSC databases contain records of at least 695 deaths (in 513 incidents) from CO poisoning caused by consumer use of a generator in the period of 1999 through 2011 **(**see **TAB A)**. There were an additional 60 CO poisoning deaths (in 44 incidents) involving consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 755 CO poisoning deaths (in 557 incidents) involving generators for the same 13-year period. Figure 2 shows the count of deaths involving a generator in CPSC databases for each of these years. Nearly three-fourths (553 out of 755 deaths) occurred between 2005 and 2011. It should be noted that due to incident-reporting delays, statistics for the most recent 2 years should be considered incomplete and are likely to change in future reports. Incident and death counts may change for other years but to a much smaller extent.

Figure 2. Number of Reported Non-Fire Carbon Monoxide Poisoning Deaths Associated with Generators Entered in CPSC Databases by Year, 1999-2011



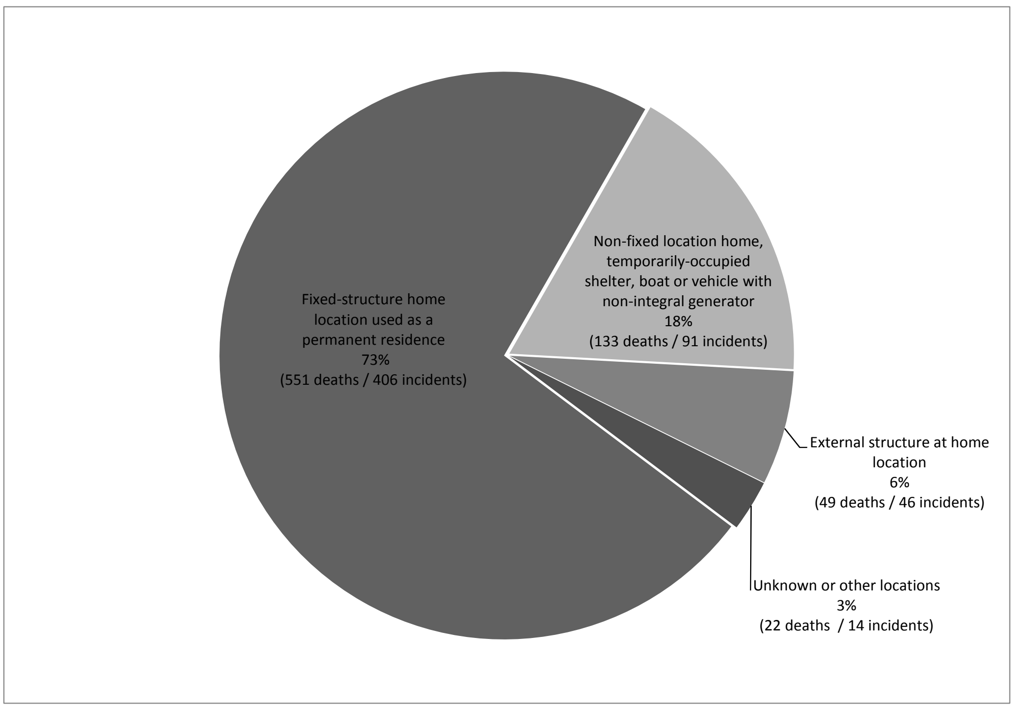
Source: Hnatov, Matthew, *Incidents, Deaths, and In-Depth Investigations Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 1999-2011*, July 2012.

2.2. Hazard Patterns of Consumer CO Deaths Associated with Generators

While **TAB A** contains great detail on staff's analysis of the CPSC's generator-related CO death data, some of the most salient information regarding the hazard patterns is included here to support staff's rationale for the strategy being pursued to address the hazard.

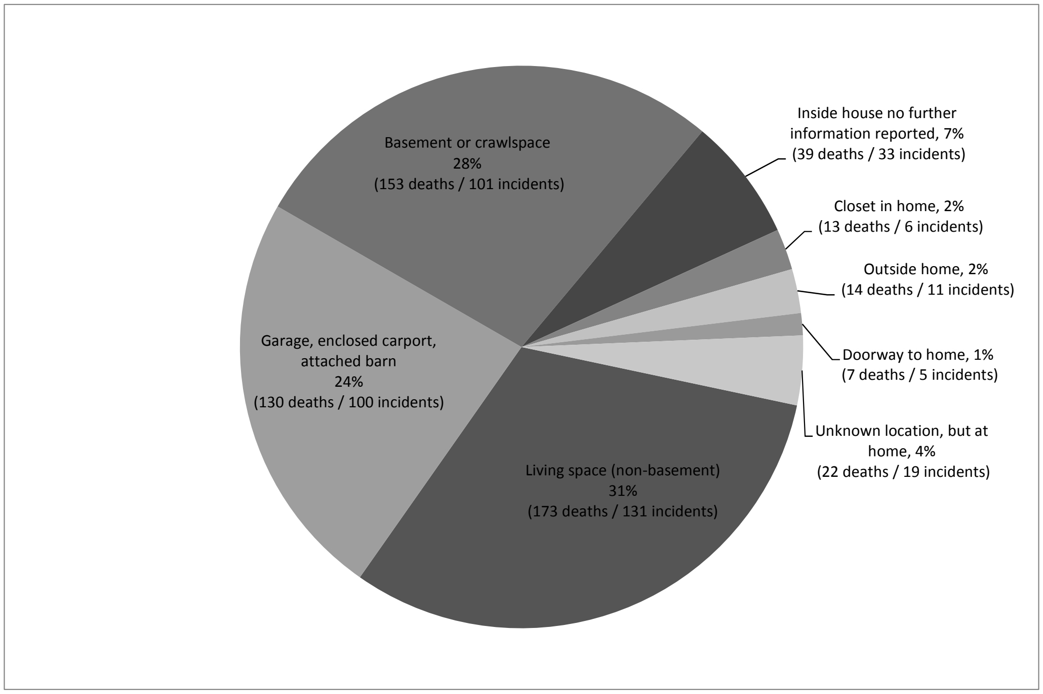
Staff categorized the incident data according to the location where the incident occurred. See Figure 3. Seventy-three percent of deaths (551 deaths out of 755; 406 incidents out of 557) occurred in a fixed structure home location, which includes detached and attached houses, apartments, fixed mobile homes, and cabins used as a permanent residence. Another 6 percent occurred in external structures at home locations, such as detached garages or sheds. Eighteen percent occurred in non-fixed location homes (including travel trailers and houseboats), temporary shelters (locations the victims were occupying temporarily), and boats and vehicles in which the consumer brought the generator on board or into the vehicle. The remainder occurred in other or unknown locations. Of the 551 deaths that occurred in a fixed structure home location, information was available for 469 deaths (85%) regarding the victim's location in relation to the generator. One hundred-eight of these 469 deaths (23%) occurred in the same room or space as the generator.

Figure 3. CO Deaths Associated with Generators by Location of the Incident, 1999-2011



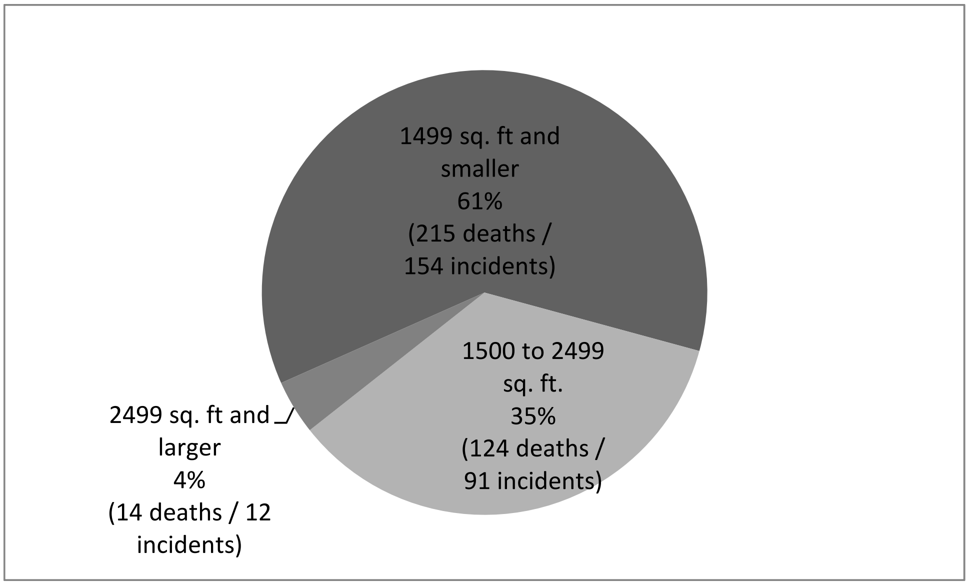
The 551 deaths that occurred in a fixed structure home location were further classified by the specific location of the generator within the home (See Figure 4). Sixty-nine percent of the CO deaths at home locations occurred when a generator was placed inside the home, including the living space, a basement or crawlspace, closet, doorway, or "inside the house," with no further information provided. The category "Living space" includes rooms reported as bathrooms, landings, rear rooms, enclosed porches, and converted garages. Another 24 percent occurred when the generator was placed in an attached garage, enclosed carport, or attached barn. Fourteen deaths were associated with generators that were placed outside the home near open windows, doors, or vents, where the exhaust entered the home.

Figure 4. CO Deaths Associated with Generators that Occurred in a Fixed Structure Home Location, by Specific Location of the Generator, 1999-2011



Of the 551 deaths that occurred in a fixed structure home location, they were also classified according to the size of the home involved in the incident. For 36 percent (198 of 551) of the deaths (149 of 406 incidents), CPSC staff could not ascertain the size of the home. Of the 353 deaths that occurred in a known house size, 61 percent occurred in houses smaller than 1,500 sq. ft.; 35 percent occurred in houses 1,500 to 2,499 sq ft; and only 4 percent occurred in houses larger than 2,499 sq ft. See Figure 5. Fatal incidents that occurred in detached structures are not included in this figure.

Figure 5. CO Deaths Associated with Generators in Fixed Structure Home Locations, by Size of Home, When Size of Home was Ascertained, 1999-2011

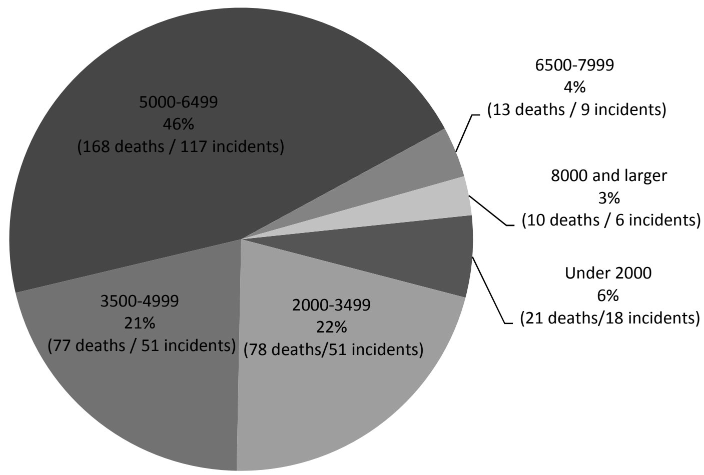


The reason the consumer was using the generator was determined in 633 out of the 755 deaths. Two of the main reasons reported for using a generator were to provide electricity to a location that did not have it due to a power outage stemming from a weather problem or a problem with power distribution (35% or 220 deaths out of the 633 that had a known reason) and to provide electricity after power was shut off to the residence by the utility company due to bill dispute or nonpayment (23% or 143 deaths out of the 633).

For the 220 fatalities associated with a power outage due to weather or a problem with power distribution, 91 percent (201 deaths) of the fatalities associated with power outages were due to outages caused by a known specific weather condition. Ice or snow storms were associated with the largest percentage of weather-related CO fatalities (47 percent or 104 deaths). From 2006 to 2011, the percentage of weather-related CO deaths associated with ice and snow storms is even higher at 54 percent. Hurricanes are also associated with a large percentage of CO deaths (29 percent or 63 deaths out of the 220). But nearly half of the hurricane- or tropical storm-related deaths occurred in 2005 (31 of 63).

The size of the generator involved in a CO fatality was identified in 367 of the 755 deaths. In most cases, the advertised continuous wattage rating was used to categorize the generator; however, in some instances, a wattage rating was used in which it could not be determined whether this rating was the rated continuous wattage or maximum/surge wattage. Nearly half of the CO fatalities, in which the generator size was reported, were associated with generators in the 5000 to 6499 watt range. See Figure 6. Almost all of the generators were referred to as gas- or gasoline-fueled generators. Five fatalities from 3 incidents were associated with fixed, as opposed to portable, generators and these were fueled by propane.

Figure 6. CO Deaths Associated with Generators, Categorized by Generator Wattage Rating, When Size of Generator was Reported, 1999-2011



2.3. CPSC Staff on Estimating CO Injuries and the Potential for Severe Injuries Associated with Generators

While CPSC staff is aware of many incidents in which nonfatal CO poisoning injuries occurred as a result of generator use, CPSC staff currently does not estimate, conduct counts, or investigate these incidents. The reason for not making estimates is that injury estimates are based on injuries treated in the emergency rooms of hospitals participating in the National Electronic Injury Surveillance System (NEISS), a probability sample of about 100 U.S. hospitals, and NEISS cases involving CO poisoning often lack the necessary detail to confirm the poisoning or identify the CO source. Also, cases involving mild CO poisoning may be misdiagnosed because they can be difficult to distinguish from common non-fatal illnesses. NEISS cases of CO poisoning have varied in severity, from an individual receiving a precautionary examination in response to activation of a CO alarm, to an unconscious individual receiving treatment in a hyperbaric oxygen chamber and/or being hospitalized for further treatment. [C, 2]

The prognosis for CO poisoning survivors can be difficult to predict, but given the extremely high CO levels in generator exhaust, and particularly if incidents involve a fatality, survivors of generator-related CO poisoning incidents can be at significant risk of developing the phenomenon of delayed neurological sequelae (DNS), which can manifest a few days or weeks

[C] A hyperbaric oxygen (HBO) chamber is a facility used for exposing patients to 100 percent oxygen under supra-atmospheric conditions to shorten the time it otherwise normally takes for the CO to leave the bloodstream and to increase the amount of oxygen dissolved in the blood. A broad set of recommendations has been established for HBO treatment for CO poisoning, which includes a carboxyhemoglobin (COHb) level (see next footnote) above 25 percent, loss of consciousness, severe metabolic acidosis, victims with symptoms such as persistent chest pain or altered mental status, and pregnant women. Treatment is not recommended for mild-to-moderate CO poisoning victims, other than those at risk for adverse outcomes.[5]

after apparent recovery from the initial CO poisoning incident.[3,4,5, TAB G] Symptoms can include: emotional instability, memory loss, dementia, psychosis, Parkinsonism, incontinence, blindness, paralysis, and peripheral neuropathy. Symptoms of DNS may respond to hyperbaric oxygen therapy and/or may resolve spontaneously over a 2-year period; however, victims exhibiting the most severe symptoms, such as Parkinsonism, blindness, and paralysis are often permanently affected. While loss of consciousness is typically associated with more serious outcomes, it is not necessary to have lost consciousness to sustain DNS from CO exposures. CPSC staff has reports of victims who survived a serious CO exposure; however, CPSC staff does not conduct follow-up interviews with victims at significantly later times after exposure to inquire about their long-term outcome. Although current understanding of DNS does not allow very accurate prediction of DNS occurrence in nonfatal CO poisoning cases, some authorities regard 20% COHb [D] as an approximate lower threshold of concern for DNS.

2.4. CO Injuries Associated with Generators in Published Literature

Following Hurricanes Katrina and Rita in 2005, the Centers for Disease Control and Prevention (CDC) investigated 27 incidents of CO poisoning in hurricane-affected counties in Alabama and Texas, 25 of which were caused by gasoline-powered generators. Most of the generators involved were placed outside but close to the home, in order to power window air conditioners (ACs) or to connect to central electric panels.[6] These 27 incidents resulted in 78 (57 confirmed and 21 probable) nonfatal cases and 10 deaths. The 10 deaths were associated with four incidents, three of which involved indoor use of generators and one that involved indoor use of a portable gas stove. Information regarding hospital outcomes was available for 68 of the 78 nonfatal cases. Ten of the 68 people were hospitalized and 24 had poisonings severe enough to require hyperbaric oxygen treatment. People from the households involved in 18 of the 27 incidents were interviewed. Nine of the 18 households had placed generators outside in the open (not enclosed by a roof or walls); five had placed generators in a partially enclosed area (attached porch or carport), two were in a fully enclosed area (enclosed porch, garage, or shed), and two were inside the home. Generators placed outside were an average of 3.2 feet away from the home (range 1 to 7 feet). Among people poisoned by generators located outside in the open, nine (out of the 24 mentioned above) were severe enough to require hyperbaric oxygen treatment.

In another post-hurricane disease surveillance study, after four major hurricanes hit Florida in August and September 2004, the CDC gathered data from select hospital emergency departments and hyperbaric oxygen chambers in Florida and conducted interviews.[7] There were five incidents involving six fatal CO poisonings, all resulting from indoor operation of a portable generator. There were also 51 nonfatal CO exposure incidents, 46 of which resulted from portable generator operation, injuring a total of 167 people. A total of 154 people were treated and released from the emergency department; 13 others were hospitalized. Overall, 77 people were treated with hyperbaric oxygen. In 22 of the 46 nonfatal generator incidents, the generators had been operated outside the dwelling, 15 inside the garage, and seven inside the home; the location of the generator was unknown for two incidents. Interviews with respondents representing 35 of the 51 nonfatal incidents revealed that households with CO poisoning with

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[D] % COHb reflects the percentage share of the body's total hemoglobin pool occupied by CO. Although the relationship is not absolute, % COHb levels can provide a useful index of CO poisoning severity. It is measured with a blood sample from the exposed person.

their generators outside reported placing the generator an average of 7 feet from the nearest door or window of the home (range 1 to 30 ft).

In 2009, the National Institute for Standards and Technology (NIST) conducted computer modeling simulations to try to ascertain a minimum safe distance from a house to operate a generator outdoors.[8] The infiltration of the generator exhaust into a house is affected by multiple factors, including but not limited to, size and location of openings to the home relative to the generator placement, house geometry, and wind speed and direction. The simulations, conducted on a one-story manufactured house, found that positioning a generator 15 feet from open windows may not be far enough to avoid excessive CO entry into the house.

In spite of these findings and numerous other published reports on CO poisoning deaths and injuries associated with generators, CPSC staff is not aware of any generator manufacturer who provides specific guidance regarding a safe distance to operate a generator, either fixed or portable, from occupied spaces, or spaces that could be occupied. In fact, some portable generator manufacturers recommend use of extension cords that are as short as possible, preferably less than 15 feet, to prevent voltage drop and possible overheating of wires. [9] Others also recommend that portable generators be placed under cover when it is wet outside because, although these products are intended for outdoor use only, they are not weatherized for safe use in wet conditions where they can present a risk of shock or electrocution. Staff believes that these recommendations to place the generator under cover and to minimize extension cord length can put the consumer at serious risk of CO exposure because the recommendations may encourage generator operation in close proximity to a residence or in an enclosed environment. The placement of the unit is especially significant when considering the fact that consumer use of, and demand for, portable generators to power home appliances increases dramatically in times of storms with wet or icing conditions that cause power outages. For extended outages in particular, homeowners experience a sense of urgency for basic needs, such as heat and refrigeration; yet the power cord on many home appliances commonly is not long enough to reach windows or other openings where the consumer could connect the appliance to a 15-foot extension cord that is located entirely outdoors. Furthermore, staff believes that it may not be possible in many settings for consumers to place a generator more than 15 feet away from all neighboring occupied buildings.

2.5. CO Hazard Reduction Strategy Based on Reduced Engine CO Emission Rate

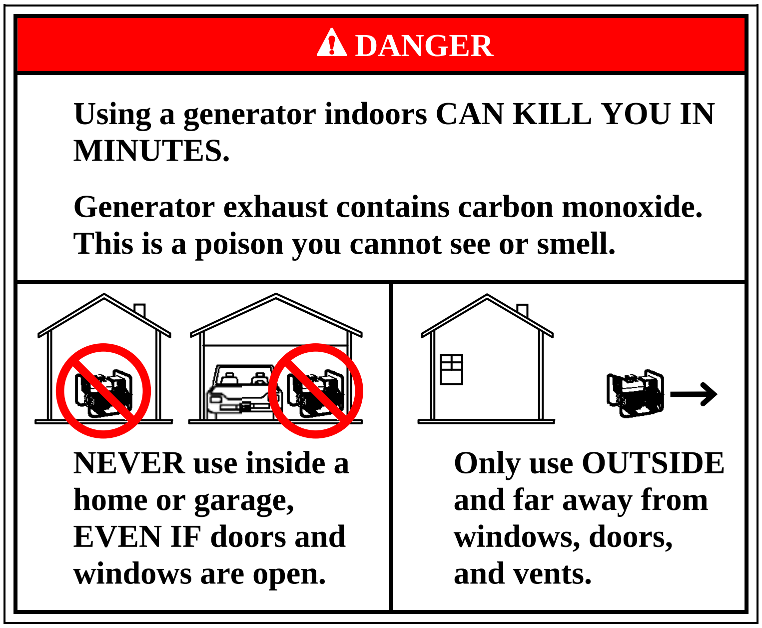
CPSC staff's preferred approach in addressing any hazard is to attempt to eliminate or reduce the hazard at the source; therefore, the strategy of substantially reducing the engine's CO emission rate is considered the most appropriate for addressing the CO poisoning hazard associated with this product. This will not only help to reduce the hazard for those who, either knowingly or unknowingly expose themselves to the risk of CO poisoning by operating a generator in an indoor location, but will also help to protect those who are making a conscious effort to use the product properly in an outdoor location. Staff's goal is not to reduce the CO emission rate to make generators safe to run indoors so that occupants can remain in the exposure without serious health consequences, but rather, to reduce it enough, such that symptom onset is delayed, and the rate of progression of worsening symptoms is significantly reduced. Staff believes this could give occupants a realistic chance to recognize that their symptoms are indicative of a developing hazardous situation, even if they are not aware of the cause, as well as a longer period of awareness which will provide them an opportunity to remove themselves from the exposure before being incapacitated. The high CO emission rate of current generators can result in situations where the COHb levels of exposed individuals rise suddenly and steeply, causing them to experience extremely quick onset of confusion, loss of muscular coordination, loss of consciousness, and death, without having first experienced milder CO poisoning symptoms associated with low or slowly rising CO-induced hypoxia. [Ref is TAB G] Without the warning provided by milder symptoms, victims have very little, if any, time to recognize that an imminent life-threatening environmental hazard is occurring or to seek safety or take other actions that could help their situation after the initiation of the exposure.

With this strategy in mind, staff created a technology development and demonstration program to see if a portable generator powered by an engine with a substantially reduced CO emission rate could be developed to reduce the risk of fatal and severe CO poisoning when used in an indoor location that is frequently reported in generator-related consumer fatalities. This demonstration program is described in subsequent sections of this memorandum and in the TABs contained in this package.

In October 2006, in response to the then Chairman's request for a review of portable generator safety, staff presented a briefing package to the Commission in which they stated their belief that the most reliable way to limit consumer exposure to harmful CO levels was to limit the engine's CO emission rate. With the goal as stated above, staff recommended that the Commission initiate rulemaking.[10] In December 2006, the Commission voted to approve an advance notice of proposed rulemaking (ANPR) for staff to begin research to investigate technologies that could reduce the risk of CO poisoning associated with portable generators. The ANPR was published in the *Federal Register* on December 12, 2006.[11]

In addition, on January 12, 2007, the Commission published a final rule that specified warning label requirements for portable generators as an intermediate step to help address the growing CO hazard. [15, 16] As documented in the 2006 staff briefing package, staff found that many generator manufacturers used warning labels and language in the owner's manual about the CO hazard that staff believed were inadequate and ambiguous, such as warnings that advised consumers to "provide proper ventilation." Also, as indicated in section 2.4, at least some manufacturers have included, and continue to include, language concerning use in wet conditions and/or extension cord length, which relates to shock and fire hazards concerns, but presents inherent conflicts to avoid the CO poisoning hazard. To help address the ambiguity, staff developed the mandatory label depicted in Figure 7, which became effective on May 14, 2007.

Figure 7. On-Product Carbon Monoxide Poisoning Hazard Label for Portable Generators



2.6. The U.S. Environmental Protection Agency and its Regulation of Small Spark-Ignition Engine Emissions

Because CPSC staff is pursuing a strategy of reducing the CO emission rate as the preferred means to reduce the generator-related CO poisoning hazard, it is germane to discuss the role of the U.S. Environmental Protection Agency (EPA) and their standards in regulating the emissions from engines that are used to power portable generators. To protect public health and welfare, the Clean Air Act gives authority to the EPA to set emission standards for small utility spark-ignition engines ("small SI engines") that provide power for a wide range of products typically owned by consumers, including portable generators. As a result, since 1995, the EPA has issued a series of emission regulations to help reduce pollutant emissions from small SI engines that contribute significantly to unhealthy air quality as assessed by nonattainment of the National Ambient Air Quality Standards (NAAQS) for ozone and CO. The most recent and stringent of these regulations was adopted on October 8, 2008, "*Control of Emissions from Nonroad Spark-Ignition Engines and Equipment; Final Rule*" ("Phase 3").[12] Phase 3 includes exhaust emission standards for the two classes of nonhandheld small SI engines (the classes are distinguished by engine displacement) that provide power to portable generators, as well as many other product applications. These standards target hydrocarbons and oxides of nitrogen (HC+NOx) emission reductions of approximately 35 percent below the EPA's previous Phase 2 standard (Phase 2 was promulgated in 1999, and was phased-in completely in 2007). The CO standard in Phase 3 remains unchanged from the Phase 2 standard, except for one important exception of a more stringent exhaust CO emission standard that applies uniquely to water-cooled small SI engines used in marine generator applications. This precedent-setting exception addresses acute life-threatening personal exposures to CO and is discussed in more detail in section 5 of this memorandum. The regulation of HC+NOx emissions is a higher priority than CO, due to the EPA's emphasis on attaining NAAQS for ozone, of which NOx and HC are precursors.[28] Table

1 shows the Phase 3 exhaust emission standards that applied starting in 2011 for the larger sizes of nonhandheld small SI engines (Class II) and in 2012 for the smaller sizes (Class I). [E]

Table 1. Phase 3 Small SI Nonhandheld Engine Exhaust Emission Standards and Schedule

Engine Displacement Class (cubic centimeters [cc])	Model Year	HC+NOx (g/kW-hr)	CO[(1)] (g/kW-hr)
Class I (>80 cc to <225cc)	2012	10.0	610
Class II (≥225 cc, up to 19 kW [25 hp])	2011	8.0	610

(1): As discussed in the paragraph above, the Phase 3 regulation has one important exception to the 610 g/kW-hr CO standard. This exception is a more stringent exhaust CO emission standard that applies uniquely to water-cooled small SI engines used to power marine generators. While these engines are covered under the nonhandheld small SI engines standards included in this table, Phase 3 has a CO standard of 5 g/kW-hr specifically for engines used in this particular application to address acute life-threatening personal exposures to CO. The background behind this particular standard is discussed in more detail in section 5 of this memorandum.

While the EPA set the Phase 3 HC+NOx standard to a relatively stringent level, the CO standard of 610 grams/kilowatt-hour (g/kW-hr) is comparatively high. This is because the EPA expects that many small engine manufacturers will use three-way catalysts with relatively low precious metal loading to favor HC+NOx selectivity over CO selectivity.[13] There is a desire to minimize CO oxidation in the catalyst because this is a highly exothermic reaction, releasing a significant amount of heat, which can present fire and burn-related safety concerns. The EPA also expects that some manufacturers will also need to make improvements in engine designs, cooling system designs, and fuel delivery systems to meet the HC+NOx standard. And for larger, multicylinder Class II engines, the EPA expects some may use electronic fuel injection (EFI).[12, 13]

Class I and II engines certified to the Phase 2 standard, as well as Class II engines now certified to meet Phase 3, are typically well below the 610 g/kW-hr CO emission standard. Based on CPSC staff's cursory review of the EPA's Certification Database[14] for engines used in portable generator applications, their CO emissions are generally in the range of 200 to 400 g/kW-hr, with some higher and some slightly lower. Class II engine emissions are generally lower than that of Class I.

3. Technology Demonstration Program

3.1. Overall Plan

As stated in section 2.5, staff created a technology development and demonstration program to show that a portable generator powered by an engine with a substantially reduced CO emission rate could be developed in order to reduce the risk of fatal and severe CO poisoning by

[E] In consumer-grade products, the engines are typically air-cooled, single-cylinder models and can be in either Class I or II. Large Class II engines may have two or three cylinders, and premium models with higher power may be water-cooled. Staff's understanding is that the nominal power rating that separates Class I engines from Class II engines is 6.5 horsepower (hp; 6.5 hp is equivalent to 4.8 kilowatts (kW)). Further, staff understands that portable generators that are powered by a Class I engine have an advertised continuous electrical power output rating up to nominally 3.5 kW. Portable generators powered by a Class II engine are nominally rated for continuous electrical power output between 3.5 kW and 18 kW.

significantly delaying the onset and rate of progression of CO poisoning symptoms. This demonstration program occurred in two separate series of efforts. The first involved developing a prototype low CO emission portable generator and demonstrating its performance with respect to durability and compliance with the EPA's small engine exhaust emissions standards at end of life. The steps for this effort included the following:

- Estimating the CO emission reduction needed to reduce the rate of progression of worsening symptoms of the CO exposure so that occupants have the opportunity to remove themselves from the home before being incapacitated.
- Soliciting through a request for information (RFI) possible techniques to significantly reduce the CO emission rate.
- Developing a prototype by modifying a commercially available portable generator with commercially available components to achieve the target CO emission rate while maintaining the HC+NOx emissions level within the standard specified on the engine's emission certification label.
- Evaluating the durability of the prototype generator engine and its adapted components as well as an unmodified, equipment as-manufactured (OEM) version of the same model by accumulating operating hours on both generators up to the rated useful life of the engine.
- Periodically measuring the exhaust emissions (at beginning, intermediate intervals, and after the durability program) to evaluate and compare engine and emission performance of the unmodified and prototype units.
- After completion of the durability program, subjecting the prototype engine to emission testing that meets EPA regulations, to ascertain if the prototype engine meets the regulated standard for HC+NOx, which the engine was originally labeled as being certified to, and confirming the CO emission rate.

A separate series of efforts involved demonstrating the prototype generator's performance with respect to predicted health impacts on hypothetical home occupants when empirically tested in a scenario frequently reported in fatal consumer incidents. The steps for this effort included the following:

- Conducting tests with an unmodified, OEM unit used for the prototype operating in the attached garage of a single family home to produce empirical data on the CO accumulation in the garage and infiltration into the house.
- Modifying that unit into the prototype configuration and retesting it in the same series of conditions used to test the unmodified OEM unit.
- Performing health effects modeling on the empirical results to predict the CO poisoning effects on hypothetical occupants in different areas of the house.
- Comparing the timing of predicted health impacts from both the unmodified OEM and prototype units to assess the efficacy of the prototype in providing a greater time interval for exposed persons to escape before incapacitation from CO poisoning is expected to occur.

Further details on each of these steps are provided in sections 3.2 through 3.5.

3.2. Staff's Estimated Need for CO Emissions Reductions, Challenges to Reducing CO Emissions, and Request for Information to Solicit Ideas

In 2004, staff tested a portable generator with an advertised continuous electrical power output rating of 5.5 kW, powered by a 7.46 kW air-cooled, carbureted SI Class II engine, in a one-zone environmental chamber to determine its CO generation rate under various conditions.[F,17] Using that data, staff performed preliminary indoor air quality (IAQ) modeling and estimated that a 92 percent reduction from staff's experimentally derived CO emission rate would likely result in a significant delay and reduced severity of the CO exposure in areas of a home remote from the generator location.[19]

Staff recognized that striving for CO reductions of this order on a single-cylinder air-cooled utility engine presented challenges. A simplified, brief explanation is provided here to help the reader understand the issues involved (more extensive details are provided throughout ref 13). The level of CO in the exhaust from an engine (called engine-out emissions) is primarily a function of the air-to-fuel ratio (AFR) at which the engine operates. This is because CO is produced when there is incomplete combustion of fuel, and incomplete combustion is most likely to occur at low AFRs (also called rich operation) in the engine. AFR, however, affects not only emissions, but also torque and power output, fuel consumption, and engine temperatures. Air-cooled engines are typically operated rich of stoichiometry (the theoretical point for complete combustion, which is 14.6 AFR for typical gasoline formulations) for increased engine torque output, reduced engine temperatures (to reduce the thermal load on the air-cooling system), and to ensure adequate fuel flow to the combustion chamber during load transients and when imperfect air-fuel mixing occurs. Rich operation results in higher HC and CO emissions and increased fuel consumption but works well for keeping the engine relatively cool and reducing engine-out NOx emissions. Reducing engine-out CO emissions can be achieved by running the engine at leaner AFR to attain more complete combustion; however, the higher combustion temperatures must be handled by the engine's cooling system to maintain engine durability, and there is a risk of abnormal combustion (*i.e.*, lean misfire and combustion knock), which impacts engine performance and durability. Engine-out NOx emissions can increase with the higher combustion temperatures of leaner operation, however, they can be reduced further post-combustion (called aftertreatment) using an exhaust catalyst designed for NOx reduction. Reducing CO emissions in an exhaust catalyst designed for promoting CO oxidation, on the other hand, releases a tremendous amount of heat, which can present fire and burn safety concerns. Therefore, in order to achieve significant reductions in CO exiting the tailpipe from a portable generator powered by an air-cooled engine, a challenge exists in determining both the appropriate AFR and catalyst formulation and geometry to maintain engine durability and performance, control engine-out and tailpipe emissions, optimize catalyst performance, and manage the heat produced to minimize surface temperatures out of concern for fires and burns. [G]

[F] A 5.5 kW generator was used because this size is in the range most commonly involved in fatal incidents in which the size of the associated generator was reported (see Figure 6), and it is also in the size range most commonly sold to consumers. [18]

[G] Even though the catalysts anticipated for EPA Phase 3-compliant engines are expected to favor HC+NOx selectivity over CO selectivity, which would minimize heat released in the catalyst, the EPA was required by Congress to assess potential safety issues, including the risk of fire and burn to consumers associated with the then-proposed catalyst-based Phase 3 emission standards for Class I and Class II engines. As a result, the EPA conducted

With this in mind, staff issued a request for information (RFI) in March 2006, to solicit ideas for substantially reducing the tailpipe exhaust CO emissions from gasoline engines used to power portable generators to levels that could reduce the number of CO poisoning deaths and injuries.[20] Providing a target CO emission reduction of 90 percent, staff sought solutions that would: (1) not negatively affect engine performance and engine life, (2) be able to meet the then-anticipated EPA Phase 3 HC+NOx standard for nonhandheld small SI engines, (3) minimize any increase in the fire and burn risk associated with increased temperatures on the exterior of the exhaust system, and (4) minimize incremental cost increases associated with the CO emission-abatement equipment to be consistent with product marketability.

A total of nine respondents to the RFI suggested a variety of approaches to address the hazard. Seven of the respondents identified catalytic exhaust aftertreatment, alone or coupled with a fuel injection system that would replace the existing carburetor fuel delivery system, as a viable technique to reduce CO emissions. According to some of the respondents, using a closed-loop electronic fuel injection (EFI) system greatly reduces the amount of unburned fuel in the engine-out exhaust, which would allow a catalyst to be used as an aftertreatment to reduce the amount of CO leaving the tailpipe in the range of 90 to 95 percent without causing unmanageable heat buildup in the catalyst. They indicated that catalytic converters and fuel injectors are used on small displacement 2-stroke and 4-stroke engines on motor-scooters in countries such as China and India and on small displacement motorcycles in the U.S.[21-25] One respondent in particular provided greater detail, stating that a closed-loop EFI system, based on low cost components similar to those used in the Asian scooter market, could be used to achieve less than 100 g/kW-hr of engine-out CO by calibrating the AFR near 12 for high power settings and stoichiometric AFR for light and part loads. He noted that two catalysts could be used in series for exhaust aftertreatment; the first would be a three-way catalyst brick, to convert NOx emissions that would be expected to be elevated from operating near stoichiometric conditions; and the second catalyst would be an oxidation catalyst, located downstream of the first catalyst. Furthermore, he noted that secondary ambient air could be injected between the two catalysts to provide more oxygen to the secondary catalyst, and thereby, achieve further reduction of the remaining CO. This respondent stated that the CO coming out the tailpipe could be reduced to below 25 g/kW-hr CO.[25]

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a safety study in addition to their extensive research, development, and testing evaluation efforts performed to assess potential technology applications that could meet their proposed Phase 3 requirements. The safety study involved thorough laboratory and field assessments of both Class I and Class II engines. Twelve Class I engines from four engine families that were certified to the Phase 2 standard were tested; they represented 96 percent of all gasoline small SI Class I engine sales for model year 2004. Eight Class II engines from three engine families, two of which were certified to the Phase 2 standard, were tested; they also represented families with high-volume sales in the small gasoline SI Class II engine category. The EPA safety study evaluated the incremental impact on safety of moving from the Phase 2 HC+NOx standard to the proposed Phase 3 HC+NOx standard and concluded that the then-proposed (later adopted in 2008) Phase 3 standard posed no incremental increase in the risk of fire or burn for Class I and Class II nonhandheld engines and, in fact, demonstrated a directional decrease in risk in a number of circumstances.[27]

3.3. Prototype Development, Durability Testing, and Certification Emission Testing at End of Rated Useful Life

Based on the information received in response to the RFI, in September 2006, the CPSC advertised a request for proposal (RFP) to develop and test the durability of a prototype low CO emission portable generator using a commercially available unit and commercially available fuel injection/electronic control technologies along with a catalyst for exhaust aftertreatment. Subsequently, a contract for this task was awarded to the University of Alabama (UA). The objectives, as stated in the contract, were to reduce the engine's CO emissions to the lowest possible level without negatively impacting engine power output, engine durability, maintainability, fuel economy, and risk of fire and burn. In addition, the prototype engine should continue to meet the emissions regulation to which the engine was originally certified. CPSC staff specified a target CO emission rate of 30 g/kW-hr, to be consistent with a nominal 90 percent reduction in CO from that of typical single-cylinder air-cooled engines that power portable generators with an advertised continuous electrical power output rating of 5.0 kW.

The contract with UA consisted of the following major tasks:

- Purchasing two new identical model, commercially available 5.0 kW portable generators, the first of which is to be left in its unmodified, OEM configuration (designated as the baseline unit); and the other is to be modified into the prototype configuration (designated as the prototype unit);
- Measuring the emissions on both units in their unmodified OEM configurations, before the unit designated as the prototype is modified;
- Modifying the prototype unit with commercially available EFI components and a catalyst to achieve the desired exhaust CO emission rate, while maintaining the engine's exhaust HC+NOx emission rate below the standard to which it was certified, as determined by the engine's emission certification label;
- Conducting a durability test program on both the prototype and baseline generators, whereby each is operated under identical load profiles for the full useful life of the engine, as rated by the engine manufacturer; and
- Measuring the exhaust emissions with the engine installed in the generator units before, during, and after the completion of the durability program.

The portable generator model chosen for the technology demonstration program was powered by a single-cylinder, air-cooled gasoline engine with an advertised rated power of 8.2 kW. The engine was labeled by the engine manufacturer as certified to the EPA's Phase 2 Class II emission standards with a rated useful life of 500 hours. Durability testing of both the unmodified and modified units was specified to allow direct comparison of any degradation in the prototype's engine performance or component life compared to that of the baseline unit over the 500 hours. The durability program was conducted with the engines installed in the generators so that the manifestation of any product-specific issues that might result from the adapted emission control technologies on the end-use consumer product could be observed.

TAB B contains a staff description of the prototype design and durability program, as well as an analysis and summary of the prototype's performance relative to the baseline unit. **TAB C** contains UA's final report, with detailed descriptions of the prototype construction, operation and implementation of the engine management system, test methods, test results, and post-durability analyses. A brief summary is provided here.

UA constructed the prototype by retrofitting the OEM engine with an engine management system (EMS) for EFI and integrating a small 3-way catalyst into a different muffler. The EFI was calibrated to operate at stoichiometric (14.6) AFR at all six loads in the load profile and the catalyst formulation primarily targeted NOx reduction. This AFR/catalyst combination was believed to be optimum to achieve the desired exhaust emission levels and to keep the engine cylinder head temperature below the engine manufacturer's recommended limit, the engine-out exhaust gas temperature within the catalyst manufacturer's recommended operating range, and the tailpipe exhaust gas and muffler surface temperatures within some moderate range of the temperatures of the unmodified baseline unit. To accommodate the catalyst, the muffler selected for the prototype generator was a different model that did not have the extensive internal baffling as that of the muffler on the baseline unit, and a shroud was added to reduce the risk of fires and burns.

The EMS included the following: an electronic control unit (ECU) with an internal manifold air pressure (MAP) sensor; fuel pump, hosing, and pressure regulator; fuel injector (replacing the existing carburetor fuel bowl and main metering jet); MAP tube inserted into the head downstream of the throttle body, and 300 millimeter (mm) hose to connect the tube to the MAP sensor mounted integral with the ECU; crank position sensor and toothed timing wheel; ignition coil; intake air temperature sensor; oil temperature sensor; a switching (binary) oxygen sensor for closed-loop control, installed in a custom-made exhaust manifold pipe between the exhaust port and muffler; and a wiring harness. A 12-volt battery was also added to power the ECU, ignition coil, and an electric starting motor that was added to replace the pull start mechanism because the latter interfered with the crank sensor hardware. Finally, UA installed a plug seat thermocouple and a thermocouple in the exhaust manifold pipe to monitor engine temperatures and mounted thermocouples on the hottest area, identified with an infrared camera, on the muffler surface and a custom-made muffler shroud.

The comparison of engine and emission performance of the prototype generator to the baseline generator was assessed by way of tests that UA performed, referred to as "generator emission tests," when the engines were new, during the durability program after 150 and 250 hours of operation, and after the 500-hour durability program. For the durability program, an automated hourly cyclic load profile consisting of six resistive loads of specific duration was applied through the generator's 240-volt receptacle with the intention of replicating the six-mode rated speed test cycle that the EPA uses in its emission test procedures for nonhandheld small SI engines designed for generator applications. The EPA's applicable regulations for the engine model in the generators that UA used are specified in 40 CFR part 90, *Control of Emissions from Nonroad Spark-Ignition Engines at or Below 19 Kilowatts* (this regulation sets the emission standards for Phase 2 small SI nonroad engines) and 40 CFR part 1065, *Engine-Testing Procedures* (this is the EPA's overall regulation covering Phase 2 engine emission test procedures). Staff's understanding is that the EPA's six-mode test cycle was developed by industry to replicate typical in-use operation of small utility engines when used in all types of engine-driven products. The test cycle calls for six specific modes, or loads, to be applied to the engine as measured with the engine installed on a dynamometer test platform. Mode 1 is full engine power and the five other modes (modes 2 through 6), are percentages (75%, 50%, 25%, 10%, and no load, respectively) of mode 1 power. With the engine installed in the generator, full engine power, as determined on the dynamometer by disabling or decoupling the governor from the throttle and physically holding the throttle wide open, was not achieved. The electrical power that was applied for mode 1 was the maximum that could be sustained without tripping the generator's breakers on the 240-volt circuit. This was found to be 5.5 kW, 500 watts greater than the advertised, continuous electrical power rating of the generator. For modes 2 through 6, the engine manufacturer's advertised 8.2 kW maximum power rating of the engine was used in conjunction with the generator manufacturer's alternator efficiency curve to estimate the electrical load that needed to be applied to achieve those desired engine loads. The resulting automated sequence of load bank settings for the hourly load profile used by UA during the 500-hour durability program is shown in Table 2.

Table 2. Hourly Load Profile Applied Throughout 500-hour Durability Program

Mode	1	2	3	4	5	6
Load bank setting (kW)	5.5	4.7	3.2	1.5	0.6	No resistive load
Duration (minutes)	5.5	12.0	17.5	18.0	4.0	3.0

The most notable findings from the durability program are as follows:

- After 500 hours of operation, the prototype demonstrated an approximate 30 percent reduction of HC+NOx and 93 percent reduction of CO, compared to the unmodified baseline unit.
- The prototype engine cylinder head temperature remained below the engine manufacturer's limit, and the exhaust manifold gas temperatures were within the catalyst manufacturer's recommended operating range.
- The integrity of the adapted emission control components was maintained throughout the durability test program, demonstrating the ability to reduce emissions, while not shortening the expected life of the engine or generator.
- The prototype reduced the average fuel consumption by approximately 20 percent, compared to the unmodified baseline unit.
- The prototype's muffler surface temperatures across all six modes ranged from 50° Celsius (C) to 83° C hotter than the muffler on the unmodified baseline unit. Factors contributing to the increased temperature on the prototype muffler surface may have been the muffler configuration, as the prototype muffler configuration differed from that of the unmodified, original muffler. The temperature of the prototype's muffler shroud, which was added to reduce the risk of fire and burns, was 110° C or less when the engine was operated over the range of deliverable power and is significantly lower than the muffler surface temperature range (266 to 434° C), measured on the surface of the unmodified baseline unit's unshrouded muffler.

After completion of the UA durability testing, staff issued an RFP for conducting independent laboratory exhaust emission testing on the prototype engine in accordance with the EPA's regulations and test procedures specified in 40 CFR parts 90 and 1065. The purpose for this testing was to ascertain, at the end of the engine's rated useful life, if the prototype engine's HC+NOx emission rate would meet the EPA's Phase 2 standard, which the unmodified OEM version of the engine was originally labeled as being certified to, as well staff's target exhaust CO emission rate. A contract was awarded to Intertek Carnot Emission Services (Intertek CES), a research and development facility, specializing in the offroad engine industry, whose emission measurements have been used for lab-to-lab correlation with the EPA and other major engine manufacturers' emissions test facilities. Intertek CES conducted the emission tests of the prototype when equipped with the muffler containing the integrated catalyst and when equipped with a muffler that did not have an integrated catalyst. CPSC staff requested tests without the catalyst in order to assess its effectiveness.

A staff analysis and summary of the prototype's end-of-life emission test results are included in **TAB B**, and Intertek CES's test report is located in **TAB D**. The results of testing the prototype engine on the dynamometer show the following:

- The prototype configuration of EFI and catalyst muffler had a HC+NOx emission rate of 6.7 g/kW-hr, which is approximately 45 percent below the EPA Phase 2 standard (which is 12.1 g/kW-hr for Class II engines) and approximately 16 percent below the Phase 3 standard (which is 8.0 g/kW-hr for Class II engines [see Table 1]). For the prototype configuration of EFI, but without the catalyst, the HC+NOx emission rate was 13.0 g/kW-hr, which exceeds both the Phase 2 and 3 standards. These results indicate that the catalyst is required for the prototype to comply with both the OEM engine's applicable EPA Phase 2 and the now current Phase 3 HC+NOx emissions standard for Class II engines.
- The prototype configuration of EFI and catalyst muffler had a CO emission rate of 6.0 g/kW-hr, well below staff's 30 g/kW-hr target, achieving CO emissions reduction of more than 95 percent, compared to the published CO emission certification data for the unmodified engine, and 99 percent below the Phase 2 and Phase 3 CO standard of 610 g/kW-hr. For the prototype configuration of EFI, but without the catalyst, the CO emissions were 28.1 g/kW-hr.
- The prototype generator's cylinder head temperature remained below the engine manufacturer's recommended limit, and the prototype generator's exhaust gas manifold temperature, at all modes, remained within the catalyst manufacturer's recommended operating range.
- The prototype engine delivered a maximum power of 7.9 kW, which is within 0.3 kW of the advertised rated power for the unmodified OEM carbureted engine.

3.4. Generator Testing in Common Fatal Consumer Scenario

In addition to the work described above, UA also built two additional prototype generators for the CPSC to be used in a sequence of tests where a generator was operated in the attached garage of a single-family home, a common fatal scenario found in the CPSC's incident data. The purpose of this testing was to measure the CO accumulation in the garage and its infiltration into the house resulting from a generator operating in its unmodified OEM condition, as well as after being modified into the prototype configuration. Under an Interagency Agreement (IAG) between the National Institute of Standards and Technology (NIST) and the CPSC, the testing was performed by NIST in their “test house,” a double-wide manufactured home that is designed for conducting residential indoor air quality (IAQ) studies and is located on the NIST campus. The tests for both generator configurations were performed under the same set of controllable test conditions (*i.e.,* position of doors and status of the heating, ventilation, air conditioning (HVAC) fan) and relatively similar uncontrollable conditions (*i.e.* ambient temperature and wind speed and direction). (NIST’s test report is located in **TAB E**). Staff then performed health effects modeling on NIST’s resulting CO-time course profiles to predict the onset and rate of progression of worsening CO poisoning symptoms in hypothetical house occupants. A summary of that health effects assessment is provided in section 3.5.

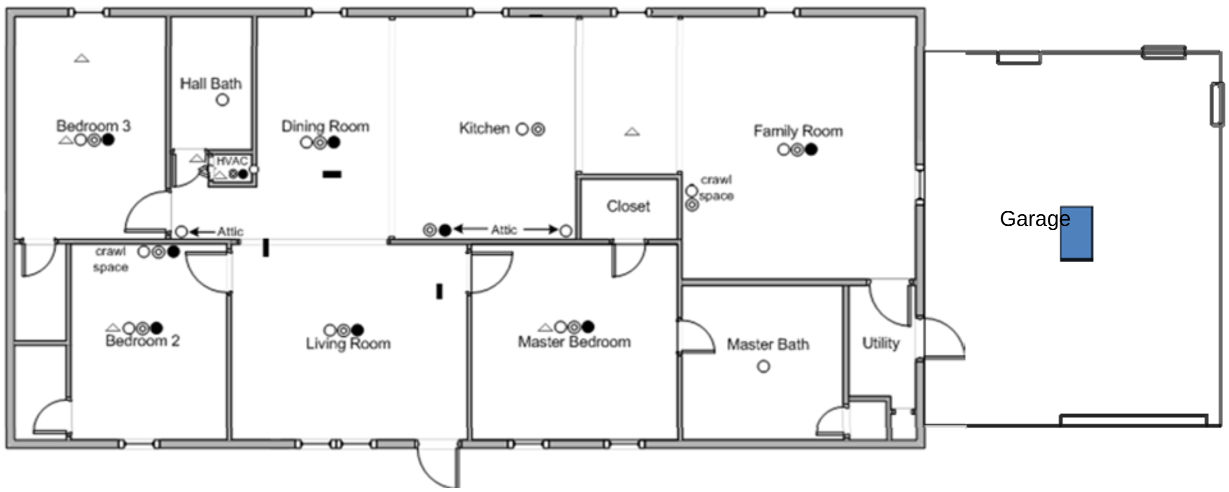
Because only a limited number of conditions could be tested, NIST will supplement the empirical data by using their multizone airflow and IAQ simulation program CONTAM to predict CO accumulation and infiltration data under a variety of additional conditions. NIST will perform their modeling, using the engine CO emission rates they determined from testing the prototype generator in a one-zone shed. The results of that modeling work will be presented in a future report from NIST to CPSC.

3.4.1. NIST Test House

The test house includes three bedrooms (MBR, BR2, BR3), living room (LR), family room (FR), kitchen (KIT), and an attached garage. An aerial view and floor plan of the house are shown in Figures 8 and 9. 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 105 m^2 (1130 ft^2) and a volume of 89.4 m^3 (3150 ft^3). The house is instrumented to measure ventilation rates due to infiltration and mechanical ventilation, interzone airflow rates, building air pressures, and ventilation air distribution. Room air samples, drawn from the center of each room at a point 5 feet above the floor, were routed to a variety of engine exhaust analyzers.

Figure 8. Aerial View of NIST Manufactured Test House.

Figure 9. Floor Plan of NIST Manufactured Test House.



Note: Circular symbols represent locations where tracer gas is injected and relative humidity and temperature are measured in each interior room. Rectangle in garage represents the location of the portable generator.

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, listed in Table 3[H] in section 3.4.4, included two different garage bay door positions (fully closed or open nominally 24 inches [in]), two connecting door settings between the garage and the family room (fully closed or open nominally 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 various configurations. Different positions of the bay door and garage-house door were investigated because, 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 the oxygen. The degree of either door's opening will greatly impact whether 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 and is also important for understanding how these variables influence the rate of exhaust infiltration into different areas of the test house from the garage. In addition, variations of these different conditions can be found in CPSC staff's investigation reports of fatal CO poisonings involving generators. These reports include cases in which consumers were seemingly aware of the CO poisoning hazard because they attempted to provide what they considered "proper ventilation" by operating the generator in a partially open garage. A bay door opening of 24 inches was selected, in particular, based on it being within the range of openings that can be modeled using CONTAM. The house door opening of 2 inches was selected because it is a reasonable opening amount to allow the passage of an extension cord from the generator into the house. The status of the HVAC fan, which circulates the interior air throughout the

[H] The tests reported in Table 4 are a representative subset of numerous tests that were performed with the generators operating in NIST's test house garage. A complete listing of the tests that were performed and their results will be provided in NIST's pending report referenced in section 3.4.

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 crawlspace.[26] 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.

3.4.2. The First Generation Prototype, "mod GenX"

The first prototype built for testing at NIST was identical to that of the durability-tested prototype, using the same model generator, including the engine, as well as the EMS and its associated sensors and components; it was also calibrated to operate at stoichiometric AFR and used the same catalyst formulation and geometry integrated into the same model muffler. Before UA modified it into the prototype configuration, NIST tested this unit in its unmodified, OEM carbureted condition in the test house in each of the seven different test house configurations to obtain the CO infiltration data. In the unmodified OEM condition, this generator is referred to as "unmod Gen X." This unit was then shipped to UA for modification into the prototype configuration. After UA modified it, the unit was shipped back to NIST for the comparative series of tests in the test house. In the prototype configuration, this unit is referred to as "mod Gen X."

3.4.3. The Second Generation Prototype, "Gen SO1"

Even before mod Gen X was constructed, CPSC staff tasked UA to construct a second prototype in response to staff's concern regarding the possibility that the prototype engine's CO emission rate might increase when operated in a confined space, in situations where the engine potentially might consume the available oxygen at a rate exceeding the rate at which it could be replenished by air exchange. Staff had uncertainty about the minimum oxygen level in the intake air that would be required by the prototype to maintain adequate combustion and catalyst efficiency and, correspondingly, to maintain the target CO emission rate. Thus, a task order was issued to see if UA could develop, and program into the ECU of this second prototype generator, a switchable (on/off, for testing purposes) algorithm that, when enabled, would sense when the generator was operating in an enclosed space and respond by automatically shutting off the engine. CPSC staff specifically directed that the algorithm should not rely on any additional sensors beyond those already integral to the existing EMS so as to serve as a tamper-proof, supplementary approach to further reducing the risk of CO poisoning associated with the prototype generator, without adding any additional component cost.

Although the preference was to use the same model generator for this second prototype as that of the baseline unit, durability-tested prototype, and Gen X, that model was no longer available by the time this task order was added. The OEM generator used for this second prototype, referred to as "Gen SO1," used the same engine but had a different alternator with an advertised continuous electrical power output rating of 7 kW. Also, the ECU that was previously used on the durability-tested prototype and mod Gen X was no longer supported by its manufacturer, so an upgraded version provided by the same manufacturer was used for the Gen SO1 prototype. This ECU differs from the previous model in that it uses an external MAP sensor and a heated switching oxygen sensor, and it also has some programmed features for improved fuel control. UA conducted testing at their laboratory in an enclosure and developed an algorithm intended to sense confined space operation, based on trends of specific engine operating parameters. The ECU manufacturer, working in conjunction with UA, then programmed the algorithm into the controller and incorporated a test operator-controlled feature to enable or disable it. Aside from these differences, the other hardware used in the construction of Gen SO1 was identical to those components used on the durability-tested prototype and mod Gen X. The ECU was calibrated to operate with the same stoichiometric AFR and a catalyst with the same formulation/geometry was integrated into the same model muffler as that of the durability-tested prototype and mod Gen X.

Although the algorithm performed well when tested in UA's test enclosure, three specific issues surfaced sporadically during testing of the algorithm at NIST:

- With sudden and significant load changes, and much less frequently under constant load, the algorithm would sometimes cause the engine to shut off when operated in an unconfined condition outdoors.
- The algorithm would rarely cause the engine to shut off when operated at extremely light loads in an enclosed environment.
- The algorithm would generally shut off the engine when operating in an enclosed environment above very light loads, but on rare occasions, including high loads, it failed to shut off the engine.

As a result, the algorithm was disabled for the seven different test house configuration tests that were performed with Gen SO1.

UA's testing and development effort for the shutoff algorithm, along with the programming logic, is documented in **TAB F**. Even with the identified limitations of the algorithm, it demonstrated its capability to shut off the engine when the algorithm's logic rendered a shutoff decision. Work on the initial algorithm also provided information for another possible approach, based on employing data from the ECU to estimate the oxygen concentration in the intake air. UA is continuing to work on this as an alternative strategy for a shutoff algorithm.

3.4.4. Summary of Tests Conducted and their Results

All tests were conducted with the generator placed in the middle of the garage with the exhaust pipe pointing toward the garage wall adjoining the house. The generator was operated using reformulated gasoline containing 10 percent ethanol obtained from the NIST motor pool, which is purchased to the same specification year-round. A portable alternating current (AC) resistive load bank, with 250-watt switches, was connected to the generator's 240-volt receptacle to draw electrical power as a surrogate for consumer appliance loads. An hourly cyclic load profile—very similar to that used by UA during the durability program—was applied; however, it was applied in the reverse order, with progressively increasing loads (no resistive load for 3 minutes, 0.5 kW for 4 minutes, 1.5 kW for 18 minutes, 3.0 kW for 17.5 minutes, 4.5 kW for 12 minutes, and 5.5 kW for 5.5 minutes). The delivered power was measured during all tests.

Because staff's goal is to demonstrate that the prototype generator extends the time interval between symptom onset and incapacitation, the intention with all of the tests was to operate the generator at least long enough to produce CO time course profiles in the house that would correlate to the time of predicted incapacitation. In practice, the duration of some tests varied due to a variety of circumstances, and sometimes, some tests were shorter than desired. Because it is not staff's intention to make the prototype generator safe for indoor operation, such that occupants would be expected to survive without serious CO injuries if they do not escape, no tests were run until the generator exhausted a full tank of fuel. Longer duration data will be modeled subsequently, using CONTAM software. For most tests, after the generator was stopped, an exhaust fan located on an exterior wall of the garage was turned on immediately in order to mechanically (*i.e.,* force) vent the exhaust out of the house and garage. In a few tests, where time and circumstances permitted, natural decay was allowed to occur for some length of time after the generator was stopped, prior to initiation of forced venting.

All tests with unmod Gen X were conducted in April and May 2008. Tests with mod Gen X and Gen SO1 were conducted in April and May 2010. Table 3 is a summary of the tests reported here and their results. Unfortunately, limitations in the test program would not support continued testing of both prototypes; therefore, the performance of each prototype was compared to the other after tests O and R were conducted with mod Gen X, and Tests N and T were conducted with Gen SO1. The decision was made to continue the remainder of the generator testing with Gen SO1. Three of the remaining five tests with Gen SO1 were performed with a muffler that did not have a catalyst ("noncat" muffler) in order to get an indication of the catalyst's performance in further lowering the CO emissions.

To monitor prototype engine operation, both prototypes were outfitted with a plug seat thermocouple and thermocouples located in the oil sump and in the exhaust upstream of the muffler. A Lambda sensor measured the AFR upstream of the muffler. For some of the tests, muffler and muffler shroud temperatures were measured, using thermocouples mounted directly on their surfaces, at the hottest locations previously identified by infrared cameras during UA's prototype tests.

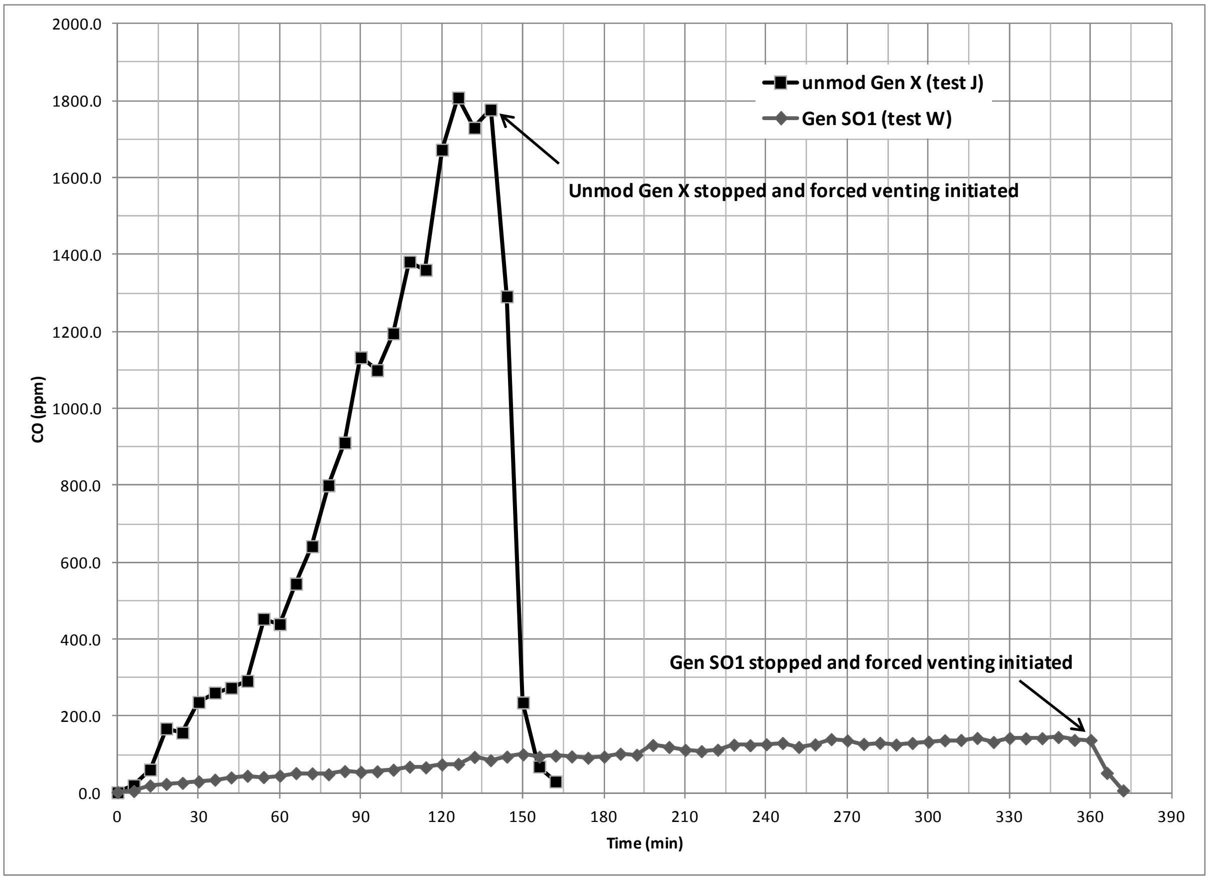
Table 3. Summary of Tests Conducted at NIST and Results

Generator	Test ID	Garage bay door	Garage to house entry door	HVAC fan	Outdoor Temp (°C)	Wind speed (m/s)	Test Duration (h)	Garage Peak CO Concentration (ppm_v)	% Reduction based on garage	Peak CO concentration in house (ppm_v)
unmod GenX	B	Closed	Open 2"	OFF	20.1	6.5	3	19,500 (12,800 at 2 h)	NA	6500
modGenX	O	Closed	Open 2"	OFF	22	6.5	4.5	3000 (1,400 at 3 h)	93	800
SO1	N	Closed	Open 2"	OFF	19.9	6.3	2	300	98	140
unmod GenX	F	Open 24"	Closed	OFF	22.8	7.7	4	1,500	NA	200
modGenX	R	Open 24"	Closed	OFF	19.9	6.7	4	30	98	5
SO1	T	Open 24"	Closed	OFF	13.4	6.9	3	300 (20 after initial spike)	98	50
unmod GenX	I	Closed	Open 2"	ON	22.8	7.4	4	18,600	NA	10,600
SO1 with noncat muffler	Z	Closed	Open 2"	ON	28.3	6.7	4.75	630	97	360
unmod GenX	J	Closed	Closed	ON	18.2	9.6	2.25	21,300	NA	1,800
SO1	W	Closed	Closed	ON	17.8	9.5	6	960 (640 at 2.25 h)	97	145
unmod GenX	D	Closed	Closed	OFF	12.2	8.2	2	23,000	NA	1660
SO1 with noncat muffler	AH	Closed	Closed	OFF	15.6	6.5	5	2,300	90	470
unmod GenX	G	Open 24"	Open 2"	ON	25.1	7	2	1,100	NA	220
SO1	U	Open 24"	Open 2"	ON	20.4	7.8	2	260 (< 30 after initial spike)	97	90
unmod GenX	K	Open 24"	Open 2"	OFF	13.84	7	>2	680	NA	320
SO1 with noncat muffler	V	Open 24"	Open 2"	OFF	15.8	6.5	>2	430 (50 to 80 after initial spike)	85 to 88	135

These tests document that the prototype generator Gen SO1—equipped with the catalyst-muffler—achieved a 97 percent reduction in CO, compared to the unmodified OEM carbureted version of the same engine in unmod Gen X, based on the peak CO concentrations achieved in the garage after equivalent durations of generator operation. An example that graphically shows the resulting CO time-course profiles in the family room from both generators for one of the test house configurations is shown in Figure 10. In this test house configuration, the garage bay door was fully closed, the connecting door between the garage and utility room was fully closed, and the house HVAC fan was on. Test J with unmod Gen X was run for 2.25 hours, and the CO concentration in the family room at this time reached a peak of about 1800 ppm.[I] In contrast, Gen SO1 was run for 6 hours in Test W, and the family room CO concentration reached a peak of about 145 ppm at that time. In both tests, after the generator was stopped, the house and garage were mechanically vented, causing the CO level to drop much more rapidly than if the CO were allowed to decay naturally.

[I] After 2.25 hours, the garage oxygen level was about 16 percent, and the generator was operating so poorly that the test operator chose to end the test. The engine did not stall out. It should be noted that CPSC staff's investigation reports commonly note that the generator involved in a fatal incident with the generator located indoors was found with the switch in the "on" position and the fuel tank exhausted. Even with oxygen depletion occurring, the engine continues to run, "limping along" with very poor combustion occurring, until it runs out of fuel.

Figure 10. CO Time Course Profiles in Family Room with Generator Running in Garage and Garage Bay Door Fully Closed, Garage/Utility Room Door Fully Closed, and HVAC Fan On



A complete description of the generator test program and test results are provided in NIST's report, contained in **TAB E**.

3.5. Health Assessment of Empirical Data Obtained from NIST Testing

Staff performed health effects modeling of the CO time-course profiles obtained from the seven pairs of tests performed at the NIST test house as an initial means to assess the efficacy of the prototype in reducing the risk of fatal and severe CO poisoning relative to that of the unmodified unit. While **TAB G** fully documents staff's analyses, a summary of the most pertinent information is provided here.

A computer model of the nonlinear form of the Coburn-Forster-Kane (CFK) equation [J] was used to estimate, from the CO time-course profiles, the expected corresponding COHb time-course profiles of hypothetical adult occupants in particular locations of the house. The percent COHb level serves as a useful, although inexact, approximation of acute CO uptake by the body, and of symptom severity. Table 4 shows the approximate correlation. Staff cautions that this

[J] The CFK is widely recognized as being the most physiologically accurate, predictive model for estimating COHb levels that has the broadest application across different CO exposure scenarios.[4]

relationship is not absolute; that there is variation among individuals due to different physiological characteristics and/or health status; and staff advises that the symptoms should be regarded as a continuum of health effects with overlapping transitions. Furthermore, staff notes that in situations where COHb levels rise steeply and suddenly, it is possible for exposed individuals to experience extremely quick onset of confusion, loss of muscular coordination, loss of consciousness, and death, without having first experienced milder CO poisoning symptoms associated with low or slowly rising CO exposures.

Table 4. Approximate Correlation Between Acute %COHb Levels and Symptoms in Healthy Adults

% COHb	Symptoms
<10%	No perceptible ill effects*
10-20	Mild headache, labored breathing, decreased exercise tolerance
20-30	Throbbing headache, mild nausea
30-40	Severe headache, dizziness, nausea, vomiting, cognitive impairment
40-50	Confusion, unconsciousness, coma, possible death
50-70	Coma, brain damage, seizures, death
>70	Typically fatal

(Source: Burton, 1996) ***** *Some studies have reported adverse health effects in some cardiac patients at 2-5% COHb)*

Staff modeled COHb profiles from the empirical NIST test house CO profile data and, from those predicted results, estimated the times when occupants in the garage, family room (FAM), and master bedroom (MBR) would be expected to be aware of obvious adverse symptoms (20% COHb), be incapacitated by (40% COHb), and potentially die from (60% COHb) the CO exposure. After preliminary examination of the NIST CO data, the FAM and MBR were selected as being generally representative of the test house living space areas that had the highest and lowest CO exposure profiles, respectively. Table 5 provides a summary of the 14 tests showing the predicted times of perceptible and obvious symptom onset, incapacitation, and death for victims in the FAM and MBR living spaces and also in the garage location of the generator. This table also includes the estimated times in which the mandatory alarm activation criteria for a residential CO alarm were reached. By determining the predicted time intervals between these critical events, staff assessed the increased opportunity to escape that the prototype generator can provide, compared to that of the unmodified unit for each of the paired tests. To illustrate the results, a detailed discussion of the paired tests involving Gen SO1 equipped with the cat muffler, compared to unmod Gen X is provided here. These are tests J and W, tests B and N, tests G and U, and tests F and T. After the end-of-life exhaust emissions tests—which were performed by Intertek CES after the NIST testing was completed— determined that the prototype engine with the noncat muffler did not meet the Phase 2 or Phase 3 standards for HC+NOx, staff decided that the Gen SO1 with noncat muffler test results are of less importance, and so, they are not discussed here.

Table 5. Predicted Times to Onset of Perceptible Symptoms, Obvious Symptoms, Incapacitation, and Death as Assessed by Attainment of COHb levels of Approximately 10%, 20%, 40%, and 60%, for Occupants in Garage, FAM, and MBR of NIST Test House During Generator Tests.

Test ID	B	N	I	Z	D	AH	J	W	K	V	G	U	F	T
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 noncat	Unmod GenX	SO1 noncat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 noncat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Garage Bay Door	closed	closed	closed	closed	closed	closed	closed	closed	24"	24"	24"	24"	24"	24"
Connecting Door to utility room	2"	2"	2"	2"	closed	closed	closed	closed	2"	2"	2"	2"	closed	closed
HVAC fan	off	off	on	on	off	off	on	on	off	off	on	on	off	off
Engine Run Time (minutes)	185	138	245	281	121	301	140	361	130	140	126	123	250	182
Decay (min) v Forced Venting	FV	D (45)	D (60)	FV	FV	D (45)	FV	FV	FV	FV	FV	D (30)	D (60)	FV
GARAGE														
Time to 10% COHb - mins	20	76	16	42	15	30	17	30	35	ERT	25	ERT	25	ERT
Time to 20% COHb - mins	26	ERT	22	84	20	50	22	66	64	ERT	68	ERT	61	ERT
Time to 40% COHb - mins	34	ERT	30	241	28	85	29	162	ERT	ERT	ERT	ERT	121	ERT
Time to 60% COHb - mins	40	ERT	36	ERT	34	111	35	ERT	ERT	ERT	ERT	ERT	189	ERT
Minutes from 20% to 40% COHb	8	ERT	8	157	8	35	7	96	ERT	ERT	ERT	ERT	60	ERT
FAM - Earliest CO alarm times	44	312	33	104	53	161	67	402	31	NR	80	NR	191	NR
Time to 10% COHb - mins	47	ERT	47	114	67	160	67	258	93	ERT	102	ERT	174	ERT
Time to 20% COHb - mins	64	ERT	62	193	88	220	91	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 40% COHb - mins	83	ERT	72	ERT	117	ERT	120	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 60% COHb - mins	99	ERT	86	ERT	ERT	ERT	149	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Minutes from 20% to 40% COHb	19	ERT	10	ERT	29	ERT	29	ERT	ERT	ERT	ERT	ERT	ERT	ERT
MBR - Earliest CO alarm times	69	312	56	120	120	163	98	400	99	NR	132	NR	372	NR
Time to 10% COHb	76	210	67	132	120	160	97	324	103	ERT	138	ERT	270	ERT
Time to 20% COHb	93	ERT	76	216	ERT	222	121	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 40% COHb	118	ERT	93	ERT	ERT	ERT	156	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 60% COHb	136	ERT	108	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Minutes from 20% to 40% COHb	25	ERT	17	EFT	ERT	ERT	35	ERT	ERT	ERT	ERT	ERT	ERT	ERT

NR: CO alarm activation criterion was not reached   ERT: exceeded the engine run time; the specific % COHb level was not reached during the duration of the test.

Note: COHb data was modeled with an assumed breathing rate of 15 liters per minute (l/min), which staff considers reasonable for healthy adults performing light-to-moderate indoor activities. (The majority of victims in the CPSC's incident data were adult males.)

Tests J and W:

Test J was performed with unmod GenX operating in the garage for 140 minutes with the bay door fully closed, the connecting door from the garage to the utility room closed, and the house HVAC fan turned on.[K] The times to reach obvious symptom recognition in the garage, FAM and MBR were 22, 91, and 121 minutes, respectively, after the generator was started. Incapacitating exposures were reached 7, 29, and 35 minutes later, respectively. Lethal CO exposures were reached 6 and 29 minutes after incapacitation in the garage and FAM, respectively. The lethal exposure in the FAM room was attained nine minutes after the generator was stopped and forced venting initiated to help remove the exhaust from the test house. Without forced venting, the FAM lethal exposure would have occurred sooner. With forced venting occurring, a lethal CO exposure was not attained in the MBR. Contrasting that to the paired test W with Gen SO1 equipped with the cat muffler operating in the garage for 361 minutes with the same conditions for the doors and HVAC fan, the time to reach obvious symptom recognition in the garage was 66 minutes after the generator was started. Incapacitation was reached 96 minutes later. While the predicted COHb level did not quite reach the probable death level (60% COHb) in the garage during the 6-hour run time, the estimated time to *possible* death *(~50% COHb*) was reached about 56 minutes after incapacitation. In the FAM and MBR, projected peak COHb levels of 14 percent and 12 percent, respectively, did not reach the level of obvious symptom recognition within the 6 hours of engine run time.

As for activation of a CO alarm, if one was located in the MBR[L] during test J with unmod Gen X, it would be expected to activate [M] at about 98 minutes after the generator was started. The occupants in the FAM at that time would be expected to have obvious onset of symptoms with a COHb level of about 25 percent, leaving an estimated 22 minutes to escape before being incapacitated. The CO level in the garage at this same time was approximately 18,500 ppm, which would incapacitate anyone within 3 minutes who entered the garage for any reason, such as to check on the generator, rescue someone, or exit through the garage. In test W with Gen SO1equipped with the cat muffler, CO levels in the MBR did not reach the activation criteria required for an alarm, although it is projected that alarm activation would occur at least by 400 minutes, assuming CO levels remained at least above 70 ppm. Staff projects that the CO level in the garage at 400 minutes would be below 1,200 ppm, which is the CO level defined by the

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[K] During test J, the load profile was inadvertently applied in reverse order (high load to no load). As concluded in NIST's interim report, the resulting CO time-course profile in the garage did not appear to be affected by this, based upon comparison with the garage time-course profile during test D, which only differed from test J by the status of the HVAC fan and the load profile going from no to high load.

[L] CPSC advises consumers to locate CO alarms near sleeping areas.

[M] Predicted times for alarm activation are based on alarm threshold requirements specified in *Underwriters Laboratories (UL) Standard for Safety for Single and Multiple Station Carbon Monoxide Alarms, UL 2034, Third Edition, dated February 28, 2008* (including revisions through February 20, 2009 incorporating changes to the title page that designate UL 2034 as an ANSI standard, ANSI/UL 2034).

National Institutes of Occupational Safety and Health (NIOSH) as being *Immediately Dangerous to Life and Health (IDLH).*[N]

<u>Tests B and N</u>:

Test B was performed with unmod GenX operating in the garage for 185 minutes with the bay door fully closed, the connecting door from the garage to the utility room open 2 inches, and the house HVAC fan turned off. The times to reach obvious symptom recognition in the garage, FAM, and MBR were 26, 64, and 93 minutes, respectively, after the generator was started. Incapacitating exposures were reached 8, 19, and 25 minutes later, respectively. Lethal CO exposures were reached 7, 16, and 18 minutes after incapacitation, respectively. Contrasting that to the paired test N with Gen SO1 equipped with the cat muffler operating in the garage for 138 minutes [O] with the same conditions for the doors and HVAC fan, the COHb levels predicted in all three areas did not reach the 20% COHb threshold, where appearance of obvious symptoms might be expected. In all the living spaces, levels were just around the 10% COHb threshold, where symptom recognition might begin. Although Gen SO1 was run for 47 fewer minutes than unmod Gen X, it is known that it would take more than 138 minutes of run time for the COHb to reach the point of obvious symptom recognition in the garage, and even longer in the house.[P]

As for activation of a CO alarm, if one was located in the MBR during test B with unmod Gen X, it would be expected to activate at about 69 minutes after the generator was started. The occupants in the FAM at that time would be expected to have obvious onset of symptoms with a COHb level of about 25 percent, leaving an estimated 14 minutes to escape before being incapacitated. The CO level in the garage at this same time when the CO alarm activated in the MBR was approximately 8,400 ppm, which would incapacitate anyone who entered the garage within a few minutes. In test N with Gen SO1equipped with the cat muffler, CO levels in MBR did not reach the activation criteria required for an alarm, though it is projected that alarm activation would occur at least by 312 minutes, assuming CO levels remained at least above 70 ppm.

[N] The NIOSH IDLH is defined as: "*An acute respiratory exposure that poses an immediate threat of loss of life, immediate or delayed irreversible adverse effects on health, or acute eye exposure that would prevent escape from a hazardous atmosphere within 30 minutes.*"

[O] This test was terminated prematurely after the generator unexpectedly dropped the load and an investigation was initiated to determine the cause. It was determined to be caused by a blown fuse on the load bank.

[P] If Gen SO1 had been run in test N for the same 6-hour duration as it ran in test W, the peak COHb for garage occupants would be expected to be less than the 50 percent predicted in test W, when the connecting door between the garage and the utility room was closed. (This is because opening the connecting door two inches significantly impacts the CO migration out of the garage, as evidenced by comparing the garage CO levels between tests W and N that were reached at identical engine run times.) On the other hand, Test N's peak COHb levels in the FAM and MBR would likely have exceeded the respective 14 percent and 12 percent levels predicted in test W, and a greater disparity between the two areas would be expected with the HVAC fan off. (The HVAC fan evenly distributes CO entering from the garage throughout the living spaces.) It is important to note that because the house volume is almost four times that of the garage, the increase of COHb levels in the FAM and MBR would be significantly less than the decrease of the COHb in the garage.

Tests G and U:

Test G was performed with unmod GenX operating in the garage for 126 minutes with the bay door open 24 inches, the connecting door from the garage to the utility room open 2 inches, and the house HVAC fan turned on. The time to reach obvious symptom recognition in the garage was 68 minutes after the generator was started. The peak COHb was about 35 percent, which is associated with moderate to severe symptoms, and was estimated to be reached about 60 minutes later. In the FAM, the onset of possibly perceptible symptoms (10% COHb) started about 102 after generator start up and reached a projected peak of 14% COHb after 144 minutes, which was 18 minutes after the generator was stopped and forced venting initiated to help remove the exhaust. A peak of 10% COHb was reached in the MBR at this same time. Contrasting that to the paired test U with Gen SO1 equipped with the cat muffler operating in the garage for 123 minutes with the same conditions for the doors and HVAC fan, predicted COHb levels in all three areas did not exceed 4% COHb, which is regarded as a level where healthy individuals would be asymptomatic.

As for activation of a CO alarm, if one was located in the MBR during test G with unmod Gen X, it would be expected to activate at about 6 minutes after the generator was stopped. With forced venting in effect, removing the exhaust from the house and garage by then, the CO level in the garage at this same time had dropped to approximately 200 ppm. Alarm activation should allow an adequate time interval for hypothetical occupants to exit the test house and have a non-life-threatening impact on those who might choose to exit through the garage. In Test U with Gen SO1 equipped with the cat muffler, the CO levels in the FAM and MBR did not reach the CO alarm activation criteria, and predicted COHb levels remained below 4% COHb.

Tests F and T:

Test F was performed with unmod GenX operating in the garage for 250 minutes with the bay door open 24 inches, the connecting door from the garage to the utility room closed, and the house HVAC fan turned off. The times to reach obvious symptom recognition in the garage was 61 minutes after the generator was started, with incapacitation occurring 60 minutes later, and death occurring 68 minutes after incapacitation. In the FAM, the onset of possibly perceptible symptoms starts about 174 minutes after generator startup; however, during unmod Genx's 250-minute run time, plus the following 60 minutes of natural decay that occurred before forced venting was initiated, the projected 18% COHb peak level at 312 minutes approached, but did not reach, the level of obvious symptom recognition (20% COHb). In the MBR, the onset of possibly perceptible symptoms started about 20 minutes after the generator was stopped, while the exhaust was naturally decaying from the house. The projected 12% COHb peak level at 312 minutes did not reach the level of obvious symptom recognition (20% COHb). Contrasting that to the paired test T with Gen SO1 equipped with the cat muffler operating in the garage for 182 minutes, predicted COHb levels in all three areas did not reach 5% COHb, which is regarded as a level where healthy individuals would be asymptomatic. Although Gen SO1 was run for 68 fewer minutes than unmod Gen X, it is known that it would take more than 3 hours of run time if the COHb were to reach the point of obvious symptom recognition in the garage and even longer in the house.

As for activation of a CO alarm during test F, if one were located in the MBR, it would not be expected to activate; however, if it were located in the FAM, it would be expected to activate at about 190 minutes after the generator was started. The CO level in the garage at this same time would be approximately 1,110 ppm, which is approaching the IDLH limit of 1,200 ppm. In this open bay door test house scenario, as that of test G, the relatively slow rate of rise of CO in the living spaces should allow a more-than-adequate time interval for escape for hypothetical occupants in all locations to exit the test house slightly before they reach 10% COHb. In Test T with Gen SO1 equipped with the cat muffler, CO levels in the FAM and MBR were below 5 ppm, which does not raise specific health concerns, and did not reach the CO alarm activation criteria.

It is clear from the analysis of all seven paired tests that, relative to the unmodified unit, the reduced CO emission rate of the prototype dramatically delays formation of COHb, and therefore, significantly delays the onset and progression of CO poisoning symptoms for hypothetical occupants in all spaces of the NIST test home. By significantly reducing the engine's CO emission rate, the Gen SO1 prototype, particularly if equipped with the catalyst muffler, definitely increases the exposure time needed to cause COHb levels to rise to incapacitating levels in even the most extreme circumstances for the occupant co-located with the generator in the garage. In the garage, regardless of the house door position, but with the bay door closed, for all tests with unmod GenX, the estimated time from obvious symptom recognition to death (20% to 60% COHb) takes only 13 to 14 minutes, and an exposed individual would likely be conscious for only 7 to 8 of these minutes. In the corresponding two tests with Gen SO1 equipped with the cat muffler, due to the shorter duration of test N, only test W resulted in death being the *possible* outcome for the garage occupant. In this test (test W), the estimated time in the garage from obvious symptom recognition to possible death is expected to be significantly longer at 152 minutes, with the exposed individual likely conscious for 96 of these minutes. This example shows a twelve-fold increase in the time interval that occupants have for recognizing a hazardous situation is developing after the onset of obvious symptoms, providing them a greater opportunity escape the CO exposure before becoming incapacitated. The increased opportunity to escape applies to individuals already inside the garage and individuals who, for any reason, enter the garage while the Gen SO1 cat unit is operating. The paired tests show that the time interval for hypothetical occupants in the living spaces of the house is extended even further, relative to the garage location. Staff recognizes that this does not guarantee safety because, even with slowed progression of symptoms, it will depend upon individual behavioral responses; however, staff believes the additional time will ultimately result in many lives saved.

4. Conclusions

CPSC staff's technology demonstration program of a prototype low CO emission portable generator was performed under the Commission's ANPR to address the CO poisoning hazard associated with consumer use of portable generators. CPSC's databases had reports, as of April 2012, of at least 755 generator-related CO deaths in the 13-year period of 1999 through 2011. In the demonstration program, closed-loop EFI with stoichiometric AFR fuel control and a three-way catalyst were adapted onto a small, air-cooled, single-cylinder Class II engine, powering a portable generator with an advertised continuous electrical power output rating of 5.0 kW. The prototype generator was subjected to a durability program in which the generator engine was loaded with a resistive 6-mode cyclic load profile, from no load to a 5.5 kW load applied through the alternator's 240-volt receptacle, for a total of 500 hours, which is the rated useful life of the engine. Periodic emission measurements were made at select times during the 500 hours. A baseline, unmodified unit was subjected to the same durability program and emissions measurement procedures in order to compare performance of the prototype relative to an identical model unmodified OEM carbureted unit. The CO emission rate of the prototype unit was reduced by 93 percent, compared to that of the unmodified baseline generator at the end of the durability program. After the durability program was completed, end-of-life emission testing, conducted in accordance with the EPA small SI engine test procedures, was performed on the prototype generator engine. The prototype engine, equipped with the catalyst installed in the muffler, had an HC+NOx exhaust emission rate of 6.7 g/kW-hr, which is 16 percent below the EPA's Phase 3 HC+NOx standard for a Class II engine, and a CO exhaust emission rate of 6.0 g/kW-hr, which is 99 percent below the EPA's Phase 2 and Phase 3 CO standard. For the prototype configuration of EFI, but without the catalyst, the HC+NOx emissions were 13.0 g/kW-hr, which exceeds both the Phase 2 and Phase 3 standards.

In a parallel effort that was also part of the demonstration program, a similar generator was tested, in both OEM and prototype configurations, at the NIST test house facility. Tests were conducted under seven different house configurations that were variations of a common fatal consumer scenario of a generator operating in the attached garage of a single-family home. This testing was performed to make an assessment of the efficacy of the prototype in reducing the risk of fatal and severe CO poisoning in terms of allowing a greater time interval for hypothetical occupants to recognize symptom onset and escape before being incapacitated. The NIST test results showed that the prototype generator equipped with the catalyst muffler achieved a 97 percent reduction in CO, compared to the unmodified OEM carbureted version of the same engine, based on the peak CO concentrations achieved in the garage after equivalent durations of generator operation. Collectively, the 14 paired tests provide strong evidence that the reduced CO emission rate of the prototype significantly reduced the rate of CO accumulation in all home areas and consequently, based on staff's modeling of the health impacts, the time interval for all hypothetical occupants—even those located in the garage with the generator—to perceive and react to the developing CO hazard before being incapacitated, is extended. Staff recognizes that extending this interval does not guarantee safety, which even with slowed progression of symptoms, will depend upon individual behavioral responses; but the empirical test results indicate that the reduced CO emission rate achieved by the prototype has significant potential for translating into reduced CO deaths and injuries compared to current designs.

Staff reiterates that its goal is not to make generators safe to run indoors, but rather, to reduce the CO emission rate to give occupants a greater opportunity to recognize and react appropriately to a developing CO exposure in order to escape. The CO emission rate achieved by the prototype generator reached staff's goal, based on health effects modeling of the empirical results from testing in NIST's test house. It is even more imperative that the CO emission rate be reduced when considering the following three important observations from CPSC staff's most recent incident data analysis relative to the scenarios tested at NIST: (1) at least 61 percent of the deaths that occurred in homes were smaller, when the size of the involved home was ascertained, than the test house's 1,500 sq ft footprint (see Figure 5); (2) at least 24 percent of the deaths occurred in structures other than fixed-structure home locations, such as detached garages, sheds, and temporary shelters (see Figure 3), many of which are presumably even smaller than the test house; and (3) seven percent more deaths occurred with the generator operating in the living space of the home, where occupants are more likely to be located, compared to the garage or other non-living spaces attached to the home (see Figure 4). The predicted time interval for occupants to escape from these locations will be less than that predicted with the prototype operating in the test house garage.

5. Feasibility of Technical Approach Using EFI and Catalytic Aftertreatment to Substantially Reduce CO Emissions from Engines Installed in Portable Generators

In the preamble for Phase 3 (ref 12), as well as in its regulatory impact analysis (RIA) for Phase 3 (ref 13), the EPA stated that it considered a regulatory alternative with an even more stringent standard for HC+NOx emissions for Phase 3 than the 35 percent reduction relative to Phase 2 that was adopted. The EPA stated that it rejected the steeper reductions due to the key concern that manufacturers needed more lead time to comply, on the order of 3 to 5 years, because it would lead to use of closed-loop fuel injection systems and catalysts on all Class II engines, almost all of which are air-cooled. The EPA further stated that the closed-loop EFI would replace carburetors, to keep engine air-to-fuel mixture closer to stoichiometry without increasing the risk of abnormal combustion, and to provide an optimum environment for the maximum reduction in HC+NOx by a three-way catalyst, which would likely involve a more active mix of precious metals in the catalyst substrate. The EPA also noted that improved engine design (such as redesign of cooling fins, fan design, combustion chamber design, and a pressurized oil lube system) would also be required in some of the Class II engines commonly used in residential products. It further stated that the leaner air-to-fuel ratios (*i.e.*, operating just rich of stoichiometry) resulting from advanced fuel systems and changes to improve mixing of the air and fuel entering the combustion chamber can significantly reduce engine-out HC and CO emissions and fuel consumption, and can provide more oxygen in the exhaust for improved catalytic control of HC and CO. The EPA's feasibility assessment indicated that it may be technically feasible to apply this emission control strategy to the entire small SI Class II engine inventory and could be the basis for more stringent Phase 4 emission standards at some point in the future. [Q]

[Q] It is important to note that the EPA did *not* reject the steeper HC+NOx reductions that were considered, yet rejected, for Phase 3 for Class II engines on the basis that closed-loop EFI, catalysts, and engine design improvements were cost prohibitive. Furthermore, as part of their congressionally mandated safety study for Phase 3 (mentioned in the footnote in section 3.2), the EPA demonstrated that the application of EFI and high-efficiency catalysts on two single-cylinder Class II air-cooled engines achieved approximately 85 percent HC+NOx emissions reduction below the Phase 2 standard and greater than 60 percent reduction in CO emissions compared to the OEM

CPSC's prototype low CO emission engine used closed-loop EFI with fuel control *at* stoichiometry and a three-way catalyst. It achieved an approximate 45 percent reduction in HC+NOx relative to the Phase 2 standard and a 6.0 g/kW-hr CO emission rate at the end of the rated useful life of the engine. These were achieved without having made any of the engine design improvements discussed above. Staff acknowledges that operation at full-engine load, as determined on the dynamometer by disabling or decoupling the governor from the throttle and physically holding the throttle wide open, was not achieved during either the durability program or during the operational testing at NIST's test house; however, the significantly reduced CO emission rate of the installed engine substantially extended the interval of time between symptom onset and incapacitation compared to the unmodified OEM unit. As stated previously, the purpose in conducting the durability program with the engine installed in the generator as opposed to on a dynamometer was to allow the manifestation of any issues that might result from the adapted emission control technologies on the end-use product. There were none.

Based on the data patterns in the CPSC's incident data, staff believes that many future fatal and serious CO poisonings involving consumer use of generators can be prevented if industry were to adopt a stringent CO emission standard for engines installed in generators on the order of that achieved with operation of the CPSC prototype. Generator manufacturers could use an engine selection and product integration strategy that limits installed engine operation to light or partial loads, where emission control using closed-loop EFI and catalytic aftertreatment can be focused to reduce CO emissions, precluding installed operation at high loads in cases where fuel enrichment that causes high CO emissions is needed for engine and catalyst protection. Alternatively, as suggested by one of the respondents to the RFI, an oxidation catalytic aftertreatment system, designed specifically for safely reducing the larger amounts of CO

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configuration. The EPA used low-cost engine management and fuel injection systems, similar to that which UA used for the CPSC prototype generator, that were originally developed for motor-scooter and small motorcycle applications. Per references 27 and 28, for both engines, open loop EFI was calibrated rich of stoichiometry at moderate to high loads and near stoichiometry at light load conditions to achieve the desired emission control of HC+NOx, while maintaining or improving fuel consumption, engine durability, and performance. Integrated catalyst-muffler systems were developed for each, with catalyst formulations selected to prioritize NOx reduction and HC oxidation over CO oxidation to reduce catalyst-muffler heat rejection associated with CO oxidation. The EPA achieved a HC+NOx emission rate of 1.8 g/kW-hr on one of the engines and improvement in brake-specific fuel consumption by 6 to 12 percent. Even though the catalysts were selected to favor HC+NOx selectivity and minimize CO oxidation, the tailpipe CO exhaust emission rate was reduced to 120 g/kW-hr on one of the engines.[27, 28] While the resulting CO emission rates of the two engines may not be sufficient in a generator application to prevent many fatal and severe CO poisonings associated with consumer use of portable generators as has been reported in the CPSC's databases, they could potentially reduce personal CO exposures for operators of all different types of equipment powered by Class II engines. The EPA expressed in the RIA their concern about widespread operator exposure to CO due to the fact that a large segment of the population uses small SI engine-powered lawn and garden equipment on a regular basis. It stated that the adopted Phase 3 standards were expected to reduce these exposures. CPSC staff believes that the steep CO reduction that would be realized with the steeper HC+NOx reductions that were considered, yet rejected for Phase 3, could reduce personal CO exposures even further.

As for Class I engines, ref 13 details a number of reasons that adapting the same emission control technologies would be more technically challenging than on a Class II engine. One of these is that Class I engines are available in both overhead valve (OHV) and side valve (SV) configurations; however, the less-expensive SV engines are the predominant type, and their emissions are typically higher and deteriorate more than OHV engines. (OHV engines have largely replaced SV engines in Class II, and with implementation of Phase 3, Class II SV engines are expected to disappear entirely from the engine inventory.)[13]

produced at higher loads, could be integrated into the exhaust system downstream of a catalyst designed primarily for NOx reduction. Regardless of the approach, CPSC staff believes that significantly reduced CO exhaust emission rates from engines installed in generators can be achieved that are expected to result in far fewer deaths and injuries caused by this product.

Within the last several years, the marine industry, prompted by market demand, found consensus to voluntarily adopt a stringent CO emission standard that applies uniquely to small water-cooled SI engines used to power marine generators. They took this action specifically to address acute exhaust emission exposures that were identified as causing CO deaths and injuries on and around recreational boats. Events that led to this action started when an interagency team, consisting of the National Park Service, the U.S. Department of the Interior, and the National Institute for Occupational Safety and Health, began identifying boating-related CO deaths and injuries attributed to exhaust from both onboard generators and propulsion engines. They identified 113 CO deaths and 458 nonfatal CO poisonings that occurred in the years between 1984 and 2004. In response to this activity, the marine industry, U.S. Coast Guard, American Boat and Yacht Council, and other stakeholders met regularly for several years to try to mitigate the risk of CO poisoning in boating-related scenarios. Mitigation strategies that were discussed at these meetings included: labeling, education, diverting the exhaust flow with smoke stacks, CO detectors, low CO emission technologies, and emission standards.[13] By 2005, the two marine generator manufacturers who produce the vast majority of gasoline-powered marine generators developed low CO emission designs using closed-loop EFI and catalytic control, which reduced CO emissions by more than 99 percent.[29,30] They were able to achieve this by using the available lake or river water to dissipate the additional heat produced in the engine block and exhaust system as a result of leaner engine operation and the oxidation of the engine-out CO in the catalyst, respectively. Both manufacturers stated that they developed their low CO designs in response to demands from boat builders to reduce the risk of CO poisoning. Because both manufacturers had certified low CO engines capable of complying with a 5.0 g/kW-hr CO standard, [R] and each stated their intention to offer only these designs in the near future, the EPA decided that it was necessary to adopt this level as a CO standard uniquely applicable to water-cooled marine generator engines in their Phase 3 regulation. The EPA states this was done "to prevent backsliding in CO emissions that could occur if new manufacturers were to attempt to enter the market with less expensive, high-CO designs." [12] In their analysis of regulatory alternatives, the EPA did not consider a less stringent standard because it "could enable market penetration of new engine offerings which potentially endanger public health." [13]

Given that there have been at least 755 consumers who died from CO poisoning involving small air-cooled SI engines providing power to generators in the 13-year period from 1999 through 2011, CPSC staff strongly encourages industry consensus, similar to that accomplished within the marine industry, to achieve a reduced CO emission rate on engines used in generators that is expected to reduce the risk of fatal and severe CO poisoning associated with consumer use of this product.

[R] CPSC staff is unaware of any health effects modeling of specific scenarios that were performed to establish the EPA's 5 g/kW-hr CO standard applicable only to marine generator engines. Staff's understanding is that the standard was based on the emission rate that the manufacturers found to be achievable and that they largely expected would reduce CO deaths and injuries on and around boats from exposure to marine generator engine emissions.

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TAB A

Incidents, Deaths, and In-Depth Investigations Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 1999–2011

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U.S. Consumer Product Safety Commission
Directorate for Epidemiology
Division of Hazard Analysis
4330 East West Highway
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July 2012

CPSA 6(b)(1) CLEARED for PUBLIC
✓ NO MFRS/PRVTLBLRS OR PRODUCTS IDENTIFIED
__ EXCEPTED BY: PETITION RULEMAKING ADMIN. PRCDG
__ WITH PORTIONS REMOVED: ______
7/26/12

This analysis was prepared by the CPSC staff and it has not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

Table of Contents

Executive Summary

This report summarizes non-fire carbon monoxide (CO) incidents associated with engine-driven generators and other engine-driven tools that occurred between 1999 and 2011, and were reported to the U.S. Consumer Product Safety Commission (CPSC) staff as of April 20, 2012. It should be noted that due to incident reporting delays, statistics for the most recent years should be considered incomplete. In this report, the two most recent years, 2010 and 2011, are identified as being incomplete since these figures are most likely to change in future reports. Throughout this report, the number of deaths represents a count of the fatalities reported to CPSC staff associated with generators and other engine-driven tools, such as power lawn mowers, garden tractors, portable pumps, power sprayers and washers, snow blowers, and concrete saws. Also included in this report are summaries of fatal, non-fire CO incidents, where an engine-driven tool (EDT) and one or more other fuel-burning consumer products[1] also may have been involved and the EDT was believed to be, at least, a contributing factor to the fatal levels of CO. These fatalities are characterized in the "Multiple Product" category. This report also provides a more detailed summary of fatal, non-fire CO poisoning incidents associated with engine-driven tools, with particular emphasis on cases involving generator use, based on information found in the CPSC's In-depth Investigation (INDP) File.

Some of the findings of this report are provided below.

CO Fatalities Associated with All EDTs and by EDT Product Type:

- The total number of fatalities for 1999 through 2011 increased by 141 from the 740 fatalities summarized in the July 2011 report, which reported fatalities for the period 1999 through 2010 as of February 17, 2011. Fifty-three of the newly recorded fatalities occurred prior to 2011. This is a larger than usual number and can be attributed to a later-than-usual cut-off date for reports than the prior year (April instead of February) and a larger-than-usual number of late death certificate submissions from a few states.
- From 1999 through 2011, 881 fatalities from 680 fatal incidents were associated with the use of engine-driven tools, or engine-driven tools used in conjunction with another potentially CO-emitting consumer product.
- As of April 20, 2012, there were 88 reported non-fire CO fatalities in 2011, from 62 incidents. Seventy-three of these deaths (49 incidents) involved only a generator and no other product; 8 deaths (8 incidents) were associated with a non-generator other engine-driven tool (OEDT); and 7 deaths (5 incidents) were associated with multiple fuel-burning consumer products, one of which was a generator.
- From 1999 to 2011, 695 (79%) of the 881 fatalities from 513 incidents were associated with generators; 121 fatalities (14%) from 118 incidents involved other engine-driven tools; and 65 fatalities (7%) from 49 incidents involved multiple fuel-burning consumer products, one product of which was a generator (59 of 65 deaths) or OEDT (5 of 65 deaths) or both a generator and an OEDT (1 of 65 deaths).

[1] Combustion consumer products produce heat or energy by burning a fuel source. It should be noted that all fuel-burning consumer products may produce gases that contain CO because CO is a by-product of incomplete combustion.

- Of the 49 incidents that involved multiple consumer products, all but two incidents involved a heating or cooking product, most commonly a portable LP- or kerosene-fueled portable heater. One incident involved a generator and an OEDT (a lawnmower), and another incident involved two gasoline-fueled OEDTs (a lawnmower and trimmer).
- Twenty-six percent of generator-related, non-fire CO incidents caused multiple fatalities, while only three of the OEDT-related incidents (3%) involved multiple fatalities. Twenty-seven percent of multiple product-related, non-fire CO incidents caused multiple fatalities.
- Nearly three-fourths (553 of 755) of generator-related fatalities detailed in this report (including fatalities involving multiple products where one product was a generator) occurred between 2005 and 2011.

Socio-Demographic Characteristics of Victims and EDT-Use Patterns:

- Eighty-three percent of generator-related victims (including multiple product incidents where a generator was involved) were known to be 25 years old or older, where the age of the victims was known. By contrast, 99 percent of OEDT-related victims were 25 years old or older.
- Nearly three-quarters of the generator-related, non-fire CO victims were male, while 97 percent (all but four) of the OEDT-related fatalities were male.
- Nearly half (49%), of generator-related, non-fire CO fatalities (371 of 755, including multiple product incidents) occurred in the four colder months of the year (November through February), while CO fatalities associated with OEDTs were only slightly more prevalent in the colder months (40%) than in the transitional and warm months (34% and 25%, respectively).
- Seventy-three percent of the generator-related fatalities and 75 percent of fatalities from multiple products, where one was a generator, occurred in fixed-structure homes, while 59 percent of OEDT fatalities occurred in fixed-structure homes.
- Fifty-five percent of the EDT-related fatalities are known to have occurred in urban areas. Seventeen percent occurred in small rural and isolated areas, nearly double the proportion of the U.S. population that lives in such areas.

CO Alarm Usage:

- A CO alarm was reported to have been present in only 21 of 265 incidents where alarm presence was known, which accounted for 30 of 368 (8%) EDT-related CO fatalities. In nine of the incidents (16 deaths), the alarm was inoperable due to no batteries, batteries inserted incorrectly, or no electric current. The alarm sounded in six incidents (six deaths), and in three incidents (three deaths), the alarm was powered but did not sound. Additionally, there were three incidents (five deaths) in which the presence of a CO alarm was noted, but it is unknown if the alarm sounded during the event.

Hazard Patterns Associated with Generators:

- Twenty-nine percent of all generator-related, non-fire CO deaths (220 of 755) were associated with power outages. Of these 220 fatalities, 53 (24%) occurred in 2005. Thirty-one of the 2005 fatalities were related to hurricanes or tropical storms, and another 20 were related to ice or snow storms. (Additionally, one fatality was associated with a thunderstorm; and for one fatality, it could not be determined what caused the power outage.)

- Five hundred and fifty-one non-fire CO fatalities that occurred in fixed-structure homes were associated with a generator or a generator in use with another CO-generating consumer product. Seventy percent (385 of 551) occurred when the generator was placed inside the living area of the home, including the basement, closets, and doorways, but excluding the attached garage, enclosed carport, or attached barn.
- In recent years, the most common location of generators associated with CO fatalities has shifted from the basement to the non-basement living space of the home. From 2004 through 2011, 38 percent (169 of 442) of CO fatalities in the home occurred with a generator placed in the non-basement living space of the home, compared to only 21 percent (23 of 109) of non-basement use of generators from 1999 through 2003.
- Nearly two-thirds (66%; 205 of 312) of generator-related, non-fire CO fatalities in fixed-structure homes (for which information on ventilation of the generator was available) occurred when no ventilation of the generator was attempted.
- Sixty-one percent (215 of 353) of generator-related, non-fire CO fatalities in fixed-structure homes, where the size of the home was known and the generator was not located in an external structure, occurred in houses less than 1,500 square feet in size; 84 percent (298 of 353) occurred in houses less than 2,000 square feet in size.
- Two-thirds (67%; 245 of 367) of CO fatalities where the size of the generator was known were associated with generators in the 3500 to 6499 watt range, and nearly half (46%; 168 of 367) were associated with generators in the 5000 to 6499 watt range.

Carboxyhemoglobin Levels in CO Fatality Victims:

- Of the CO fatality victims associated with engine-driven tools, more than 81 percent had carboxyhemoglobin (COHb) levels above the 50 percent level when the COHb level was known (405 of 499).[2]

Note: Throughout this report, the years 2010 and 2011 are italicized in table headings, indicating that incident and death counts may change as additional information is received. Incident and death counts may change for other years but to a much smaller extent.

[2] As levels rise above 40 percent COHb, death is possible in healthy individuals and becomes increasingly likely with prolonged exposures that maintain levels in the 40 percent to 60 percent range.

Introduction

The following U.S. Consumer Product Safety Commission (CPSC) databases were searched to prepare the statistics recorded in this report: the In-depth Investigation (INDP) File, the Injury or Potential Injury Incident (IPII) File, and the Death Certificate (DTHS) File. See Appendix A for the codes and keywords used in the database searches. The data records were combined and collated to develop the most complete records possible in a single database. At this stage, each record was reviewed to determine if the incident was in scope for this report and to correct any discrepancies between information from the different sources. (See Appendix A for the specifics of scope determination.) It should be noted that reporting may not be complete, and this report reflects only those incidents reported and entered into CPSC databases on or before April 20, 2012. All fatal, unintentional, non-fire carbon monoxide (CO) incidents associated with engine-driven tools (EDTs) found during the database search that were determined to be in scope were included.

CPSC records contain information on 881 non-fire CO fatalities associated with EDTs during the years 1999 through 2011. This is an increase of 141 fatalities from the 740 fatalities reported in the July 2011 report on non-fire CO fatalities associated with EDTs which included data entered in CPSC databases as of February 17, 2011.[3] Eighty-eight of these 141 fatalities occurred in 2011, while the remaining 53 occurred in previous years but were reported after the July 2011 report. Eighty-one of the 88 fatalities were associated with generators or other engine-driven tools (OEDT) as the only known source of the CO. Seven additional fatalities were associated with multiple, combustion fuel-burning consumer products. Incidents associated with generators that were specifically reported as integral parts of recreational vehicles (RVs), motor homes, or boats are not within the jurisdiction of the CPSC, and thus, were considered out of scope and were not included. For example, generators that were reported as mounted to an RV were not included, nor were boat generators that were installed by the boat manufacturer. Since incidents in recreational vehicles and boats can be associated with a portable generator or an integral generator, those incidents in which the type of generator could not be determined were also excluded from the analysis.

Any incident that was determined to be other than accidental in nature was considered to be out of scope, as were work-related incidents, which are not within the jurisdiction of the CPSC.

This report is divided into four sections:

I. Reported Numbers of Fatalities by EDT Product Type. This presents an overall picture of CO fatalities associated with engine-driven tools.

II. Socio-demographics of Victims and EDT Use Patterns. This presents various socio-demographic summaries helpful in identifying specific characteristics of CO fatality victims and usage patterns, such as when and where fatalities occurred.

III. Alarm Usage. This presents information on CO alarm usage during fatal CO events.

[3] Hnatov, M. V. *Incidents, Deaths, and In-Depth Investigations Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 1999–2010. U.S. Consumer Product Safety Commission. July 2011.*

IV. Hazard Patterns Associated with Generators. This presents data specific to generator usage patterns that may lead to fatal CO poisoning events.

Additionally, Appendix B presents summary findings on carboxyhemoglobin levels in the blood of victims of CO poisoning involving EDT use, which are helpful in assessing the hazard presented by the product and the speed of onset of harm.

I. Reported Numbers of Fatalities by Engine-Driven Tool (EDT) Product Type

As of April 20, 2012, CPSC staff had records indicating that there were 62 fatal, non-fire carbon monoxide (CO) exposure incidents involving engine-driven tools between January 1, 2011 and December 31, 2011. Eighty-eight deaths occurred in these 62 fatal CO incidents. Table 1 presents the reported fatal incidents and the number of deaths in 2011, along with a summary of CO incidents and fatalities associated with engine-driven tools for the 13-year period from 1999 through 2011. The table records the number of incidents and deaths by the broad categories of "Generators," "Other Engine-Driven Tools," and "Multiple Products." Multiple product incidents are fatal CO poisonings that involved multiple fuel-burning consumer products that generate CO, at least one being an EDT, or in which investigating authorities could not determine which of multiple consumer products in use at the time of the incident was the source of the CO. CPSC staff is aware of 65 fatalities associated with multiple consumer products occurring between 1999 and 2011; seven of these fatalities occurred in 2011. Multiple product incidents where one of the sources of CO is not under the CPSC's jurisdiction, such as automobiles, boats, or recreational vehicles, were determined to be out of scope and are not included in this report.

It should be noted that fatality and incident counts from years prior to 2011 may have changed from the previous report. The changes are due primarily to the addition of new data that were made available to CPSC staff. New to this report are 53 reported fatalities that occurred before 2011, and 88 fatalities that occurred in 2011.

Within each broad category, the frequency of reports is summarized by product type. Staff is aware of 680 incidents with a total of 881 deaths due to non-fire CO exposure that occurred between 1999 and 2011, involving engine-driven tools.

In Table 1, the product type "welder" appears in both the "Generator" and "Other Engine-Driven Tool" categories. Some welding equipment is designed to be used as a welder or as an electric generator. Two of the fatal, non-fire CO incidents associated with the use of welding equipment that occurred between 1999 and 2011, involved the use of the welder as a generator during a power outage. Each of these two incidents involved a single death. There were six fatal, non-fire CO incidents between 1999 and 2011 that were associated with the use of welder equipment, where it was not specifically identified as being used as a generator. Of these six incidents, one incident (involving two deaths) occurred when the welder was being used as a source of heat, and, in the other five incidents (six deaths: four single-fatality incidents and one two-fatality incident), the welder was being used for welding purposes or the method of usage could not be ascertained. These latter five incidents were included in the "Other Engine-Driven Tools" category because there was no evidence indicating that the welders were being used as generators.

In 2011, there were three incidents (five fatalities) involving non-portable, fixed-location generators that were either installed inside the home or were located too close to a vent or window, allowing CO to enter the home. This category has been added to Table 1. However, these incidents will be included in the “Generator” category for further analysis similar to the scenarios involving welders used as generators.

All but two of the 65 non-fire, CO fatalities in the “Multiple Products” category for 1999–2011 involved a heating- or cooking-related consumer product other than an EDT. One incident involved a generator and a lawn tractor being run in a closed garage. The other incident involved a gasoline-fueled walk behind mower and gasoline-fueled trimmer also running in a closed garage.

Table 1: Number of Reported Fatal Non-Fire Carbon Monoxide Exposure Incidents and Deaths Associated with Engine-Driven Tools, 1999–*2011*

Product	***2011***		**Total: 1999–*2011***	
	Number of Incidents	***Number of Deaths***	**Number of Incidents**	**Number of Deaths**
Total Engine-Driven Tools	***62***	***88***	**680**	**881**
Generators	***49***	***73***	**513**	**695**
Generator, portable	*46*	*68*	508	688
Generator, fixed	*3*	*5*	3	5
Welder (used as a generator)[1]	*0*	*0*	2	2
Other Engine-Driven Tools (OEDT)	***8***	***8***	**118**	**121**
Riding lawn mower/Garden tractor	*5*	*5*	62	62
Push lawn mower	*0*	*0*	3	3
Powered lawn mower, unspecified type	*0*	*0*	5	5
Power washer/sprayer	*1*	*1*	9	9
Snow blower	*1*	*1*	11	11
All-terrain vehicle	*0*	*0*	7	8
Welder (used as welder or other reason)[1]	*0*	*0*	6	8
Water pump	*0*	*0*	4	4
Concrete saw	*0*	*0*	3	3
Air compressor	*0*	*0*	2	2
Paint sprayer	*0*	*0*	1	1
Snowmobile	*0*	*0*	1	1
Go-cart	*0*	*0*	1	1
Tiller	*0*	*0*	1	1
Small engine (unknown use)	*0*	*0*	1	1
Edger	*1*	*1*	1	1
Multiple Products[2]	***5***	***7***	**49**	**65**
Generator + Other Consumer Product[3]	*5*	*7*	44	60
OEDT + Other Consumer Product	*0*	*0*	5	5

1 Some welding equipment is designed to be used as either a welder or a generator.

2 “Multiple Products” includes incidents involving generators or OEDTs with other combustion fuel-burning consumer products. “Other Consumer Products” includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and an OEDT (lawn tractor) in operation.

3 This category includes one incident involving one fatality where a generator and an OEDT were being used concurrently.

Note: Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Five hundred-thirteen of the 680 incidents reported to CPSC staff were associated with a generator and accounted for 695 of the 881 CO deaths (79%). Additionally, 60 other CO fatalities from 44 incidents were associated with the use of a generator and another combustion consumer product—most commonly an LP- or kerosene-fueled heater. One of these fatalities involved a generator and another engine-driven tool (lawn tractor). For the rest of this report, this incident will be included in the tables and discussions in the category *Multiple Products* involving a generator. Throughout the remainder of this report, incidents associated with all non-generator engine-driven tools are reported as a group. In addition, because the majority of incidents were associated with generators, characteristics of these incidents are reported separately in Section IV. More than half of the non-fire, non-generator CO fatalities (62 of 121) involved a garden tractor or other powered lawn mower (including multiple product incidents). Deaths associated with powered lawn mowers were often associated with an individual repairing or working on the product in an enclosed space.

CPSC staff examined the number of deaths associated with each fatal incident (Table 2). Of the 680 fatal incidents, 78 percent involved a single fatality. Seventy-four percent (379 of 513) of the fatal generator-related incidents involved a single fatality. One incident involving a generator resulted in the deaths of six individuals, and two others involved five fatalities, one of these five-fatality incidents occurred in 2011. Of the 118 fatal incidents in the "Other Engine-Driven Tools" category, three incidents resulted in more than one fatality. Twenty-six percent of multiple-product, fatal CO incidents resulted in multiple fatalities.

Table 2: Number of Reported Fatal Non-Fire Carbon Monoxide Exposure Incidents and Deaths Associated with Engine-Driven Tools by Number of Deaths per Incident, 1999–*2011*

Number of Deaths Reported in Incident[1]	Total		Generator		Other Engine-Driven Tools		Multiple Products[2,3]	
All Incidents	**680**	**100%**	**513**	**100%**	**118**	**100%**	**49 (44)**	**100%**
1	530	78%	379	74%	115	97%	36 (31)	73%
2	113	17%	100	19%	3	3%	10 (10)	20%
3	26	4%	23	4%	0	0%	3 (3)	6%
4	8	1%	8	2%	0	0%	0 (0)	0%
5	2	< 1%	2	< 1%	0	0%	0 (0)	0%
6	1	< 1%	1	< 1%	0	0%	0 (0)	0%

1 SPECIAL NOTE ABOUT COUNTS IN THIS TABLE ONLY: One incident included in this table involved an in-scope, generator-related death and an out-of-scope death (work related). Because two fatalities were involved in the incident, this incident is included as a two-fatality incident. The out-of-scope fatality is not included elsewhere in the report. Therefore, in this table only, there is one additional fatality reported. The fatality was a generator-related fatality, so it is included in the "Generator" and "Total" columns.

2 "Multiple Products" includes incidents involving generators or OEDTs with other combustion fuel-burning consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn tractor) in operation.

3 Numbers in parentheses indicate incidents involving a generator and another product, including a case where a generator and an OEDT (lawn mower) were used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

CPSC staff summarized the number of reported deaths associated with engine-driven tools by year of death (Table 3). It should be noted that the values in Table 3 represent the number of deaths reported to CPSC staff as of April 20, 2012. Some deaths are reported to CPSC staff shortly after an incident occurs, while other deaths are reported to CPSC staff months or even years after an incident occurs. Therefore, counts for more recent years may not be as complete as counts for earlier years and may change in the future. Fifty-three of the 141 reported fatalities new to the report were for years prior to 2011. For the 13 years covered by this report, 71 percent (629 of 881) of the deaths were reported in the most recent seven years (2005 through 2011).

The average number of non-fire CO fatalities associated with both generators and other engine-driven tools for years 2007 through 2009 is also presented in Table 3. These three years represent the most recent years for which CPSC staff believe reporting is substantially complete. Due to reporting delays, these averages may change slightly in the future when data are complete. Figure 1 illustrates the trend in generator-related, non-fire CO fatalities since 1999.

Table 3: Number of Reported Fatal Non-Fire Carbon Monoxide Exposure Incidents and Deaths Associated with Engine-Driven Tools by Year, 1999–*2011*

Year	Total		Generators		Other Engine-Driven Tools		Multiple Products[1,2]	
	Incidents	Deaths	Incidents	Deaths	Incidents	Deaths	Incidents	Deaths
Total	***680***	***881***	***513***	***695***	***118***	***121***	***49 (44)***	***65 (60)***
1999	12	12	6	6	5	5	1 (0)	1 (0)
2000	22	28	14	20	7	7	1 (1)	1 (1)
2001	19	25	14	17	2	2	3 (3)	6 (6)
2002	47	58	34	42	8	9	5 (4)	7 (6)
2003	51	67	38	52	9	9	4 (3)	6 (5)
2004	50	62	34	46	14	14	2 (1)	2 (1)
2005	93	116	73	94	13	13	7 (7)	9 (9)
2006	80	111	60	89	16	16	4 (4)	6 (6)
2007	68	81	53	65	11	11	4 (4)	5 (5)
2008	76	101	63	87	6	6	7 (6)	8 (7)
2009	56	77	44	65	10	10	2 (2)	2 (2)
2010	*44*	*55*	*31*	*39*	*9*	*11*	*4 (4)*	*5 (5)*
2011	*62*	*88*	*49*	*73*	*8*	*8*	*5 (5)*	*7 (7)*
Average: 2007–2009	67	86	53	72	9	9	5 (4)	5 (5)

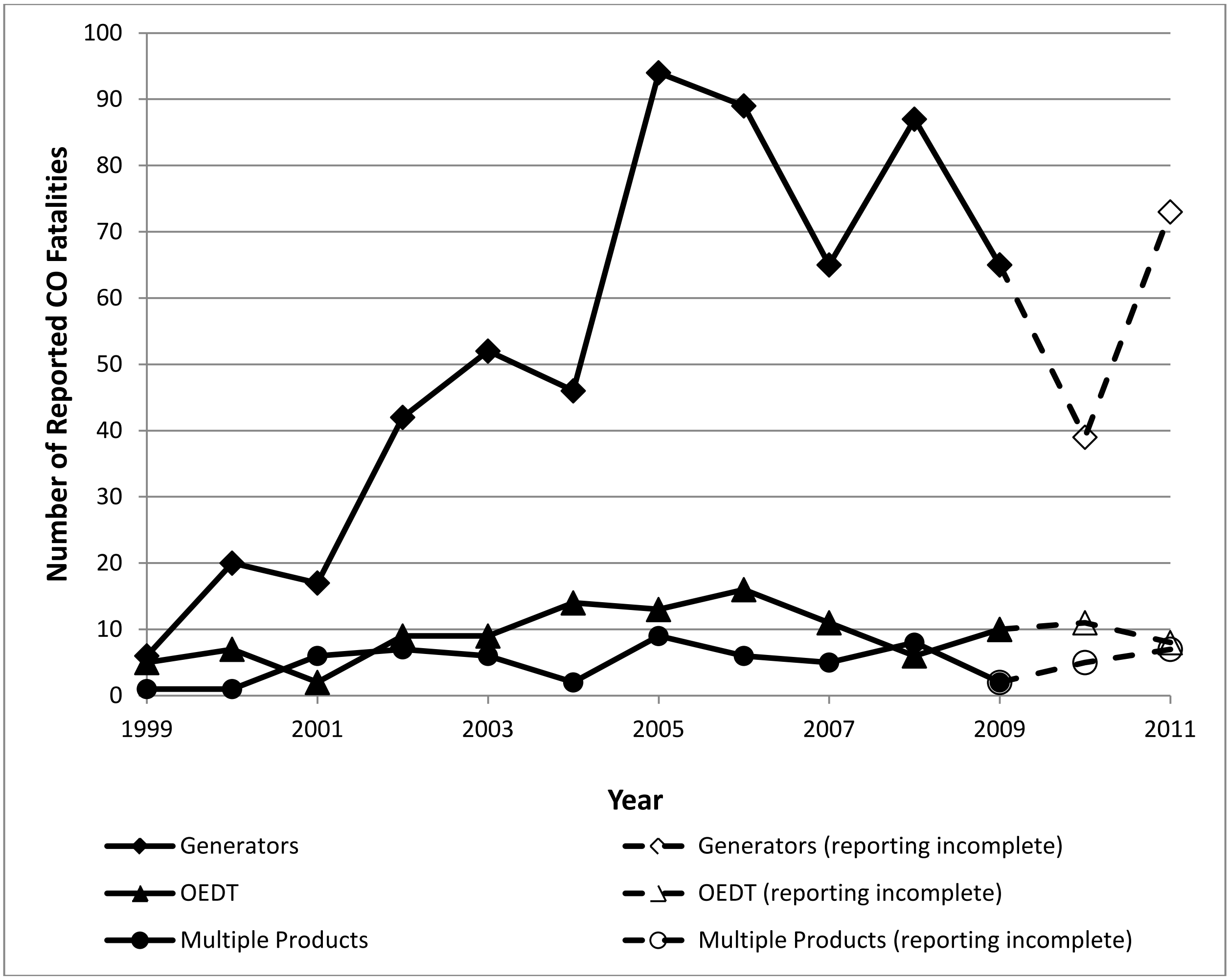
1 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn tractor) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn tractor) were used concurrently.

Notes: Detail averages may not sum to total average due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Figure 1: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Engine-Driven Tools, 1999–*2011*



II. Socio-Demographic Characteristics of Victims and EDT Use Patterns

This section presents socio-demographic information about the victims of reported fatal CO incidents associated with engine-driven tools (EDTs). Tables 4 and 5 present the distribution of age and gender of the victims, respectively. Table 4 shows that victims aged 25 years or older accounted for about 85 percent (745 of 873) of reported non-fire, CO poisoning deaths associated with all engine-driven tools where the victim's age is known. Victims with a reported age of 25 years or older accounted for about 83 percent (620 of 747) of non-fire CO poisoning deaths associated with generators (including multiple product related deaths where one product was a generator) and accounted for nearly all of the deaths associated with other engine-driven tools. Eighty-five percent of the non-fire CO fatalities associated with non-generator engine-driven tools (107 of 126) involved victims age 45 or older, with only one reported fatality of an individual younger than 25. Male victims accounted for 78 percent of the deaths associated with all engine-driven tools when the gender of the victim is known. Male victims comprised 75 percent of the deaths associated with generators and 97 percent of non-generator, engine-driven tool fatalities (Table 5).

Table 4: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Engine-Driven Tools by Age of Victim, 1999–*2011*

Age	Number of Deaths Reported to CPSC											
	All Engine-Driven Tools			Generators			Other Engine-Driven Tools			Multiple Products[1,2]		
	Deaths	Percentage of All Cases	Percentage when Age is Known	Deaths	Percentage of All Cases	Percentage when Age is Known	Deaths	Percentage of All Cases	Percentage when Age is Known	Deaths	Percentage of All Cases	Percentage when Age is Known
Total	**881**	**100%**	**100%**	**695**	**100%**	**100%**	**121**	**100%**	**100%**	**65 (60)**	**100%**	**100%**
Under 5	14	2%	2%	14	2%	2%	0	0%	0%	0 (0)	0%	0%
5–14	29	3%	3%	29	4%	4%	0	0%	0%	0 (0)	0%	0%
15–24	85	10%	10%	76	11%	11%	1	1%	1%	8 (8)	12%	12%
25–44	261	30%	30%	226	33%	33%	18	15%	15%	17 (17)	26%	26%
45–64	332	38%	38%	239	34%	35%	62	51%	51%	31 (28)	48%	48%
65 and over	152	17%	17%	103	15%	15%	40	33%	33%	9 (7)	14%	14%
Adult, age unknown	6	1%	-	6	1%	-	0	0%	-	0 (0)	0%	-
Unknown age	2	< 1%	-	2	< 1%	-	0	0%	-	0 (0)	0%	-

1 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were used concurrently.

Notes: Totals may not add to 100 percent due to rounding.

Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Table 5: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Engine-Driven Tools by Gender of Victim, 1999–*2011*

Gender	Number of Deaths Reported to CPSC											
	All Engine-Driven Tools			Generators			All Other Engine-Driven Tools			Multiple Products[1,2]		
	Deaths	Percentage of All Cases	Percentage when Gender is Known	Deaths	Percentage of All Cases	Percentage when Gender is Known	Deaths	Percentage of All Cases	Percentage when Gender is Known	Deaths	Percentage of All Cases	Percentage when Gender is Known
Total	**881**	**100%**	**100%**	**695**	**100%**	**100%**	**121**	**100%**	**100%**	**65 (60)**	**100%**	**100%**
Male	682	77%	78%	509	73%	74%	117	97%	97%	56 (51)	86%	86%
Female	195	22%	22%	182	26%	26%	4	3%	3%	9 (9)	14%	14%
Unknown	4	< 1%	-	4	1%	-	0	0%	-	0 (0)	0%	-

1 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Staff examined reported deaths associated with engine-driven tools by the time of year that the incident occurred (Table 6). The non-fire CO fatalities were classified into one of three categories, depending on the month in which the incident occurred: Cold months, Warm months, and Transitional months. "Cold months" are defined as November, December, January, and February; "Warm months" as May, June, July, and August; and "Transitional months" as March, April, September, and October.

Nearly half (47%, or 49% when multiple product incidents where a generator was involved) of the non-fire CO deaths associated with generators occurred in the cold months of November through February. Many of the fatalities can be directly associated with the use of generators during power outages due to weather conditions such as ice or snow storms. Thirty-one percent of the generator-related CO deaths occurred in the transitional months of March, April, September, and October. A large portion of the non-fire CO fatalities in the transitional months can be directly associated with the use of generators during power outages due to hurricanes and tropical storms, many of which occurred in September and, to a lesser extent, October. Further details on this issue are presented in Section IV of this report.

For OEDTs, CO fatalities were only slightly more prevalent in the cold months (40%) than the transitional months (34%) and warm months (26%). The *Multiple Products* category had a very large proportion of fatalities in the cold months (75%), with 22 percent in the transitional months and three percent occurring in the warm months. This large percentage of fatalities in the cold months can be explained by examining the other fuel-burning consumer products in use at the time of the deaths. Of the 65 CO fatalities that involved multiple consumer products, 60 involved the use of a generator, and all but two involved a heating or cooking product, most commonly a portable LP- or kerosene-fueled portable heater. Heaters are used almost exclusively in the cold and transitional months.

Table 6: Number of Reported Non-Fire Carbon Monoxide Incidents and Fatalities Associated with Engine-Driven Tools by Season, 1999–*2011*

Season Incident Occurred		Number of Incidents and Deaths Reported to CPSC							
		All Engine-Driven Tools		Generators		Other Engine-Driven Tools		Multiple Products[1,2]	
Total	**Incidents**	**680**	**100%**	**513**	**100%**	**118**	**100%**	**49 (44)**	**100%**
	Deaths	**881**	**100%**	**695**	**100%**	**121**	**100%**	**65 (60)**	**100%**
Cold months	Incidents	327	48%	242	47%	48	41%	37 (35)	76%
	Deaths	422	48%	324	47%	49	40%	49 (47)	75%
Transitional months	Incidents	201	30%	152	30%	39	33%	10 (8)	20%
	Deaths	269	31%	214	31%	41	34%	14 (12)	22%
Warm months	Incidents	152	22%	119	23%	31	26%	2 (1)	4%
	Deaths	190	22%	157	23%	31	26%	2 (1)	3%

1 “Multiple Products” includes incidents involving generators or OEDTs with other CO- generating consumer products. “Other Consumer Products” includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were being used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Incidents involving deaths are further summarized in Table 7 by the location where the death occurred. The majority of non-fire, CO poisoning deaths (737 of 881, or 84%) reported to CPSC staff associated with engine-driven tools occurred at home locations. Seventy-one percent of the deaths occurred at fixed-structure residences, which includes single-family homes, apartments, townhouses, and mobile homes. Another 10 percent occurred in external structures at home locations, such as detached garages or sheds. And another two percent occurred in nontraditional homes, such as travel trailers, houseboats, or storage sheds used as permanent residences. The “Temporary shelter” category includes incidents in which victims died from CO poisoning from portable generators or other engine-driven tools while the victims were temporarily occupying trailers, horse trailers, recreational vehicles (RVs), cabins (used a temporary shelter), tents, and campers. Incidents that occurred in a temporary shelter, where the generator was an integral part of the temporary shelter, such as built-in generators or generators built specifically for use in an RV, were determined to be out of scope for this report and were excluded. The “Boat/Vehicle” category only includes incidents in which a generator or other engine-driven tool was not an integral part of the boat—but was brought onto the boat—and incidents where an EDT was brought into a vehicle, such as a van. As with temporary shelters, incidents involving generators that were built-in or specifically designed for a boat are not considered in scope and are not included in this report. The "Other" category includes incidents that occurred in the following locations: office buildings, utility buildings, and storage sheds (offsite from home).

Table 7: Number of Reported Non-Fire Carbon Monoxide Incidents and Fatalities Associated with Engine-Driven Tools by Location, 1999–*2011*

Location		Number of Incidents and Deaths Reported to CPSC							
		All Engine-Driven Tools		Generators		Other Engine-Driven Tools		Multiple Products[1,2]	
Total	**Incidents**	**680**	**100%**	**513**	**100%**	**118**	**100%**	**49 (44)**	**100%**
	Deaths	**881**	**100%**	**695**	**100%**	**121**	**100%**	**65 (60)**	**100%**
Home, fixed Structure[3]	Incidents	478	70%	372	73%	70	59%	36 (34)	73%
	Deaths	624	71%	506	73%	71	59%	47 (45)	72%
Home, detached Structure[4]	Incidents	87	13%	45	9%	38	32%	4 (1)	8%
	Deaths	91	10%	48	7%	39	32%	4 (1)	6%
Home, non-house[5]	Incidents	19	3%	13	3%	4	3%	2 (2)	4%
	Deaths	22	2%	16	2%	4	3%	2 (2)	3%
Temporary shelter	Incidents	61	9%	54	11%	2	2%	5 (5)	10%
	Deaths	95	11%	84	12%	2	2%	9 (9)	14%
Boat/Vehicle	Incidents	18	3%	15	3%	1	1%	2 (2)	4%
	Deaths	24	3%	19	3%	2	2%	3 (3)	5%
Other	Incidents	13	2%	11	2%	2	2%	0 (0)	0%
	Deaths	16	2%	14	2%	2	2%	0 (0)	0%
Not reported	Incidents	4	1%	3	1%	1	1%	0 (0)	0%
	Deaths	9	1%	8	1%	1	1%	0 (0)	0%

1 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were used concurrently.

3 This refers to a fixed-structure used as a residence, including: houses, mobile homes, apartments, townhouses, and structures attached to the house, such as an attached garage.

4 This refers to detached structures at home locations, including detached garages and sheds.

5 This refers to non-fixed location residences, including travel trailers and houseboats.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Table 8 presents the number of non-fire, CO poisoning deaths reported to CPSC staff and associated with EDTs categorized by the population density of the place of death. All fatal incidents were assigned to one of four rural/urban categories, based on the Rural-Urban Commuting Area (RUCA) codes developed by the Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA). Recently, the four urban/rural categories were changed to delineate further the large urban category. Formally, the four broad categories were “Urban,” “Large Rural,” “Small Rural,” and “Isolated.” In the newer categorization, the “Urban” category was divided into “Urban Core” and “Sub-Urban.” Additionally, the “Small Rural” and “Isolated” categories are now combined into the “Small Rural/Isolated” category. Details on the process of determining population density, or rurality can be found at the USDA website at: http://www.ers.usda.gov/briefing/Rurality/. Additional information regarding the cross-referencing of zip codes to RUCA codes can be obtained from the University of Washington, WWAMI[4] Rural Health Research Center website at: http://depts.washington.edu/uwruca/.

Fifty-five percent (485 of 881) of CO fatalities associated with the use of engine-driven tools reported to CPSC staff occurred in urban areas while the estimated proportion of the U.S. population living in urban core areas is 71 percent. Forty-five percent (396 of 881) of CO fatalities occurred in non-urban core areas where an estimated 29 percent of the U.S. population lives. There appears to be an unusually high proportion of fatalities in small rural/isolated areas. Seventeen percent (149 of 881) of the CO fatalities known to CPSC staff to be associated with EDTs occurred in small rural and isolated areas where only an estimated nine percent of the U.S. population lives. The high proportion of fatalities in small rural/isolated areas can partly be explained by the fact that 23 percent of these occurred in temporary or boat/vehicle location and not in homes.

[4] The WWAMI name is derived from the first letter of each of the five cooperating states in a partnership between the University of Washington School of Medicine and the states of Wyoming, Alaska, Montana, and Idaho.

Table 8: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Engine-Driven Tools by Population Density of Place of Death, 1999–*2011*

Population Density		Estimated Percentage of U.S. Population[1]	Number of Deaths Reported to CPSC							
			All Engine-Driven Tools		Generators		Other Engine-Driven Tools		Multiple Products[2,3]	
Total	**Incident**	**100%**	**680**	**100%**	**513**	**100%**	**118**	**100%**	**49 (44)**	**100%**
	Deaths		**881**	**100%**	**695**	**100%**	**121**	**100%**	**65 (60)**	**100%**
Urban Core	Incident	71%	369	54%	292	57%	59	50%	18 (18)	37%
	Deaths		485	55%	401	58%	60	50%	24 (24)	40%
Sub-Urban	Incident	10%	96	14%	68	13%	17	14%	11 (7)	22%
	Deaths		129	15%	97	14%	17	14%	15 (11)	24%
Large Rural	Incident	10%	99	15%	70	14%	19	16%	10 (9)	20%
	Deaths		118	13%	86	12%	20	17%	12 (11)	19%
Small Rural /Isolated	Incident	9%	116	17%	83	16%	23	19%	10 (10)	20%
	Deaths		149	17%	111	16%	24	20%	14 (14)	17%

1 Estimated 2010 U.S. population categorized by RUCA designation. U.S. population estimates by RUCA classification were determined from by cross-referencing the WWAMI RUCA zip code table with the 2010 U.S. Census population estimates by zip code area, the most current census data available by zip code area.

2 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer "Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

3 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were being used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.
WWAMI Rural Research Center at the University of Washington Economic Research Group, USDA.
U.S. Census Bureau, 2011.

III. Alarm Usage

Table 9 presents a summary of CO fatalities known to CPSC staff characterized by CO alarm usage and alarm status. In 61 percent of the fatal incidents (415 of 680) and 58 percent of reported CO poisoning deaths (513 of 881), the presence of a CO alarm at the location of the incident was unknown or unreported. Of the 265 fatal incidents (368 CO fatalities) associated with engine-driven tools in which it was known whether a CO alarm was present or not, a CO alarm was present in only 21 incidents (8%) involving 30 CO fatalities. Of these 21 fatal incidents, the alarm was known to be inoperable in nine incidents (16 fatalities) due to missing or improperly installed batteries in a battery-powered alarm (non-plug-in type), or because the alarm was a plug-in type and power was out at the location of the incident. Seven of the nine fatal incidents (14 fatalities) with inoperable alarms were associated with generator usage.

For the remaining 12 fatal incidents (14 fatalities) where an alarm was known to be present, the alarm was known to have sounded in only six incidents (six deaths). Four of the six incidents occurred in an attached garage of a home with the alarm sounding inside the house. In one incident, the victim's family reportedly did not understand that the alarm sounding pattern (sounding every few minutes) was indicating CO present in the home and thought it simply meant that the alarm was working. In another incident, the victim was found in a home where a CO alarm was sounding. It is unclear if the alarm triggered after the victim became incapacitated by CO poisoning or if the victim simply misunderstood or ignored the signal. In an additional three CO deaths from three separate incidents, an apparently operable CO alarm failed to sound, even though lethal levels of CO were present in the home. There were also five deaths from three incidents in which a CO alarm was present in the house, but it was unknown whether it sounded or if it was even operable.

Table 9: Carbon Monoxide Alarm Usage Associated with Engine-Driven Tools Non-Fire Carbon Monoxide Poisoning Deaths, 1999–*2011*

CO Alarm Status	Number of Deaths and Percentage of Deaths when Alarm Status was Known											
	All Engine-Driven Tools			Generators			Other Engine-Driven Tools			Multiple Products[1,2]		
	Incidents	Deaths	% of Deaths	Incidents	Deaths	% of Deaths	Incidents	Deaths	% of Deaths	Incidents	Deaths	% of Deaths
Total	**680**	**881**	**-**	**513**	**695**	**-**	**118**	**121**	**-**	**49 (44)**	**65 (60)**	**-**
Alarm Status Known	**265**	**368**	**100%**	**214**	**310**	**100%**	**31**	**33**	**100%**	**20 (17)**	**25 (22)**	**100%**
No Alarm	**244**	**338**	**92%**	**200**	**287**	**93%**	**28**	**30**	**91%**	**16 (14)**	**21 (19)**	**84%**
Alarm Present	**21**	**30**	**8%**	**14**	**23**	**7%**	**3**	**3**	**9%**	**4 (3)**	**4 (3)**	**16%**
Alarmed	6	6	2%	2	2	1%	3	3	9%	1 (1)	1 (1)	4%
Did not alarm, batteries removed or incorrectly inserted	4	8	2%	3	7	2%	0	0	0%	1 (1)	1 (1)	4%
Did not alarm, plug-in type, no power	5	8	2%	4	7	2%	0	0	0%	1 (0)	1 (0)	4%
Did not alarm, though powered	3	3	1%	2	2	1%	0	0	0%	1 (1)	1 (1)	4%
Alarm present, Unknown if it alarmed	3	5	1%	3	5	2%	0	0	0%	0	0 (0)	0%
Alarm Status Unknown	**415**	**513**	**-**	**299**	**385**	**-**	**87**	**88**	**-**	**29 (27)**	**40 (38)**	**-**

1 "Multiple Products" includes incidents involving generators or OEDTs with other CO-generating consumer products. "Other Consumer Products" includes one or more of the following: portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with a generator and another engine-driven tool (lawn mower) in operation.

2 Numbers in parentheses indicate incidents involving a generator and another product, including the case where both a generator and an OEDT (lawn mower) were used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

IV. Hazard Patterns Associated with Generators

This section presents information about the usage patterns associated with fatal CO poisoning specific to generators, as well as information about the homes where fatal generator incidents occurred. As of April 20, 2012, CPSC staff is aware of 557 generator-related incidents in 1999 through 2011that resulted in non-fire CO fatalities. Five hundred-thirteen of these incidents involved only a generator. The remaining 44 incidents involved a generator and another combustion fuel-burning consumer product, including one that was another engine-driven tool. Staff completed In-depth Investigations (IDIs) for 520 of 557 (93%) fatal CO incidents associated with generators that occurred from 1999 through 2011. For the remaining 37 incidents in which an IDI was not performed or was not completed by the April 20, 2012 cut-off date, attempts were made to augment the data from reports of the incident in the Injury and Potential Injury Incidents (IPII) records or from death certificate information. Summaries of generator-related incidents in this section also include incidents where multiple fuel-burning consumer products were involved, including a generator.

A review of records for the 575 incidents resulting in 755 generator-related, non-fire CO deaths reported to CPSC staff, which includes 513 incidents (695 fatalities) involving a generator alone and 44 incidents (60 fatalities) involving a generator and another CO-producing consumer product, suggests two main reasons reported for using a generator. One reason cited was to provide electricity to a location that did not have electricity due to a temporary situation (*e.g.*, a power outage), and the other was to provide power after a shutoff to the residence by the utility company due to bill dispute or nonpayment. Table 10 provides a breakdown by year, listing the reasons why a generator was in use at the time of the incident. Twenty-nine percent (220 of the 755 reported deaths) of the generator-related, non-fire CO fatalities involved the use of generators during a temporary power outage stemming from a weather problem or a problem with power distribution. Nineteen percent (143 of 755 deaths) of the fatalities were associated with the use of generators after a power shutoff by the utility company for nonpayment. For 122 of the reported fatalities (16%), it could not be determined why the generator was in use, or why there was no electricity at the location of the incident.

Table 10: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Generators[1] by Reason for Use, 1999–*2011*

Reason for Use		Total	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	*2010*	*2011*
Total	**Incidents**	**557**	**6**	**15**	**17**	**38**	**41**	**35**	**80**	**64**	**57**	**69**	**46**	***35***	***54***
	Deaths	**755**	**6**	**21**	**23**	**48**	**57**	**47**	**103**	**95**	**70**	**94**	**67**	***44***	***80***
Power outage due to weather, or problem with power distribution	Incidents	154	3	1	3	12	15	7	37	11	15	19	10	*5*	*16*
	Deaths	220	3	1	3	16	20	11	53	17	23	26	17	*6*	*24*
Electricity turned off by power company due to bill dispute or nonpayment	Incidents	107	0	1	1	10	4	6	11	17	13	13	6	*11*	*14*
	Deaths	143	0	2	1	13	5	6	12	23	16	19	9	*15*	*22*
Provide power to storage shed, trailer, boat, camper, cabin, campsite	Incidents	78	0	7	6	5	8	3	8	14	8	5	8	*2*	*4*
	Deaths	113	0	11	9	7	10	4	11	21	9	7	11	*5*	*8*
New home or homeowner, and power not yet turned on, home under construction or renovation	Incidents	53	0	1	1	1	4	10	4	6	5	6	5	*5*	*5*
	Deaths	80	0	1	3	1	8	14	6	9	5	12	6	*5*	*10*
Provide power to home or mobile home that normally does not have electricity	Incidents	33	0	1	4	1	1	3	6	3	4	4	2	*3*	*1*
	Deaths	43	0	1	5	1	1	4	6	5	5	5	6	*3*	*1*
Working on or preparing a home for predicted storm	Incidents	7	1	0	0	0	1	0	0	1	0	4	0	*0*	*0*
	Deaths	7	1	0	0	0	1	0	0	1	0	4	0	*0*	*0*
Provide power to a shed or garage that normally does not have electricity	Incidents	8	0	1	1	1	0	0	0	0	0	2	0	*1*	*2*
	Deaths	8	0	1	1	1	0	0	0	0	0	2	0	*1*	*2*
Other (previous fire in house, power shut off by owners, servicing power supply, or other usage)	Incidents	16	1	2	1	3	0	0	1	1	0	3	2	*1*	*1*
	Deaths	19	1	3	1	4	0	0	1	1	0	3	2	*1*	*2*
Unknown why electricity off	Incidents	101	1	1	0	5	8	6	13	11	12	13	13	*7*	*11*
	Deaths	122	1	1	0	5	12	8	14	18	12	16	16	*8*	*11*

1 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

For the 220 fatalities associated with a power outage due to weather or a problem with power distribution, Table 11 provides a further breakdown by year and cause of the power outage. Ninety-one percent (201 of 220) of the fatalities associated with power outages were due to specific weather conditions. Ice or snow storms are associated with the largest percentage of weather-related CO fatalities (47%). From 2006 to 2011, the percentage of weather-related CO fatalities associated with ice and snow storms is even higher at 54percent (61 of 113). Hurricanes are also associated with a large percentage of CO fatalities (29%) over the 13-year period from 1999 to 2011. But nearly half of the hurricane- or tropical storm-related fatalities (31 of 63) occurred in 2005.

Table 11: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Generators[1] by Reason for Power Outage, 1999–*2011*

Reason for Power Outage		Total	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	*2010*	*2011*
Total	**Incidents**	**154**	**3**	**1**	**3**	**12**	**15**	**7**	**37**	**11**	**15**	**19**	**10**	***5***	***16***
	Deaths	**220**	**3**	**1**	**3**	**16**	**20**	**11**	**53**	**17**	**23**	**26**	**17**	***6***	***24***
Ice or snow storm	Incidents	74	0	0	0	10	5	1	15	6	9	7	9	*3*	*9*
	Deaths	104	0	0	0	14	7	2	20	8	13	9	14	*4*	*13*
Hurricane or tropical storm	Incidents	42	0	0	0	1	6	5	20	1	0	6	0	*0*	*3*
	Deaths	63	0	0	0	1	9	8	31	1	0	8	0	*0*	*5*
Wind storm	Incidents	6	0	0	1	0	0	0	0	2	1	1	0	*0*	*1*
	Deaths	10	0	0	1	0	0	0	0	6	1	1	0	*0*	*1*
Thunderstorm or rainstorm	Incidents	11	0	0	1	0	2	0	1	2	1	1	0	*2*	*1*
	Deaths	13	0	0	1	0	2	0	1	2	1	2	0	*2*	*2*
Tornado	Incidents	3	0	0	0	0	0	0	0	0	0	2	0	*0*	*1*
	Deaths	5	0	0	0	0	0	0	0	0	0	3	0	*0*	*2*
Storm, unspecified	Incidents	4	0	0	0	0	0	0	0	0	2	1	0	*0*	*1*
	Deaths	6	0	0	0	0	0	0	0	0	4	1	0	*0*	*1*
Unknown or other reason for outage	Incidents	14	3	1	1	1	2	1	1	0	2	1	1	*0*	*0*
	Deaths	19	3	1	1	1	2	1	1	0	4	2	3	*0*	*0*

1 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.

Note: Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U.S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

In 2005, the number of power outage-related fatalities jumped to 53, with 52 known to be weather related. The 52 fatalities associated with weather-related power outages in 2005 were due primarily to hurricanes in September in the Gulf states, ice/snow storms in January in the Midwest, and ice storms in December in the Carolinas. Figure 2 illustrates the impact of the power outages in 2005, relative to other years. The 31 hurricane- or tropical storm-related, non-fire CO fatalities in 2005 that CPSC staff is aware of constitute more CO deaths than for any other year in this report for all weather-related outages combined. An additional 20 fatalities were associated with the use of generators during ice- or snow-related power outages in 2005, the highest total for any year covered in this report.

Figure 2: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Generators Usage During Power Outages

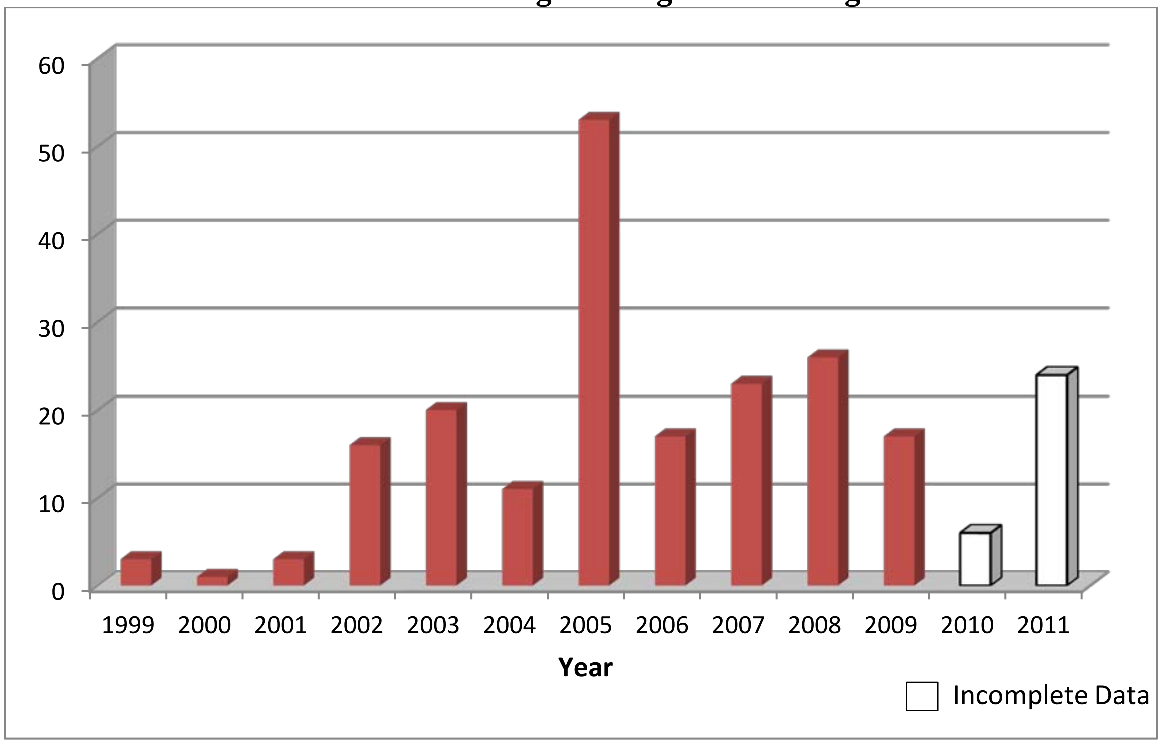


Table 7 shows 506 generator-related, non-fire CO fatalities that occurred in a fixed-structure home. For this characterization, a "fixed-structure home" is defined as a permanent, fixed residential structure, including detached and attached houses, apartments, fixed mobile homes, and cabins used as a permanent residence. Travel trailers, campers, and RVs are not included in this classification. Additionally, 45 of the 47 multiple product-related fatalities involved a generator in a fixed-structure home. Of these 551 generator-related fatalities (406 incidents) that occurred in a fixed-structure home, information was available for 469 deaths (85%, from 342 incidents) regarding the victim's location in relation to the generator. One hundred-eight of these 469 fatalities (23%) occurred in the same room or space as the generator.

The 551 deaths that occurred in a fixed-structure home were further classified by the specific location of the generator (Table 12) within the home. The category "Living Space" includes rooms reported as bedrooms, bathrooms, dens, living rooms, landings, home offices, rear rooms, enclosed porches, and converted garages. This category does not include attached garages or basements. The category "Outside Home" includes incidents where the generator was placed outside a home but near an open window, door, or vent of the home. Seventy percent (385 of 551) of the CO deaths at home locations occurred when a generator was placed inside the home, including the living space (173), a basement (153), closet (13), doorway (6), or inside the house, with no further information provided (40). Another 24 percent (131 of 551) occurred when the generator was placed in an attached garage, enclosed carport, or attached barn. More than half of the CO fatalities (284 of 551) occurred when the generator was placed in an attached structure (131), or in the basement or crawlspace (153).

Review of the yearly fatal incident data in Table 12 suggests that since 2004, more fatalities were related to generators in living areas of the home. Included in the definition of "non-basement living area of the home" are the categories "Living Space," "Closet of Home," and "Doorway of Home." Not included is the category "Inside house, no further information reported" because this could be in the living area or the basement of the house. From 2000 through 2003, there were more CO fatalities reported where the generator was placed in the basement or crawl space than in the non-basement living areas (in 1999, there were an equal number of fatalities reported where generators were placed in the basement and the living area). For each of the years 2004 through 2011, more reported CO fatalities were associated with generators in non-basement living areas than in basement or crawl space locations. Of the 109 generator-associated fatalities between 1999 and 2003, the basement was the predominant location of the generator (48 of 109, or 44%), followed by living areas (23 of 109, or 21%), including living space (17), closets (2), and doorways (4), and attached garages and other attached structures (22 of 109, or 20%). Thirteen deaths were associated with the use of a generator placed outside of the home. Usually, this involved placing the generator too near an open window or vent. This category also includes incidents where a generator was running outside the home but inside a building (*e.g.*, outside an apartment but still inside the building). From 2004 onward, there have been 442 reported CO fatalities in the home associated with the use of generators. More CO fatalities occurred with the generators placed in the non-basement living areas (169 of 442, or 38%, including living space (156), closets (11), and doorways (2)), followed by an attached garage or other structure (109 of 442, or 25%), and then the basement (105 of 442, or 24%). It is unclear why there has been a shift from the basement to the living space, but this may indicate a lack of knowledge by consumers about the severity of the CO dangers associated with the use of generators inside the home.

Table 12: Non-Fire Carbon Monoxide Poisoning Deaths in the Fixed-structure Home Location[1] by Location of the Generator,[2] 1999–*2011*

Generator Location		Total	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	*2010*	*2011*
Total	**Incidents**	**406**	**5**	**5**	**8**	**32**	**32**	**28**	**55**	**40**	**43**	**51**	**36**	***28***	***43***
	Deaths	**551**	**5**	**7**	**10**	**41**	**46**	**38**	**70**	**57**	**55**	**70**	**53**	***34***	***65***
Living space (non-basement)	Incidents	131	2	1	2	5	6	12	17	12	15	20	13	*13*	*13*
	Deaths	173	2	1	2	5	7	18	23	17	19	27	19	*13*	*20*
Garage / enclosed carport / attached barn	Incidents	100	0	1	2	8	7	6	17	13	9	13	8	*4*	*12*
	Deaths	130	0	2	2	10	8	8	18	20	14	15	11	*5*	*17*
Basement / crawlspace	Incidents	101	2	3	2	12	12	6	12	9	9	11	6	*4*	*13*
	Deaths	153	2	4	4	18	20	7	15	11	12	20	11	*7*	*22*
Inside house, no further information reported	Incidents	33	1	0	1	3	5	1	2	4	6	4	3	*1*	*2*
	Deaths	39	1	0	1	4	7	1	2	4	6	4	5	*2*	*2*
Closet in home	Incidents	6	0	0	0	2	0	0	1	1	1	0	1	*0*	*0*
	Deaths	13	0	0	0	2	0	0	6	3	1	0	1	*0*	*0*
Outdoors	Incidents	11	0	0	1	0	1	1	4	0	2	0	0	*1*	*1*
	Deaths	14	0	0	1	0	2	2	4	0	2	0	0	*1*	*2*
Doorway to home	Incidents	5	0	0	0	2	1	1	0	1	0	0	0	*0*	*0*
	Deaths	7	0	0	0	2	2	1	0	2	0	0	0	*0*	*0*
Unknown location, but at home	Incidents	19	0	0	0	0	0	1	2	0	1	3	5	*5*	*2*
	Deaths	22	0	0	0	0	0	1	2	0	1	4	6	*6*	*2*

1 This refers to a fixed-structure used as a residence, including houses, mobile homes, apartments, townhouses, and structures attached to the house, such as an attached garage. Not included here are incidents that occurred in detached structures at home locations (*e.g.*, detached garages, sheds) or at non-fixed location residences (*e.g.*, travel trailers, houseboats).

2 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Table 13 presents a summary of non-fire CO fatalities that occurred in the fixed-structure home characterized by ventilation status. Many of the incidents of generator-associated fatalities in the home (239 of the 551 deaths) did not contain information about the ventilation of the generator. In 205 of the 312 deaths (66%) in which information on ventilation of the generator was available, the generators were not vented at the time of the incident. In four of these deaths, a window or door was open during some period of use but later closed. There were 107 deaths associated with generators in which it was reported that some type of ventilation was employed. Of these 107 deaths, 82 non-fire CO deaths were associated with incidents in which it was reported that there was an open or partially open window, door, garage door, or a combination of these. Fourteen deaths were associated with generators that were placed outside the home near open windows, doors, or vents, where carbon monoxide entered the home. In 17 deaths (from 7 incidents), consumers actively attempted to vent generator exhaust outside through a window or door, or through the use of a fan, but these measures failed to adequately vent the CO from the victims' location. An additional fatality occurred when a victim placed a generator outside of an apartment in the unventilated hallway of a building.

Table 13: Non-Fire CO Fatalities in the Fixed-structure Home[1] Reported to CPSC Staff and Associated with Generators[2] Categorized by Status of Ventilation, 1999–*2011*

Ventilation Status	Number of Incidents	Number of Deaths	Percentage of Deaths	Percentage of Deaths Where Ventilation is Known
Non-fire CO fatalities in the home	**406**	**551**	**100%**	**100%**
Some ventilation attempted	**73**	**101**	**18%**	**32%**
Open window(s), open door(s), an open garage door, or a combination of these	54	69	13%	22%
Actively trying to vent either by fans or by directing exhaust out a window or door	7	17	3%	5%
Placed outside, but near a window, door or A/C unit[3]	11	14	3%	4%
Placed outside apartment, but inside building	1	1	< 1%	< 1%
No ventilation	**157**	**215**	**39%**	**68%**
Open windows or doors closed sometime later	5	7	1%	2%
No ventilation attempted[4]	152	208	38%	66%
Unknown ventilation	**176**	**235**	**43%**	**-**

1 This refers to a fixed-location structure used as a residence, including houses, mobile homes, apartments, and townhouses, as well as structures attached to the house, such as an attached garage. Not included here are incidents that occurred in detached structures at home locations (*e.g.*, detached garages and sheds) or at non-fixed location residences (*e.g.*, travel trailers and houseboats).

2 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP fueled heaters, portable kerosene fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.

3 One incident involved alternately moving the generator outside then inside after the generator would shut off, presumably because of weather conditions. After a warm-up period, the generator was again placed outside until it failed again.

4 One death occurred when a generator was placed outside an apartment in an unvented hallway and one occurred when the generator was placed outside a trailer that was located inside an enclosed, unvented garage.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Note: Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Table 14 presents a summary of the fatal CO incidents and fatalities characterized by the size of the home in which the fatalities occurred. For 36 percent (198 of 551) of the deaths (149 of 406 fatal incidents), CPSC staff could not ascertain the size of the home. Home size information was available for 353 of the 551 deaths (257 of 406 fatal incidents). Information regarding the size of the home reported in this document is from one of two sources. The first source is the CPSC In-depth Investigations (IDIs), which include information gathered from police, fire department, or public records. The second source is from Internet databases of real estate information, which contain public record data, such as *Cyberhomes.com* and *Zillow.com*. In most cases, Internet databases agree on the size of the home because both databases are based on public records from the county, state, or municipality. Occasionally, the records in the databases do not agree. In that situation, the average of the two or more sizes was used because it could not be determined which database had the more accurate figure.

Sixty-one percent (215 of 353) of the reported CO fatalities (from 154 of the 257 fatal incidents) associated with generators that occurred in the home, where the size of the structure was known, occurred in homes that were less than 1,500 square feet, and 84 percent (298 of 353 deaths from 219 of the 257 incidents) occurred in houses that were less than 2,000 square feet. This portion of the fatal incident location includes most incidents that occurred in apartments and mobile homes. Fatal incidents that occurred in a detached structure are not included in this figure. The median home size involved in fatal CO poisoning deaths, where home size information is known, was 1,350 square feet. As a point of reference, according to the U.S. Census Bureau's *American Housing Survey for the United States: 2009*, the median housing unit as of 2009 was 1,736 square feet. Comparing the percentages of fatal incidents by home size to the U.S. Census figures, it appears that the fatal CO incidents are skewed toward smaller homes. Whether this is due to economic reasons or because smaller-volume structures are more quickly filled by deadly carbon monoxide, is unclear. Perhaps it is a combination of the two factors, or some yet unidentified reason.

Table 14: Non-Fire CO Fatalities in the Fixed-structure Home[1] Reported to CPSC Staff and Associated with Generators[2] Categorized by Size of Home, 1999–*2011*

Home Size (in sq. feet)[2]	Number of Incidents	Number of Deaths	Percentage of Incidents	Percentage of Incidents Where Home Size is Known	Estimated Percentage of U.S. Housing Units (2009)[4]
Total	**406**	**551**	**100%**	**100%**	**100%**
Under 500	1	1	< 1%	< 1%	1%
500–999	57	73	14%	22%	10%
1,000–1,499	96	141	24%	37%	25%
1,500–1,999	65	83	16%	25%	24%
2,000–2,499	26	41	6%	10%	17%
2,500–2,999	5	6	1%	2%	9%
3,000 or Larger	7	8	2%	3%	14%
Unknown	149	198	37%	-	-

1 This refers to a fixed-location structure used as a residence, including houses, mobile homes, apartments, and townhouses and structures attached to the house, such as an attached garage. Not included here are incidents that occurred in detached structures at home locations (*e.g*., detached garages and sheds) or at non-fixed location residences (*e.g*., travel trailers and houseboats).
2 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.
3 Home size based on CPSC IDIs or from the Internet real estate databases, *Cyberhomes.com* and *Zillow.com.*
4 The 2009 housing unit figures are the most current figures available.
Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.
U.S. Census Bureau, American Housing Survey for the United States: 2009.
Note: Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

The size of the generator and the fuel used with the generator were both examined. The size of the generator was examined by the wattage rating (Table 15). In most cases, the advertised running wattage rating was used to categorize the generator. In some instances, however, a wattage rating was used in which it could not be determined whether it was the rated running wattage or maximum/surge wattage. When the wattage rating of the generator was known or could be determined (367 investigated deaths from 252 incidents), two-thirds of the deaths (245, 168 incidents) were associated with a generator in the 3500 to 6499 watt rating range. Nearly half (168 or 46%, 117 incidents) of the CO fatalities, where the generator size was known, were associated with generators in the 5000 to 6499 watt range. Generator sales data available to CPSC staff[5] indicate that during the time period 2003 through 2005, 56 percent of portable generators sold to consumers were in the 3500 to 6499 watt range; 23 percent of units sold had outputs below 3500 watts; and 21 percent had outputs of 6500 watts or greater. During this same period, generator size is available for incidents associated with 92 fatalities from 66 incidents. Seventy-eight percent (72 of 92, 49 incidents) of the CO fatalities were associated with generators in the 3500 to 6499 watt range; 20 percent (18 of 92, 15 incidents) were associated with units with outputs below 3500 watts; and 2 percent (2 of 92, 2 incidents) were associated with units with outputs of 6500 watts or greater. In the time period following the sales data (2006 through 2011), there were 216 fatalities from 143 incidents in which the generator size is known. Of these, 63 percent (135 of 216, 93 incidents) of

5 Smith, Charles L. *Portable Electric Generator Sets for Consumer Use: Additional Data on Annual Sales, Number in Use, and Societal Costs.* Memorandum to Janet Buyer, Project Manager, ESFS. August 24, 2006.

CO fatalities were associated with generators in the 3500 to 6499 watt range; 28 percent (61 of 216, 38 incidents) were associated with units with outputs below 3500 watts; and 9 percent (20 of 216, 12 incidents) were associated with units with outputs of 6500 watts or greater. Assessments of trends or patterns using direct comparisons of sales data and CO fatality data should be made with caution. Sales figures only reflect the proportion of newly purchased generators in each category and do not reflect the proportions of existing generators in the consumer population. Although many CO fatalities are associated with first-time users of newly purchased generators, many are also associated with older generators originally purchased for other uses or borrowed when a need for power presented itself.

Almost all of the generators that were involved in the CO poisoning incidents identified in this report were referred to as gas- or gasoline-fueled generators. One generator was identified as a propane-fueled generator, and one was identified as a natural gas-fueled generator.

Table 15: Number of Reported Non-Fire Carbon Monoxide Fatalities Associated with Generators[1] Categorized by Generator Wattage Rating, 1999–*2011*

Wattage Rating (in Watts)		Total	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	*2010*	*2011*
Total	**Incidents**	557	6	15	17	38	41	35	80	64	57	69	46	35	54
	Deaths	**755**	**6**	**21**	**23**	**48**	**57**	**47**	**103**	**95**	**70**	**94**	**67**	***44***	***80***
Under 2000	Incidents	18	0	2	0	3	0	2	3	1	2	1	1	2	1
	Deaths	21	0	2	0	3	0	2	3	1	5	1	1	*2*	*1*
2000–3499	Incidents	51	0	3	3	5	2	2	6	9	5	5	3	2	6
	Deaths	78	0	5	3	7	3	2	8	17	6	8	6	*2*	*11*
3500–4999	Incidents	51	0	1	4	1	3	2	10	6	4	9	2	3	6
	Deaths	77	0	2	8	1	5	2	13	11	7	11	2	*5*	*10*
5000–6499	Incidents	117	1	3	3	13	11	11	12	15	9	13	8	9	9
	Deaths	168	1	3	4	19	14	18	20	20	9	19	15	*11*	*15*
6500–7999	Incidents	9	0	0	0	0	0	0	1	0	1	3	1	1	2
	Deaths	13	0	0	0	0	0	0	1	0	2	4	1	*1*	*4*
8000 and larger	Incidents	6	0	0	0	1	0	1	0	1	0	1	1	*0*	1
	Deaths	10	0	0	0	1	0	1	0	1	0	1	1	*0*	*5*
Not reported	Incidents	305	5	6	7	15	25	17	48	32	36	37	30	18	29
	Deaths	388	5	9	8	17	35	22	58	45	41	50	41	*23*	*34*

1 Number of deaths associated with generators includes incidents where other consumer products may also have been involved. Other products include one or more of the following: lawn mowers, portable LP-fueled heaters, portable kerosene-fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

Note: Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Conclusion

Between 1999 and 2011, there were 881 non-fire CO poisoning deaths reported to CPSC staff that were associated with engine-driven tools. The majority of these deaths (695) involved generators. Another 60 fatalities were associated with both a generator and another consumer product (one involved both a generator and another engine-driven tool). Other engine-driven tools, including garden tractors, lawn mowers, power washers or sprayers, and others, were associated with a much smaller number of deaths. The majority of fatal incidents reported to CPSC staff involved a single fatality. Most reported deaths occurred while an individual was at home.

Victims age 25 years and older accounted for about 82 percent of the non-fire CO poisoning deaths that were associated with generators reported to CPSC staff, and the majority (73%) of the victims were male. Seventy-three percent of the reported deaths associated with generators (including deaths associated with the use of a generator and another consumer product) occurred at fixed-structure home locations. Seventy percent of the fatalities known to have occurred in the home involving generators occurred when a generator was placed in the living area or basement of the home. Another 24 percent occurred when a generator was used inside an attached garage or shed.

Generators were often used as alternative sources of electricity due to temporary power outages or as power sources for temporary shelters. Power outages, most commonly weather-related, were the single most common reason for generator usage that resulted in a non-fire CO fatality, accounting for at least 220 of the 755 fatalities (29%). Generators were often used with little or no ventilation. In only about 7 percent of the fatalities was it known that there was a CO alarm installed—and most of these were inoperable at the time of the fatal incident. Conclusions about why consumers used generators indoors or determinations about whether users were aware of the potential non-fire CO-poisoning hazard are difficult to make with the available information.

Victims age 25 years and older accounted for 99 percent (120 of 121) of the non-fire CO poisoning deaths reported to CPSC staff that were associated with other engine-driven tools. Males accounted for 97 percent (117 of 121) of the deaths associated with other engine-driven tools. Deaths associated with garden tractors and lawn mowers were often associated with an individual repairing or working on the product in an enclosed space.

Visit the CPSC's Carbon Monoxide Information Center—www.cpsc.gov/info/co/index.html—for the latest information on recalls, safety tips, safety standards, CO alarms, and downloadable injury prevention materials.

References

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Appendix A: Epidemiology Data Retrieval Specifics

The queries below were submitted through EPIR (EPIdemiology Retrieval), the CPSC staff's epidemiology data access application. Query results were reviewed to include only carbon monoxide poisoning incidents and to exclude duplicates and out-of-scope cases, which were cases that did not involve an incident that was associated with a non-fire carbon monoxide exposure and an engine-driven tool. Records from the three databases that were used in this report (the In-depth Investigation database (INDP), the Injury or Potential Injury Incident database (IPII), and the Death Certificate database (DTHS)) were then manually matched up to provide the most complete record and to eliminate additional duplicates.

For this report, a fatal incident was deemed in scope if none of the following criteria were violated:

- Carbon monoxide was the primary or contributing factor in the fatality,
- The carbon monoxide was not fire-related,
- The source of the CO was an engine-driven tool, or an engine-driven tool used in conjunction with another non-fire-related CO generating source,
- The fatal injury was unintentional in nature,
- The engine-driven tool involved was a consumer product, and
- The incident was not work-related.

Date of Queries: 04/20/2012

Incident Dates: 1/1/99-12/31/11
Product Codes: 113, 606, 800-899, 1062, 1400-1464, 3285-3287
Diagnosis Codes: 65 (Anoxia), 68 (Poisoning) – (INDP only)
ICD10 Code: X47x, Y17x – (DTHS only)
Narrative/Text Contains: 'CARB' or 'MONO'

Appendix B: Carboxyhemoglobin Levels Present In CO Fatalities

Carboxyhemoglobin (COHb) is a complex of carbon monoxide and hemoglobin that forms in red blood cells when carbon monoxide is inhaled. COHb poisoning can be fatal in large doses as it hinders delivery of oxygen to the body. Carboxyhemoglobin data is helpful in estimating the concentration of CO in the product exhaust and the lethality of the product which affects the speed of onset of harm. This information may be used by CPSC staff to assist in determining how best to address the CO hazard presented by generators and other engine-driven tools.

In healthy adults, a COHb level of 40–50 percent in the blood approximately correlates with symptoms of confusion, unconsciousness, coma, and possible death; a level of 50–70 percent approximately correlates with symptoms of coma, brain damage, seizure, and death; and a level greater than 70 percent is typically fatal.[6] COHb levels were available for 499 of the 881 fatalities (57% of the CO fatalities). Table B-1 shows the frequency of reports by COHb level categories. Percentages in the table are the category proportions of reported COHb levels. Eighty-one percent (405 of the 499) of fatalities had reported COHb levels of 50 percent or greater.

[6] Inkster S.E. *Health hazard assessment of CO poisoning associated with emissions from a portable, 5.5 Kilowatt, gasoline-powered generator*. Washington, D.C.: U.S. Consumer Product Safety Commission. 2004.

Table B-1: Carboxyhemoglobin Levels Associated with Engine-Driven Tools Non-Fire Carbon Monoxide Poisoning Deaths, 1999–*2011*

COHb Level	Number of Deaths[1]							
	All Engine-Driven Tools		Generators		Other Engine-Driven Tools		Multiple Products[2,3]	
Total	**881**	**-**	**695**	**-**	**121**	**-**	**65 (60)**	**-**
Reported Levels	**499**	**100%**	**391**	**100%**	**69**	**100%**	**39 (34)**	**100%**
Less than 30%	23	5%	18	5%	2	3%	3 (3)	8%
30–39.9%	28	6%	23	6%	4	6%	1 (1)	3%
40–49.9%	43	9%	34	9%	9	13%	0 (0)	0%
50–59.9%	100	20%	81	21%	11	16%	8 (8)	21%
60–69.9%	137	27%	110	28%	16	23%	11 (8)	28%
70–79.9%	130	26%	97	25%	18	26%	15 (13)	38%
80–89.9%	34	7%	24	6%	9	13%	1 (1)	3%
90–99.9%	4	1%	4	1%	0	0%	0 (0)	0%
Not reported	382	-	304	-	52	-	26 (26)	-

1 Percentages shown are the percentage of reported COHb levels per category.

2 "Multiple Products" includes incidents involving generators or OEDTs with other CO generating consumer products. Other consumer products include one or more of the following: portable LP fueled heaters, portable kerosene fueled heaters, camp stoves, lanterns, outdoor cookers, furnaces, and wood stoves, and one case with both a generator and another engine-driven tool (lawn mower) in operation.

3 Numbers in parentheses indicate incidents involving a generator and another product, including the case where a generator and an OEDT (lawn mower) were used concurrently.

Notes: Totals may not add to 100 percent due to rounding.
Italicized numbers indicate that reporting of incidents is ongoing. Counts may change in subsequent reports.

Source: U. S. Consumer Product Safety Commission, Directorate for Epidemiology, 2012.

TAB B

United States
Consumer Product Safety Commission
4330 East West Highway
Bethesda, MD 20814

Memorandum

Date: August 8, 2012

TO: Janet Buyer
Project Manager, Portable Generators
Division of Combustion and Fire Sciences, Engineering Sciences

THROUGH: George A. Borlase
Ph.D., P.E., Associate Executive Director
Directorate for Engineering Sciences

FROM: Susan Bathalon
Combustion Product Area Team Lead,
Office of Hazard Identification and Reduction

SUBJECT: Report on the Engine Performance and Exhaust Emission Test Results of the Low Carbon Monoxide Prototype Portable Generator

Executive Summary

Advancements in Exhaust Emission Control Technologies

Prior to the U.S. Consumer Product Safety Commission (CPSC) staff's technical work to reduce carbon monoxide (CO) on portable generators, advancements with small engine emission controls technologies were developed and manufactured for several types of small engines. The emission control developments for air-cooled lawn and garden engines were primarily aimed to reduce hydrocarbon and nitrogen oxide emissions to maintain compliance with federal and state regulations. Some examples of emission control technology included the adaptation of catalysts in handheld lawn equipment, electronic fuel-injection systems on twin cylinder ride-on lawn mower engines, and developmental catalyst with engines sized for walk-behind mower applications.

Marine generator water-cooled engines less than 25 horsepower are used for auxiliary power in recreational boating. Recently, these marine generators have adapted both fuel-injection systems and catalysts for exhaust treatment to lower carbon monoxide emissions. These newly developed marine generators are expected to reduce carbon monoxide by approximately 99 percent.[1] Staff understands that the manufacturers developed the marine generator technologies to specifically reduce the risk of carbon monoxide poisonings and, additionally, requested emission regulation in an effort to decrease the number of carbon monoxide fatalities and poisonings associated with the marine generator exhaust emissions.

Prototype Generator Design and Durability Program

From these technical advancements in small engine emission controls and their improvement in emission levels, staff believed that CO from portable generators could be significantly lowered to mitigate the risk of fatalities and poisonings shown in typical consumer scenarios from the CPSC database incidents. The prototype generator program goals were to substantially decrease CO emission rates while maintaining the generator's

[1] Environmental Protection Agency , Control of Emissions From Nonroad Spark-Ignition Engines and Equipment; Final Rule, Federal Register: October 8, 2008

performance in maximum power output, maintain equivalent hydrocarbon and nitrogen oxide emissions levels, and maintain acceptable temperature limits. The prototype development approach was to use injection technology to reduce and better control the combustion fuel and install a catalytic converter for exhaust after-treatment. Through contract work with the University of Alabama, staff developed a working prototype generator by using commercially available parts for better fuel delivery controls. The original generator carburetor engine was retrofitted with sensors and components for electronic microprocessor controls for both intake manifold fuel injection and combustion spark timing. While the prototype generator's microprocessor controlled the majority of combustion exhaust, the design also included a small three-way catalyst to convert some of the remaining exhaust constituents of carbon monoxide, hydrocarbons, and nitrogen oxides.

The prototype technology was durability tested for 500 service accumulation hours to satisfy the end-of-engine rated life. This 500-hour lifespan was determined from the certification label affixed on the original generator engine. The generator durability cyclic load profile was based on an industry-developed duty cycle that mimics typical consumer use of small utility engines in a variety of applications, including portable generators. Staff understands that the requirements for emission certification require accumulation of service hours dependent upon the manufacturer's expectation of how the engine operates in use. Staff believes that 500-hour cycles of continuous duty cycles, with periodic emission testing from full to no loading of the prototype generator, is an especially rigorous durability performance test.

Prototype Generator Results

Through the durability program, and after the accumulation of 500 hours, the prototype unit showed a reduction of carbon monoxide emissions by 90 to 99 percent. At completion of the durability test, generator emission testing was performed with an unmodified baseline generator unit and the prototype unit. Combined and weighted carbon monoxide emission levels of the prototype generator showed 93 percent reduction over the unmodified baseline generator. In addition, the prototype indicated acceptable levels for hydrocarbon and nitrogen oxide throughout the durability program. After accumulation of 500 engine hours, and at the end of durability program, the prototype unit measured lower hydrocarbon and nitrogen oxide emission levels than the unmodified baseline generator.

This prototype generator technology demonstration illustrates emission control technology adapted on a single-cylinder, air-cooled, gasoline-fueled portable generator engine. The prototype generator design was capable of achieving several important program goals, including:

The prototype generator achieved target emission results in the end-of-life testing:

- *At the end of life,* the durability-tested prototype engine met the program goals by demonstrating a 93 percent reduction of CO emission levels over the unmodified baseline unit.
- *At the end of life,* the prototype generator engine demonstrated an approximate 30 percent reduction of regulated hydrocarbons and oxide emission rates, as compared to the unmodified baseline unit.

Cylinder head and exhaust manifold gas temperatures with the prototype design reflect the leaner air-to-fuel (AFR) mixtures, which can produce hotter combustion gases when compared to the original carburetor mixture, where the unburned fuel in the combustion chamber acts as a coolant. The prototype engine cylinder head and exhaust manifold gas temperatures are well within the engine and catalyst manufacturers recommended operating range. The AFR strategy with the prototype design reduces the average fuel consumption by approximately 20 percent.

The engine manufacturer developed many versions of muffler designs, and one was chosen for the prototype that could accommodate the small-size catalyst. The original configuration of the unmodified generator muffler contained several baffles to both turn and redirect the exhaust gases to reduce noise. Differences in the muffler surface temperatures can occur from configuration variations, the catalyst acting as a mass heat sink and creating increased conduction and catalyst exothermic reactions. The averaged muffler surface temperatures of the prototype were considered acceptable at approximately 70° Celsius hotter than the OEM design. The prototype's muffler shroud temperatures were 110° Celsius or less over the range of deliverable power. There was no muffler shrouding with the unmodified generator.

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Carbon Monoxide Hazard Associated with Portable Generator Use

CPSC Fatality Data Associated with Portable Generators

From 2006 to 2008, the annual average estimate of unintentional non-fire CO poisoning fatalities associated with consumer products in the CPSC jurisdiction was 183 deaths, with 80 percent of these deaths occurring in residential locations, such as homes, sheds, and garages. The estimated CO poisoning deaths for consumer products in 2008 was 189 fatalities. In 2007, there were an estimated 86 CO deaths specifically associated with exhaust from portable generator use and an additional 7 CO deaths that included the use of a portable generator with another combustion appliance.[2] There were an estimated 62 CO deaths in 2007 associated with portable generators; 85 deaths in 2006; and 88 in 2005 (68, 88, and 97, respectively, if including the involvement of portable generator use in conjunction with another CO-producing combustion appliance (Hnatov, 2008 annual estimates).[3] In addition to providing national estimates of CO deaths, CPSC staff also counts the number of CO deaths associated with portable generators that are reported into the databases through a variety of source documents. As of April 20, 2012, CPSC databases contained records of at least 695 deaths from CO poisoning associated with consumer use of a generator in the period of 1999 through 2011.[4] Over this period, there were an additional 60 CO poisoning deaths associated with consumer use of a generator in conjunction with least one other combustion consumer appliance. Totaling the number of anecdotal CO poisoning deaths over this 13-year period, the number of fatalities associated with generator exhaust is 755.

Retail Available Sizes Associated with Portable Generators

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[2] This report provides information about the estimated number of unintentional non-fire deaths attributed to carbon monoxide (CO) poisoning that were associated with the use of consumer products in 2008, and companion statistics since 1999. It should be noted that CPSC staff continues to receive reports of CO poisoning fatalities, and the estimates may change in subsequent reports.

[3] Hnatov Matthew V., *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products, 2008 Annual Estimates.*

[4] Hnatov Matthew V., *Incidents, Deaths, and In-Depth Investigations Associated with Non-Fire Carbon Monoxide from Engine-Driven Generators and Other Engine-Driven Tools, 1999–2011*.

Portable generator use and related CO fatalities are typically associated with electrical power interruptions, such as those caused by severe weather, disconnection by the utility company because of billing disputes, or providing power to a sheds or remote cabins that are not serviced with electrical power. Current available retail gasoline portable generators are sized for deliverable power output that ranges from 1.0 to 18.0 kilowatts (kW). This lower range supports powering several small electrical appliances, while the larger size units can provide electrical power needs for an entire household.

From 2002 to 2005, the largest category of portable generators purchased by consumers was rated at 5.0 to less than 6.5 kW.[5] This power rating, 5.0 to 6.5 kW, is also the primary category associated with portable generator CO fatalities from 1999 through *2010.*[4]

Portable Generator Exhaust Emission Target Goals

Based on this retail sale information and the incident data, the power rating targeted for portable generator prototype development to reduce carbon monoxide emissions was between 5.0 to 6.5 kW. In the marketplace, this size generator uses a carburetor and mechanical governor to control the fuel delivery. Exhaust emission composition has a dependency on the fuel delivery system. At the initiation of the CPSC's low CO generator program, the marketplace for generators with carburetor fuel metering was tuned to meet the U.S. Environmental Protection Agency (EPA) and California Air Resources Board's (CARB) exhaust emissions regulations that became effective in 2000. New EPA exhaust emission standards for engines used in the majority of portable generators, including those with power ratings from 5.0 to 6.5 kW, took effect with engines manufactured in 2011. These new EPA regulations reduce hydrocarbon and nitrogen oxide (HC+ NOx) exhaust emission from 12.1 to 8 grams per kilowatt hour (g/kW-hr), which brings consistency between the EPA and CARB standards. For these portable generator engines, there are also carbon monoxide EPA exhaust emission

[5] Smith, Charles L., *Portable Electric Generator Sets for Consumer Use: Additional Data on Annual Sales, Number in Use, and Societal Costs.*

regulations for CO at less than 610 g/kW-hr that apply to all engines in a family of manufactured engines. The basis of the EPA regulation for small nonroad engines is related air attainment pollution reduction. Staff understands that these small engine regulations, including those of CO, are not based on survivability or acute poisoning scenarios, like the fatalities presented in the CPSC databases. However, the EPA's CO regulation is 5 g/kW-hr for marine water-cooled generator engines; these regulations are specifically aimed to reduce CO deaths and injuries in recreational boating.[6] With these marine generator engines, staff understands that the product manufacturers found industry consensus in emission limits to prevent CO injuries.

Responses from small engine experts initiated by a staff request for information solicitation for portable generator CO emission reduction strategies revealed potential reductions of up to 95 percent with the integration of both fuel injection controls and the presence of catalytic exhaust after-treatment. Staff estimated that if CO reduction on this order could be achieved, it could significantly improve the survivability of many of the CO fatality scenarios described in the CPSC incident data. In 2006, CPSC staff initiated a contract with the University of Alabama (UA) to develop, construct, and test a functional prototype generator designed to decrease significantly the production of carbon monoxide emissions while maintaining below the other regulated certification emission requirements according to the manufacturer's affixed label on the original engine. The contract targeted a CO emission rate at or below 30 g/kW-hr with interest in less aggressive CO reduction targets, if necessary, for considerations that may have included other exhaust component, temperatures, or engine power output. The design approach was to incorporate an electronic fuel-injection system and a catalytic exhaust after-treatment onto a typical consumer 5.0 kW portable generator.

Portable Generator Durability Program Goals

To demonstrate the performance and longevity of low CO generator technology, the program approach included emission testing generator units in the original unmodified

[6] Environmental Protection Agency , Control of Emissions From Nonroad Spark-Ignition Engines and Equipment; Final Rule, Federal Register: October 8, 2008

configuration, constructing the prototype generator, emission testing the constructed prototype generator configuration, and accumulating durability cyclic engine hours with periodic emission testing. The durability program included aging of both an original generator unit, without modification, and the prototype generator. This approach allowed for direct comparison of the prototype generator performance to an unmodified unit. The emission test equipment and procedures at the University of Alabama do not meet all 40 CFR parts 90 and 1065 regulations required for certification data. However, the University's emission data provides sound engineering practices for consistency and repeatable data. Staff considers the comparison between the prototype generator data and the baseline data to be accurate and the best method for demonstrating the University of Alabama's generator emission data. The comparisons of the prototype generator to the baseline unmodified generator, in terms of emission and engine results, are presented throughout this report.

After the completion of the durability test, the prototype generator engine was emission tested at a facility that meets EPA's CFR small engine emission testing procedures and regulations. This testing was performed at Intertek Carnot Emission Services, an independent certification emission testing laboratory. At this facility, the prototype engine was extracted from the generator and mounted on a dynamometer. Staff considers the dynamometer prototype engine test data at the independent test laboratory facility to be CFR certification-quality emission data that can be discussed in terms of meeting the regulation for emission exhaust constituents, such as carbon monoxide hydrocarbons and nitrogen oxides. These prototype engine dynamometer emission test results, according to small nonroad engine procedures in 40 CFR part 1065, are presented in this report.

Prototype Generator Design

Unmodified Retail Portable Generator Selection

To develop the prototype, a retail consumer portable generator was selected with an advertised power rating of 5.0 kW. The associated 11-horsepower, rated speed, and air-cooled engine had a carburetor fuel delivery system and a mechanical governor. The alternator component of the generator was rated at 6.6 Kva single-phase and brushless. The coupled alternator and engine components were rated for a maximum of 60 hertz and either 240 or 120 volts, depending upon the configuration of the consumer's plug-in attachment at the receptacle panel.

Modifications to the Low Carbon Monoxide Prototype Portable Generator

The primary carbon monoxide design strategy of the prototype was to incorporate the electronic management system (EMS) with a microprocessor receiving input signal from various sensors to control the fuel delivery at a combustion air to fuel ratio (AFR) near to 14.6. A binary oxygen (O_2) sensor was installed into the exhaust gas manifold to measure the proportion of oxygen in the exhaust. This binary O_2 signal indicates a value either richer or leaner than the desired set point of 14.6 AFR, and the microprocessor effectively responds by creating either a shorter or longer pulse width of available combustion fuel flow. Some important prototype throttle body modifications affecting the original generator engine were modified by replacing the carburetor and main jet with a fuel injector with fuel delivery from a fuel pump mounted into the existing fuel tank. The starter pulley and recoil mechanism was removed and replaced with an electric start system. A toothed crank wheel and crank timing sensor was positioned on the existing starter flywheel crankshaft gear. The original flywheel magneto ignition system, which generated a spark during the compression stroke and a wasted spark during exhaust stroke, was replaced with an ignition coil spark plug wired for electronic controls. Several electronic sensors were connected to the EMS controller, which is called the electronic control unit (ECU). It serves to read the input signals and control the amount of fuel delivery based on fuel map calibration tables. The ECU and electric start capabilities were powered by a 12-volt battery that was mounted within the generator chassis. The EMS and associated sensors were an off-the-shelf component package from a commercial supplier of electronics components for engines. This portable generator EMS package was being used in applications like small-scale power scooters and motorcycles in the Asian market. The differences between a portable generator EMS application and a power scooter EMS application is the calibration of the fuel map tables. Each application needs calibration fuel map table adjustments, depending on emissions, power, and fuel economy requirements. Many portions of the calibration fuel map functions were too sophisticated for the single 14.6 AFR set point needed in the prototype generator application.

After the complete build prototype generator and fuel tables were calibrated for the generator operations, the unit was tested to review emission and engine data. The 14.6 AFR strategy demonstrated significant CO reduction in no and low hours of the prototype generator. CO emission reduction was on the order of 95 percent, as specified in the prototype development contract with the University. In addition, the generator 6-mode emission testing showed combined and weighted HC + NOx emissions with satisfactory levels when compared to the EPA Phase 2 regulation and the newly published and stricter EPA Phase 3 regulation. One unknown was how typical unmodified generator emission profiles are affected with wear. This unknown emission profile, with the effects of wear, instigated the adaptation of a small catalyst, approximately sized similar to a “D” battery, for exhaust emissions. The cylindrical mental monolith catalyst is 69 mm in diameter and 50.8 mm in length. The selected muffler for the prototype generator was a version made by the engine manufacturer but not the same as the quiet muffler version installed on the unmodified generators. This prototype muffler design was selected because the catalyst package and extensive internal baffling associated with the quiet generator muffler were ill-suited. The catalyst was formulated primarily for NOx reduction that could increase after accumulation of engine life and wear. The catalyst selection also considered lowered cost, based on the high ratio of rhodium with no platinum. The combination of stoichiometric AFR restricting the oxidation and the wash coat selection of the catalyst, created the expectation of relatively low catalyst activity. Low activity of the catalyst was believed to be optimum to keep the tailpipe exhaust gases and muffler surfaces within some moderate range of the temperatures present in the unmodified unit.

As a means to demonstrate the long-term effectiveness of the prototype generator performance and success with the CO and HC + NOx emissions, the prototype generator and an unmodified generator were subjected to durability testing, which included periodic generator emission tests. These generator emission durability tests were a means to measure and record data that included engine temperature parameters, AFR, fuel consumption, and exhaust emission constituent concentrations.

Generator Durability Program

Portable Generator Emission Test Cycle and Durability Duty Cycle

During consumer operation, the portable generator engine delivers mechanical power output that is influenced by the electrical demand of appliances plugged into the receptacle panel. The electrical loading of the portable generators was intended to mimic consumer appliance-use conditions through a full- to no-load range of operations. In the generator application, the electrical demand creates a mechanical response from the engine with some level of compositional exhaust gas flow rates, including carbon monoxide concentrations. In the prototype generator emission testing, which includes all tests performed in the durability program, a 6-mode load profile was adapted to mimic the small nonroad rated speed engine test cycle of the EPA regulation, 40 CFR part 90. This regulated engine test cycle has six modes, with each mode associated with a varied engine load that represents the full range of operating conditions for small engines. This engine test cycle is widely accepted by industry as representative of the typical small-engine, consumer-use profile for a variety of engines used in lawn and garden equipment. This 6-mode generator emission duty cycle was adapted for the generator program.

The industry and EPA test cycle are test programs that involve an AC dynamometer that creates either a known speed or applied torque to the engine shaft. With the engine shaft inaccessible in the generator application, its load and speed could not be directly measured, as required in the 40 CFR part 90 regulations. With no means to directly measure engine shaft load and speed, the generator engine power needed to be estimated from a known applied load and the alternator's efficiency curve. The alternator efficiency curve was provided by the generator manufacturer. Overall, this curve showed about 75 percent power transfer over the full range of input powers, except at idle.

Mode			1	2	3	4	5	6
Rated Speed		RPM	3600	3600	3600	3600	3600	idle
Load		[%]	Full	75	50	25	10	idle
Weigh		[%]	0.09	0.20	0.29	0.30	0.07	0.05
Output Power	Engine (Estimated)	[kW]	7.6	6.2	4.1	2.1	0.82	0.4
	Generator	[kW]	5.50	4.7	3.2	1.5	0.5	none

Table 1. Generator Engine Six-Mode Emission Test and Duty Cycle

The generator duty cycle in Table 1 shows the prescribed sequence of mode 1 (full load) to mode 6 (no load) used in generator emission testing and when accumulating durability hours on the units. During hour accumulation of the generator units, a program was created to automate the cyclic profile of the resistive load bank, which provided the electrical loading at the receptacle panel. The weight percent also provided a convenient 1-hour duty cycle schedule for accumulation of durability hours. Table 1 also shows the modal generator load with associated engine power that was estimated based on the provided alternator efficiency curves. As stated, with the engine shaft inaccessible to directly measure torque, all modal generator engine power obtained in Table 1 was calculated, rather than measured.

Portable Generator Application Duty Cycle Limitations

At the onset of the durability program, the generator duty cycle presented in Table 1 included a full load of 5.5 kW, which was determined to be the maximum sustainable generator load that would not trip the circuit breakers. This full load generator setting at 5.5 kW was 500 watts above the generator advertised rated output of 5.0 kW. The intermediate generator load settings were determined as a percentage of the engine manufacturer's advertised maximum net output of 8.2 kW and the provided alternator efficiency curves. This generator 6-mode profile best represented the industry duty cycle of engine dynamometer loading at intermediate loads. Staff recognizes that when the generator engine powers the combination of the alternator and resistive load-bank, the full load and idle states of a generator are offset from the values that the engine would experience with conventional dynamometer testing. When the generator is fully loaded at mode 1, the maximum power of the engine installed in the generator is offset lower than if the engine was powered in the conventional dynamometer configuration. In the generator configuration, the governor prevents the throttle plate from achieving true horizontal position of wide open throttle (WOT). Additionally, the generator idle set point, mode 6, was determined with no applied resistive load from the load bank. Even with no applied resistive load, some generator engine power is being delivered that would not be present in dynamometer testing.

Voltage Regulator Assembly Failures Affects on the Maximum Generator Output

At the initiation of durability, and up to approximately 125 hours of durability testing, it was believed that the maximum sustainable deliverable generator output power of 5.5 kW seemed reasonable because the engine was rated for 8.2kW net power output and the generator alternator unit was rated at 6.6 kVA. However, in the interval between the zero and 150-hour generator emission testing, both the baseline and prototype unit had voltage regulator assembly failures. These failures manifested as melted connectors and wires. After these voltage regulator repairs, the maximum generator power output was degraded from the 5.5kW output to between 5.2 to 5.3 kW. This maximum generator output was limited to 5.2 to 5.3 kW, even when the load bank settings were 6.5 kW and greater. After the voltage regulator repairs, it was assumed that the alternator assembly, including the newly replaced voltage regulator connectors and wiring, had limited the maximum generator electrical output.[7] After these failure occurrences, a multimeter was used to verify the applied load with the 150-, 250-, and 500-hour generator emission tests.

After the discovery of the voltage regulator assembly failures, the duty cycle for accumulation of engine service hours in the durability test remained unchanged with the maximum load bank setting at 5.5 kW. The generator durability duty cycle was automated as a 1-hour cycle that altered the resistive load on a time profile according to the weight percentages in Table 1. It was not feasible for University of Alabama staff to verify and measure the applied load during the entire 500 hours of durability testing. Regardless of the potential of lowered power near full generator load, staff believes that

[7] More information on these generator component failures as unscheduled maintenance during durability testing are listed in the *Prototype Development and Construction* section of the University of Alabama final report.

the 500-hours of continuous duty cycles with periodic emission testing from full-to-no loading of the prototype generator is an especially rigorous durability performance test and may be beyond a duty cycle prescribed by engine manufactures' expectations from generator products.

The Table 1 estimated engine power calculations should be considered approximations that rely on the accuracy of the efficiency curves provided by the generator manufacturer. However, the effect of the voltage regulator repairs on the alternator efficiency was not known. The purpose of providing combined weighted constituent emission rates, such as a combined weighted value for CO in grams per kilowatt-hour, is to compare the unmodified baseline generator and the prototype generator.

Verification of the engine power calculations was performed after the accumulation of 500 hours of durability testing, at which time the engine was pulled from the generator configuration and tested on a dynamometer at an Independent Emissions Test Laboratory facility, Intertek Carnot Emission Services. This verification demonstrated fairly accurate engine power estimates in the generator application with the exception of mode 1. At this Independent Emissions Test Laboratory, mode 1 engine power delivery in the generator application was approximately 20 percent lower than estimates presented in Table 1. It is believed that the mode 1 deliverable generator power at the Independent Emissions Test Laboratory and during generator emission testing at the University was reduced from original power capacity, due to the generator circuitry associated with the voltage regulator assembly. It is known that the generator application limited the engine power output because when the prototype engine, with more than 500 hours, was pulled from the generator and tested on the dynamometer, deliverable dynamometer power was within 9 percent of the engine manufacturer's rated power, 8.2 kW.

University of Alabama Pre-Durability Engine and Emission Test Results for the Prototype and Baseline Generators

Exhaust Emission Testing Procedures at the University of Alabama

The duty cycle for accumulation of hours on the generators throughout the durability tests was presented in Table 1. The 500-hour durability program provided a means to compare the performance of the prototype generator to an unmodified baseline generator. The baseline generator unit remained in the original configuration without modifications to the engine, including the muffler design. The prototype design was altered with the engine and exhaust muffler modifications, as described in the earlier section, *Prototype Generator Design*.

The facility at the University of Alabama (UA) developed and built the low CO prototype generator and performed all of the durability generator emission testing. This facility does not provide certification tests results; rather the University facility is considered an engine research and test laboratory. The generator emission test procedures at the UA attempted to emulate reasonably the federal test procedures of 40 CFR part 90 Subpart D. Generator emission tests performed at the UA facility were considered most important in the comparison of emission levels between the prototype and the baseline generator emission. These UA generator emission tests do not purport to meet the procedure standards for certification emissions because of several divergences. The largest deviation from the federal test procedure is that the engine is application tested, meaning that the alternator, rather than the calibrated dynamometer, is driving the engine load. Another UA procedural variation from the federal test procedures is that the gasoline fuel used in the emission testing was a commercial grade gasoline rather than the test fuel requirements specified in 40 CFR part 90 or part 1065. To review and quantify the properties in the commercial grade gasoline, UA performed a fuel analysis. The fuel was found to be nonleaded and non-oxygenated with acceptable molecular weight of hydrocarbon fractions. A large volume of this gasoline was purchased as a batch for pressurized storage for use in emission testing with the prototype and baseline generator.

Exhaust Emission Tests with the Unmodified and Original Prototype and Baseline Generators

Initial 6-mode generator emission tests were performed on the unmodified and original baseline generator unit and the unmodified and original prototype generator unit. Throughout the program, the baseline generator remained unmodified with original equipment, including the OEM carburetor fuel delivery system. However, the initial 6-mode generator emission tests performed on the unmodified prototype generator unit is the only record of engine data and emission levels of the prototype generator's original carburetor fuel system configuration. After the initial 6-mode generator emission tests were performed on the unmodified prototype generator, its fuel delivery system would be modified to meet the program's exhaust emission goals. The purpose of the initial emission testing on the two unmodified and original generator units was to compare some of the important engine health and emission measurements, including cylinder head temperatures, exhaust manifold temperatures, muffler surface temperatures, NOx + HC levels, and CO emission levels. The emission test results for these two unmodified generator units are presented in Table 2.

Engine Modal Data										Emission Rates Unweighted			Combined Weighted Emission Rates[8]			
Baseline Generator at 0 hours																
Mode	**AFR**	**Est Eng Power** (kW)	**Cyl. Head** °C	**Oil** °C	**Manifold Exhaust Gas** °C	**Tailpipe Exhaust Gas** °C	**Muffler Surface** °C	**Muffler Shroud Temp** N/A	**Fuel Rate** kg/hr	**HC** g/hr	**CO** g/hr	**NOx** g/hr	**HC** g/Kw-hr	**CO** g/Kw-hr	**NOx** g/Kw-hr	**HC + NOx** g/Kw-hr
1	12.8	7.6	203	108	760	578	441		5.3	20.5	974.6	56.2	5.0	282.1	4.5	9.6
2	12.4	6.2	195	104	740	549	420		5.0	20.6	1147.4	25.5				
3	12.5	4.1	180	97	717	495	379		4.4	19.4	938.6	20.7				
4	11.1	2.1	154	86	653	398	313		3.4	18.5	1212.7	3.3				
5	10.9	0.8	143	81	637	356	286		2.8	17.3	1042.8	2.0				
6	10.8	0.4	136	79	629	332	269		2.7	19.1	1031.0	1.6				

Prototype Generator as Unmodified and Original Equipment at 0 hours

Mode	**AFR**	**Est Eng Power** (kW)	**Cyl. Head** °C	**Oil** °C	**Manifold Exhaust Gas** °C	**Tailpipe Exhaust Gas** °C	**Muffler Surface** °C	**Muffler Shroud Temp** N/A	**Fuel Rate** kg/hr	**HC** g/hr	**CO** g/hr	**NOx** g/hr	**HC** g/Kw-hr	**CO** g/Kw-hr	**NOx** g/Kw-hr	**HC + NOx** g/Kw-hr
1	14.0	7.6	227	115	792	597	457		5.2	10.6	423.4	74.4	2.6	186.4	7.2	9.8
2	13.7	6.2	220	113	772	578	442		5.6	9.2	637.5	56.6				
3	13.8	4.1	208	107	753	522	403		4.0	7.2	394.3	28.4				
4	11.3	2.1	172	93	653	403	306		3.1	12.0	1043.7	3.2				
5	11.3	0.8	162	89	646	373	282		2.9	12.4	1008.7	2.3				
6	11.3	0.4	157	86	650	363	275		2.7	12.1	969.4	1.8				

Table 2. Comparison of the Unmodified and As-Received Generator Units at the University of Alabama

[8] The purpose of providing combined weighted constituent emission rates, such as a combined weighted value for CO in grams per kilowatt-hour, is to compare the baseline generator to the prototype generator. The combined weighted emission rate calculations require engine power values, which are considered approximations that rely on the accuracy of the efficiency curves provided by the generator manufacturer.

Table 2 shows that the carburetor engines used in the generators have unit to unit variation in AFR, cylinder head temperatures, exhaust manifold temperatures, and exhaust emissions. Of interest is that the AFRs become leaner toward full load and maximum generator power. The original engine with the unmodified prototype generator had an AFR of 14.0 at full load (mode 1). This 14.0 AFR created cylinder head temperatures 25°C hotter than the baseline unit. As a result of this leaner AFR and hotter cylinder head temperatures, the unmodified prototype generator unit also had hotter exhaust manifold gases, muffler surface temperatures, and tailpipe exhaust gases compared to the baseline unit.

Zero Hour Exhaust Emission Testing of the Modified Prototype Generator

After these initial generator 6-mode emission tests, the prototype generator was reconfigured by adapting technologies to reduce exhaust emission. This modified prototype generator was subjected to another 6-mode generator emission test. The purpose of this emission testing of the prototype generator was to compare the performance of the adapted and reconfigured equipment to the unmodified and original unit. In other words, the pre- and post-modified prototype generator configurations could be compared. The engine and emission performance results of the reconfigured prototype generator are shown in Table 3.

Prototype Generator with Catalyst Muffler										Emission Rate Unweighted			Combined Weighted Emission Rates[9]			
Mode	AFR	Est Eng Power	Cyl. Head	Oil	Manifold Exhaust Gas	Tailpipe Exhaust Gas	Muffler Surface	Muffler Shroud Temp	Fuel Rate	HC	CO	NOx	HC	CO	NOx	HC + NOx
		(kW)	°C	°C	°C	°C	°C	°C	kg/hr	g/hr			g/Kw-hr			
1	14.6	7.6	226	117	698	597	440	89	4.2	1.1	13.5	43.1	0.1	2.4	4.6	4.7
2	14.6	6.2	217	113	690	578	425	85	3.9	0.9	9.4	47.0				
3	14.5	4.1	201	105	670	532	394	76	3.2	0.7	11.4	11.3				
4	14.4	2.1	181	96	652	455	345	67	2.5	0.3	8.5	2.3				
5	14.5	0.8	170	91	648	416	315	62	2.1	0.1	3.1	1.7				
6	14.5	0.4	163	88	652	394	299	60	1.9	0.0	2.1	1.4				

Table 3. 0-Hour Emission Test for the Prototype Generator at the University of Alabama

[9] The purpose of providing combined weighted constituent emission rates, such as a combined weighted value for CO in grams per kilowatt-hour, is to compare the unmodified baseline generator and the prototype generator. The combined weighted emission rates require engine power values, which are considered approximations that rely on the accuracy of the efficiency curves provided by the generator manufacturer.

Table 3 provides the zero-hour generator emission tests for the prototype generator. Surprisingly, when comparing these two unmodified and modified prototype generator configurations, the Mode 1 cylinder head, exhaust manifold gases, tailpipe exhaust, and muffler surface values are actually cooler in the prototype configuration than in its unmodified configuration. The contributing factor to these temperature outcomes is believed to be the influence of the AFR values of the carburetor-fueled design with 14.0 AFR and the prototype fuel-injection design with 14.6 AFR. It is believed that the 14.0 carburetor design offered no cylinder head cooling capacity over the stoichiometric prototype design.

The success in emissions and temperatures of the prototype generator allowed for the initiation of the durability program. In the durability program, the cyclic load profile presented in Table 1 was applied on an hourly basis until the 500 hours of useful life hours were accumulated. Once the end of life durability hours were completed, the prototype and baseline generator units were emission tested to the 6-mode test. This end-of-life testing was considered critical for establishing the longevity performance of the development technology for the low CO prototype.

University of Alabama Durability Engine and Emission Test Results for the Prototype and Baseline Generators

Comparison of the Prototype Generator to the Baseline Generator at 500 Engine Hours

The comparison of engine and emission performance of the prototype generator to the baseline generator was assessed at intervals during the durability program. The 6-mode generator emission test was performed after accumulation of 150, 250, and at 500 hours. All generator test results, including the 150- and 250-hour intermediate durability emission tests results can be found in the UA Final Contractor report, *Low Carbon Monoxide Emission Prototype Portable Generator: Build Description and Performance Evaluation.* The most significant of these durability interval test results was considered to be the 500-hour emission test, as it marked the end of durability testing and provided engine and emission performance at the end of rated useful life testing. This end-of-life test establishes the evaluation of the prototype closed-loop, fuel-injection system and catalyst muffler to the baseline generator with the unmodified carburetor engine and original exhaust muffler components. Some of the prototype design specifications established in the University of Alabama contract were to reduce CO emissions while maintaining HC + NOx emission levels, maintain the original generator maximum power delivery, and manage cylinder head and exhaust temperatures within a reasonable range of the original design. Table 4 shows the results of the 500-hour, 6-mode emission tests of the prototype and baseline generator performed at the UA.

Engine Modal Data										Emission Rate Unweighted			Combined Weighted Emission Rates			
Baseline Generator																
Mode	**AFR**	**Est Eng Power** (kW)	**Cyl. Head** °C	**Oil** °C	**Manifold Exhaust Gas** °C	**Tailpipe Exhaust Gas** °C	**Muffler Surface** °C	**Muffler Shroud Temp** N/A	**Fuel Rate** kg/hr	**HC** g/hr	**CO** g/hr	**NOx** g/hr	**HC** g/Kw-hr	**CO** g/Kw-hr	**NOx** g/Kw-hr	**HC + NOx** g/Kw-hr
1	13.1	7.6	196	101	647	631	434		2.4	27.3	826.1	82.4	6.6	259.5	8.0	14.6
2	12.4	6.2	183	96	612	589	403		2.3	28.4	1101.3	55.2				
3	12.4	4.1	166	87	575	527	362		1.9	24.7	870.5	34.4				
4	11.4	2.1	142	76	521	441	302		1.6	25.3	1113.0	6.7				
5	11.4	0.8	136	72	513	414	285		1.3	19.2	937.4	2.6				
6	11.2	0.4	128	69	496	384	266		1.2	17.0	896.4	1.9				

Prototype Generator with Catalyst Muffler

Mode	**AFR**	**Est Eng Power** (kW)	**Cyl. Head** °C	**Oil** °C	**Manifold Exhaust Gas** °C	**Tailpipe Exhaust Gas** °C	**Muffler Surface** °C	**Muffler Shroud Temp** N/A	**Fuel Rate** kg/hr	**HC** g/hr	**CO** g/hr	**NOx** g/hr	**HC** g/Kw-hr	**CO** g/Kw-hr	**NOx** g/Kw-hr	**HC + NOx** g/Kw-hr
1	14.6	7.6	220	117	797	669	484	110	2.2	1.1	36.6	83.1	1.0	17.5	8.9	9.9
2	14.6	6.2	212	113	788	646	479	101	2.1	0.9	28.8	75.0				
3	14.5	4.1	191	101	765	645	430	80	1.6	0.6	15.6	34.7				
4	14.4	2.1	164	88	714	592	385	66	1.3	11.6	175.0	3.5				
5	14.5	0.8	162	86	747	590	352	58	1.1	0.1	7.2	2.3				
6	14.5	0.4	156	82	759	613	338	54	0.9	0.0	5.9	1.3				

Table 4. 500-Hour Emission Test for the Prototype and Baseline Generators at the University of Alabama

The CO generation rate of the prototype generator to the baseline generator shows a mode-by-mode reduction between 84 to 99 percent. As reflected in the last columns of Table 4, the composite weighted emission rate of the prototype generator is by 93 percent CO reduction over the baseline generator unit. Even with a large CO reduction in the prototype emission rates, the HC + NOx emission rates seemed acceptable at 9.9 g/kW-hr. The original and unmodified prototype engine was labeled as certified to the EPA Phase 2 regulations, which is 12.1 g/kW-hr HC + NOx. In addition, at this 500-hour milestone, the prototype generator produced lower HC + NOx emission rates than that of the unmodified baseline generator unit.

Prototype generator emission rates pre-catalyst, and in the exhaust manifold, were measured during all generator 6-mode emission tests performed during the durability program. These prototype exhaust manifold measurements were recorded to consider an EFI prototype without a catalyst muffler. These pre-catalyst emission results can be reviewed in the UA final report, *Low Carbon Monoxide Emission Prototype Portable Generator: Build Description and Performance Evaluation.* At 500 hours, these combined weighted prototype pre-catalyst exhaust CO emissions were reduced by 91 percent and below the HC + NOx levels presented by the baseline generator. These results suggest that fuel control with stoichiometric AFR designs can adequately reduce CO and HC+NOx emissions. Leaner AFR strategies in small engines have been avoided, due to concerns with higher combustion cylinder head temperatures and NOx production; however, this was not the case with the prototype generator engine with the 14.6 AFR strategy.

The stoichiometric AFR strategy in the prototype emission results did not compromise cylinder head or exhaust gas temperatures. The prototype generator cylinder head temperatures remained within acceptable ranges of approximately 25°C hotter than the baseline unit across all modes. These cylinder head temperature differences are a reflection of the stoichiometric prototype design and excess fuel strategy of the carburetor unmodified baseline unit. The cylinder head temperatures on the prototype generator with 14.6 AFR are within manufacturer-recommended temperature limits of 270°C at all modes. With the outcomes of this acceptable stoichiometric AFR strategy with cylinder head temperatures, the significant reduction of CO and HC emission rates, and expectable NOx levels, the richer AFR values seem unnecessary. The exhaust temperatures in the prototype engine show the largest differential from the baseline unit at idle, and this differential decreases toward Mode 1, full load. These temperature differences trend with the baseline unit running richer, approximately 11.3 AFR, at idle and low loads and leaner, approximately 13.1 AFR at Mode 1. The 14.6 AFR with the prototype generator is not mode dependant. The exhaust temperatures of the prototype generator are hottest at Mode 1, which was measured at approximately 780 °C. Exhaust temperature at all modes of the prototype generator are within the catalyst manufacturer’s recommended optimum operating range of 600–900°C.

Independent Laboratory Post-Durability Engine and Emission Test Results for the Prototype Generator

Prototype Generator Engine Emission Testing on a Dynamometer

After the prototype generator was durability tested for 500 hours, which was the engine's end of rated life, it shipped to an independent laboratory for emission testing at an alternate small engines testing facility. This facility, Intertek Carnot Emission Services, provides EPA and CARB certification engine data on a variety of engine sizes, including small, nonroad engines that are used in various applications, including portable generators. Intertek's emission test facility is lab-to-lab correlated with the EPA and major manufacturer emission test facilities. This laboratory's exhaust gas sampling system and gas measurement system conform to the most recent federal regulations, 40 CFR part 1065. The dynamometer engine tests performed at Intertek meet the industry standard applicable EPA and CARB test procedure regulations, including specified test fuels.

The primary purpose for the independent laboratory tests was to measure the performance of the prototype engine at its end of rated according to standardized dynamometer 6-mode emission test procedures. The dynamometer emission tests results of the prototype engine can be compared to the federal regulation exhaust emission standards within its engine classification. The prototype engine is classified as a Class 2 nonroad, less than 25 horsepower engine. The current Phase 3 EPA regulations for the combined hydrocarbon and nitrogen oxide (HC + NOx) exhaust emission are 8 grams per kilowatt hour (g/kW-hr); these regulations became effective for engines manufactured in 2011. Both engines of the prototype and baseline generator were manufactured in 2006; they were labeled as certified to Phase 2 exhaust emission regulations. The Phase 2 regulation for HC + NOx is 12.1 g/kW-hr. The Phase 2 and 3 CO regulations remained unchanged from the Phase 1 limits at 610 g/kW-hr.

Prototype Generator Mode 4 Fluctuations Due to Unmapped Controller

At the UA facility and prior to the shipment of the prototype generator to Intertek, it was known that some AFR variations occurred at Mode 4 that were caused by incomplete calibration of the electronic control unit (ECU). The ECU is the controller portion of the EMS. This mode 4 variation was first recognized in the UA 250 hour generator emission test with longer stabilization periods occurring after transition into mode 4 when compared to other modal transitions. The mode 4 AFR excursions were only apparent after the accumulation of 500 hours.

After shipment to Intertek, it was determined that minor mapping would be performed to fully calibrate the ECU's look-up tables. This minor mapping activity extended the existing Mode 4 calibration variables over a wider range over the fuel look up tables. It is believed that this minor mapping was needed because as the prototype generator progressed through durability, the alternator degraded and the governor mechanisms experienced normal wear. This normal wear and degradation was thought to cause the prototype engine to operate into areas of the calibration tables that initially were not well mapped. In the beginning of the prototype programs, the actual generator operational ranges below the rated 3600 RPM were unknown. Consequently, the original mapping of the prototype generator's ECU fuel tables performed by UA was too narrowly restricted in the look-up tables. In other words, some of the portions of the fuel look-up tables were considered unusable for the prototype configuration and were not calibrated. The larger AFR excursions at Mode 4 during the 500 hour prototype generator emission tests caused some increase of CO and HC emissions. It is noted from Table 4, which shows the UA 500 hour emission results for the prototype and baseline generators, the combined and weighted HC + NOx values for the prototype generator remained below those of the baseline generator even when the prototype generator was experiencing mode 4 AFR excursions. In addition, the weighted CO levels for the prototype generator during this UA emission test showed higher mode 4 levels; however, the weighted CO levels remained below the program goal of 30 g/kW-hr.

Dynamometer Exhaust Emission Testing of the Prototype Engine

Intertek performed dynamometer emission testing with the prototype engine and, in addition, emission testing of the prototype generator. Emission testing was performed with and without the catalyst in both the prototype generator and dynamometer prototype engine configurations. The Intertek test results considered most significant were the dynamometer prototype engine 6-mode emission tests, as these prototype engine results can be compared to the federal regulation exhaust emission standards. With the prototype engine manufactured in 2006 and originally classified Class 2 nonroad less than 25 horsepower engine, relevant federal exhaust emission regulations are:

- Phase 2 regulations of 12.1 HC + NOx g/kW-hr.
- Phase 3 regulations of 8 HC + NOx g/kW-hr (for engines manufactured after 2011).
- Phase 2 and 3 regulation of 610 CO g/kW-hr (presiding CO emission rates were considered the program target goals of 30 g/kW-hr).

Two of the prototype engine dynamometer 6-mode emission tests conducted at Intertek are presented in Table 5. These tests show the emission results with the catalyst muffler and a configuration without a catalyst.

Engine Modal Data									Emission rate unweighted			Composite Weighted Emission Rates			
Prototype Engine with Catalyst Muffler															
Mode	AFR	Eng Brake Power (kW)	Cyl. Head °C	Oil °C	Manifold Exhaust Gas °C	Tailpipe Exhaust Gas °C	Muffler Surface °C	Fuel Rate kg/hr	HC g/hr	CO	NOx	HC g/Kw-hr	CO	NOx	HC + NOx
1	14.4	7.9	233	130	685	379	427	2.5	0.29	6.7	4.7	0.4	6.0	6.3	6.7
2	14.4	5.4	214	125	629	318	342	1.8	0.49	4.7	9.3				
3	14.4	3.7	197	116	605	286	300	1.4	0.43	4.4	6.3				
4	14.4	1.9	178	106	587	254	257	1.1	0.22	4.1	1.2				
5	14.4	0.8	167	99	593	238	236	0.9	0.02	0.5	0.2				
6	14.4	0.2	163	96	602	240	235	0.9	0.01	0.4	0.1				
Prototype Generator without Catalyst Muffler															
Mode	AFR	Est Eng Power (kW)	Cyl. Head °C	Oil °C	Manifold Exhaust Gas °C	Tailpipe Exhaust Gas °C	Muffler Surface °C	Fuel Rate kg/hr	HC g/hr	CO	NOx	HC g/Kw-hr	CO	NOx	HC + NOx
1	14.4	7.5	237	140	689	300	462	2.4	0.8	15.5	11.4	1.4	28.1	11.6	13.0
2	14.4	5.1	215	131	631	242	397	1.7	1.6	22.3	15.2				
3	14.4	3.5	196	118	603	204	351	1.3	1.5	29.1	9.0				
4	14.4	1.8	178	108	586	169	306	1.0	0.6	20.3	2.5				
5	14.4	0.8	168	100	591	158	292	0.9	0.1	3.7	0.3				
6	14.4	0.2	164	98	602	155	290	0.8	0.0	2.3	0.1				

Table 5. 500-Hour Dynamometer Six-Mode Emission Test for the Prototype Engine at an Independent Testing Laboratory

The results of the dynamometer prototype engine 6-mode emission tests show that the configuration of EFI and catalyst generated a combined weighted HC + NOx value of 6.7 g/kW-hr. With the AFR values at 14.4 across all the modes, the HC contribution is kept low and the majority of the combined weighted HC + NOx value came from the NOx constituents. However, the dynamometer prototype with the catalyst emission tests show that results below the Phase 2 and 3 regulations for HC + NOx. At the same time, the CO emissions was reduced by more than 95 percent when comparing the manufacturer's published carburetor engine certification data to these results. The combined and weighted HC + NOx value for the prototype engine dynamometer test without the catalyst muffler was 13.0 g /kW-hr. This value exceeds the Phase 2 regulations, but only marginally. The dynamometer emissions for the prototype engine without the catalyst muffler shows more than a 90 percent reduction of CO emissions when comparing the manufacturer's published carburetor engine certification data to these dynamometer results.

More independent laboratory emission test results for the prototype generator and prototype engine on the dynamometer can be viewed in the Intertek report, *Laboratory Exhaust Emission Testing Results for a Prototype Generator Engine Designed for Low Carbon Monoxide (CO) Emission Rates and EPA Phase 2 Emission Standards for Nonroad Small Spark-Ignited (SI) Nonhandheld Engines*.

Verification of the Estimated Generator Engine Power Values

In addition to the emission results, testing at the Intertek provided verification on the estimated power values while installed in the generator compared to the prototype engine mounted on an AC dynamometer. The dynamometer engine test was conducted according to EPA *6 Mode Steady-State Test Cycle B* for small (less than 25 hp) off-road engines. At this emission test lab, correlation of engine fuel consumption in the generator application and the dynamometer were matched. One purpose of correlating the fuel consumption with the engine installed on the dynamometer and the generator was to evaluate the efficiency curves provided by the generator manufacturer. This fuel consumption correlation demonstrated that the engine power estimates in the generator application were reasonable approximations for Modes 2 through 6 with an offset by approximately 20 percent at Mode 1. Table 6 shows the estimated engine power when installed in the generator and the measured engine power on the dynamometer when the fuel consumption values are matched.

Mode	Estimated Engine Power in Generator Application	Generator Engine Power Calculations by through Fuel Consumption Comparisons	Engine Power Differences in the Generator Application
	kW	kW	kW
1	7.6	6.0	1.6
2	6.2	5.8	0.4
3	4.1	4.0	0.1
4	2.1	2.0	0.1
5	0.8	1.0	-0.2
6	0.4	~	NR

Table 6. Generator Engine Power Verification based on Fuel Consumption

Table 6 shows generator engine powers derived from the Intertek dynamometer fuel consumption curves and the generator manufacturer's provided alternator efficiency curves. The Table 6 column labeled, "Generator Engine Power Calculations by through Fuel Consumption Comparisons" was found through Intertek-generated curves of power and fuel consumption from dynamometer testing with the prototype engine. With the known dynamometer fuel consumption-power curve, the fuel consumption of the prototype engine in the generator application was plotted onto the dynamometer curve to find the generator power. By matching the fuel consumption values, the generator power at each of the six modes could be found. Table 6 shows that the intermediate engine power estimates from the generator application testing at the University of Alabama were reasonably close to the Intertek curves with an error less than 0.4 kW for Modes 2–5. The estimated position at idle or Mode 6 was not a position measured load on the dynamometer. Overall, the provided generator manufacturer's efficiency curves, which were about 75 percent efficiency over the operating range, were fairly accurate except at the high loads.

During testing at the University, the maximum engine power when installed in the generators was believed to be 7.6 kW, based on the provided alternator efficiency curves. The Intertek fuel consumption curves showed the full load of the engine when installed in the generator to be 6.0 kW. This means the estimated engine power at full load in the generator that was used in the University generator emission testing, as shown in Tables 1–4, was overestimated by approximately 1.6 kW. Staff believes the voltage regulator assembly, including the necessary repairs at 125 hours of durability, limited the maximum generator output power. It is known that the generator application limited the engine power output because when the prototype engine, with more than 500 hours was pulled from the generator and tested on the dynamometer, deliverable dynamometer power was within 3–9 percent of the engine manufacturer's rated power, 8.2 kW.

It should be noted again that the importance of the UA generator emission testing is in the comparison of the baseline to the prototype generator unit. The prototype engine performance on the dynamometer at the Intertek emission test facility is significant when compared to the emission regulation levels and when compared to the manufacturer's certification data of the original carburetor engine design.

Conclusions

Several general conclusions can be made from the low CO prototype generator technology demonstration program. The durability program over the rated useful life of the engine demonstrates the longevity of the prototype EMS with its associated sensor and the catalyst muffler. The low CO prototype generator consistently demonstrated consistent or improved CO and HC + NOx emissions compared to the unmodified unit.

The integrity of the EMS system was maintained throughout the durability test program. The adapted technology of the EMS controller with associated sensors, fuel regulation, and catalyst demonstrated longevity by performing as designed throughout the durability cyclic hour accumulation and maintaining CO and HC+ NOx emission goals until and beyond the rated end of useful life. Achieving these emission goals through a 500-hour duty cycle supports that the demonstration prototype generator is capable of both reducing emissions while not shortening the life of the generator.

The design strategy of the prototype design was to incorporate the EMS and associated timing and fuel delivery components to maintain a combustion air-to-fuel ratio near to 14.6. The engine AFR is a primary performance indicator for variables of combustion cylinder head temperatures, exhaust gas temperatures, and fuel consumption. Compared to the unmodifed baseline generator, the prototype maintained a leaner AFR resulting in an approximately 25 deg Celsius increase in cylinder head temperatures. At maximum loading, the prototype’s cylinder head temperature was consistently at 220 deg Celsius, which is 50 degrees below the manufacturer’s provided guidance for maximum cylinder head temperatures. The resulting exhaust manifold gases (pre-muffler) also showed an increase of temperatures; however these temperatures are within the catalyst manufacturer’s recommended operating temperatures.

The fuel injection and AFR strategy associated with the prototype generator improved the fuel consumption from the unmodified carburetor engine by approximately 20 percent over the applied 6-mode profile.

The unmodified unit showed a combined modal weighted CO emission rate of 259.5 g/kW-hr. This number is more than eight times the 30 CO g/kW-hr target level for the prototype design. The prototype engine with electronic fuel injection and catalyst demonstrated at least a 93 percent reduction of combined weighted CO emission levels over the unmodified unit. The low CO prototype generator program demonstrates that the CO exhaust from a generator powered with an air cooled Class 2 engine can be reduced at least 90 percent, which could significantly mitigate the risk of fatalities and poisonings shown in typical consumer scenarios from the CPSC databases incidents.

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TAB C

Low Carbon Monoxide Emission Prototype Portable Generator

Build Description and Performance Evaluation

Submitted to
U.S. Consumer Product Safety Commission
Washington, DC 20207

July 2011

Submitted by
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INTRODUCTION

BACKGROUND

The University of Alabama (UA), working under contract with the U.S. Consumer Product Safety Commission (CPSC), developed a prototype low carbon monoxide (CO) emission portable generator as part of CPSC's efforts to address the CO poisoning hazard associated with consumer use of portable generators. CPSC is an independent federal regulatory agency whose mission is to save lives and keep consumers safe by reducing the risk of injuries and deaths associated with consumer products.

As of June 2010, the CPSC databases contain records of at least 542 deaths from CO poisoning associated with consumers' use of generators in the period from 1999 through 2009[1]. Additionally, CPSC estimates that 43% of the non-fire accidental CO deaths associated with the use of consumer products specifically involved portable generators for the years 2005-2007, the most recent years in which such estimates are available[2]. Most deaths occur when the generator is improperly operated in an indoor location, including the garage, basement, and living space of the home.

OBJECTIVE

CPSC staff initiated this contract (CPSC-S-06-0079) to demonstrate the technical feasibility of a portable generator with very significantly reduced CO emissions, which could potentially reduce the risk of CO poisoning deaths and injuries associated with this product category. The objective was to reduce the engine's CO emissions to the lowest possible level without negatively impacting power output, engine durability, maintainability, fuel economy, and risk of fire and burn, while continuing to meet the emissions regulation to which the engine was originally certified. CPSC specified an initial target CO emission rate at or below 30 g/kW-hr.

CPSC staff specified that a commercially available engine management system (EMS) and catalytic exhaust after-treatment be adapted to a commercially available portable generator in the 5 to 6 kW output power range powered by a small spark-ignited engine. While adhering to CPSC staff's criteria, UA staff was tasked to minimize incremental costs associated with the CO emission-abatement equipment, consistent with good engineering practices.

It was further specified that to demonstrate the longevity of the adapted technologies and the modified engine in achieving the desired CO emission reduction throughout the engine's rated useful life, the prototype generator and an unmodified baseline unit were to be subjected to a durability evaluation. Hours of generator operation with a specified

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[1] 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.

[2] Hnatov, M. V. 2011. *Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2007 Annual Estimates*; U.S. Consumer Product Safety Commission: Bethesda, MD.

resistive load profile were to be accumulated up to 500 hours with periodic emission tests.

In addition, CPSC staff contracted for the construction and delivery of two additional prototype units using the same fuel control strategy and catalyst as the durability-tested prototype. The first of these two prototype units was specified to be identical to that of the durability-tested prototype. The second unit was specified to include an automatic shutoff feature developed by UA and programmed into the prototype's engine control unit (ECU) to detect when there is engine operation in an oxygen depleted atmosphere and trigger an engine shutdown. It was further specified that this shutoff feature would not rely on any additional sensors beyond those already integral to the existing EMS design and that the feature could be enabled and disabled in the EMS controller for testing purposes.

PROTOTYPE DEVELOPMENT AND CONSTRUCTION

DESIGN STRATEGY

The strategy for the portable generator prototype design was to implement a commercially available electronic engine management system (EMS) calibrated for stoichiometric (14.6 air-to-fuel ratio (AFR) for typical gasoline) operation and adaptation of a small sized catalytic converter for exhaust after-treatment. The objective was to substantially reduce CO emissions while indicating conformance[3] to the Environmental Protection Agency (EPA) Phase 2 regulations for HC and NO_x without adversely affecting the performance of the generator unit.

The original generator chosen for this program was a retail consumer generator with an advertised power rating of 5.0 kW equipped with a 389 cm^3 displacement single cylinder engine. The EMS and associated electronic sensors and components were purchased as a complete package from an engine electronics component supplier. This commercially available electronic control package was developed for and used in the Asian market for powered scooters and small motorcycles. The catalyst was developed through a catalyst manufacturer.

This section describes the commercially available generator in the Original Equipment Manufacturer (OEM) configuration, an overview of the EMS and catalyst selected for the prototype, and the modifications made to the OEM unit required to implement these in the prototype.

[3] The emission testing performed during the development and durability testing phase described in this report was not intended to be in complete accordance with the EPA small-engine test method. The most significant deviation was that testing was done loading the engine in a generator configuration rather than using a dynamometer. The program described here was followed up with full certification testing of the prototype engine performed by an independent laboratory. Further details are provided in subsequent sections of this report. The certification tests are described in a separate report.

OEM GENERATOR

Two identical OEM units[4] were purchased for use in the durability part of the project. One was left in the OEM configuration to have a performance baseline for reference. This unit is referred to as the baseline unit. The other unit, referred to as the prototype, was modified to incorporate the EMS calibrated to maintain an AFR of 14.6 and a small-sized catalyst integrated into an OEM muffler. Generators have two main components, which are the engine and the alternator. For the purposes of this report, the engine-alternator system is referred to as the generator, whereas the electricity generating component by itself is referred to as the alternator. The engine and alternator are described in the subsections below.

OEM Engine

The generators used a 389 cc displacement, horizontal shaft, overhead valve gasoline engine rated at 11 horsepower (hp). Engine specifications are provided in Table 1. The following paragraphs describe the engine auxiliary systems as delivered in the stock generator.

Table 1: 389 cubic centimeter (cc) Displacement Engine Specifications

Bore	88 mm / 3.5 inches
Stroke	64 mm / 2.5 inches
Displacement	389 cm^3 / 23.7 in^3
Compression Ratio	8.0 to 1
Rated Power	8.2 kW / 11.0 hp @ 3600 rpm
Maximum Torque	25.1 Nm / 18.5 lb ft @ 2500 rpm
Dry Weight	31.0 kg / 68.3 lb

The fuel metering is performed by a gravity-fed side draft carburetor. The engine speed is maintained nominally at 3600 rpm by a mechanical centrifugal governor controlling the carburetor throttle-plate angle. This carburetor throttle plate design regulates the combustion air flow rate into the engine by varying the flow area as it opens and closes. Fuel enters the air flow stream through a metering jet located in the carburetor's venturi section just upstream of the throttle plate. The fuel flow rate depends on the air-flow pressure decrease caused by the flow acceleration in the venturi and the cross sectional area of the metering jet. For a fixed air density, a given air flow velocity through the venturi yields a fixed mass flow rate of fuel, thereby the carburetor controls the air-to-fuel ratio. The AFR is a key factor in exhaust emission production.

[4] A third generator unit was also designed for a lean strategy (14.9 AFR) generator. It was considered academic development design, as there was no advantage of this 14.9 strategy over the 14.6 AFR prototype unit. For the lean prototype, the full load AFR was 14.6 and the remaining modes were configured for 14.9 AFR. The unit was subjected to the durability test schedule.

The muffler with external dimensions of 203 mm x 203 mm x 89 mm (8 in x 8 in x 3.5 in) is coupled to the exhaust port with an s-shaped, 127 mm (5 in) long, 25 mm (1 in) internal diameter cast iron exhaust pipe.

The ignition system used a magneto with a fixed spark timing of 25 degrees before top dead center (BTDC). This system fires each revolution resulting in a wasted spark during the exhaust stroke.

OEM Alternator

The alternator is a single phase, 2-pole, brushless machine with center-tapped windings to provide two single phase, 120 V, line-to-neutral output circuits or a 240 V line-to-line circuit, much like a standard U.S. residential distribution setup. The alternator was directly coupled to the engine crankshaft utilizing a tapered press-fit shaft and utilized a closed-loop voltage regulator which drives the engine demand based on the applied electrical load. The voltage regulator and associated electrical connectors and wires were originally used[5] in the condition as designed and supplied by the generator manufacturer. These generators included a fuel-saving circuit, which reduces engine idle speed under no load conditions by actuating a solenoid linked to the engine speed governor to lower the idle speed to approximately 2000 rpm. To best emulate the load settings prescribed in the emission test method (discussed in the *Test Methods and Equipment* section), this fuel economy controller was deactivated for our application, thereby maintaining a nominal 3600 rpm alternator speed for all loads. The alternator receptacle panel contains a single phase 30A, 240 V twist-lock receptacle, a 30A 120 V twist lock receptacle, and two 20A, 120 V ground-fault circuit interrupter (GFCI) receptacles. The 120 V, twist-lock receptacle and one GFCI receptacle are on one circuit, and the other GFCI receptacle is on the other circuit. A 25A two-pole circuit breaker protects the 240 V output of the alternator, while two individual 20A, single-pole circuit breakers each protect one of the 120 V receptacle outlets. The neutral conductor is bonded to the grounding conductor, which is bonded to the alternator chassis.

During testing and durability operation, the resistive load banks were connected to the 240V twist lock receptacle to evenly load both legs of the alternators. OEM generators were tested for the peak load and it was found to be 235 volts, 25 amps, and 58 hertz. The maximum peak deliverable power equates to approximately 5.8 kW, provided there is no voltage drop to due to governor droop. In practice, the unit was able to sustain approximately 5.5 kW without tripping the circuit breaker.

PROTOTYPE CONSTRUCTION

This section describes the modifications made to the OEM configuration to construct the prototype. As indicated earlier, the CO reduction strategy consisted of implementing a relatively low-cost EMS and adding exhaust after-treatment using a three way catalytic converter. The major modifications to the original configuration were made to

[5] There were several generator component failures during the durability test program due to this voltage regulator that had undersized wiring and connectors. These failures necessitated altering the original design to bypass the connectors. Details are provided in an appendix of this report.

accommodate the EMS. Since the implementation and optimization of the EMS strongly affect the generator's output, emissions and efficiency, an overview of the EMS principles and function is provided prior to the description of the physical modifications made to accommodate the components of the EMS system. Finally, the significant aspects to implement and tune the EMS are described at the end of this section.

EMS Overview

Compared to traditional carbureted mechanical systems, microprocessor-controlled EMS systems can improve engine exhaust emissions and fuel consumption while maintaining power capability. The EMS is comprised of an engine control unit (ECU) microcomputer coupled to a variety of sensors and actuators to monitor and control an engine's operation. The ECU collects data from the sensors and performs calculations based upon the received sensor input data for the current operating condition. It then adjusts the engine control variable set-points accordingly to optimize performance. The output signals from the ECU primarily control engine operation by adjusting the fuel-injection and spark timing and fuel-injection pulse width to achieve the desired AFR and combustion phasing. In this application only the fuel-injection pulse width was optimized. The spark timing was maintained at 25 degrees BTDC to emulate the spark timing of the original system. This overview includes an explanation of the basic fuel control calculations used by the present EMS. A discussion of the significant aspects to its implementation and tuning is provided in the subsection following the section describing installation of the EMS sensors and components.

In order to calculate the optimum fuel quantity for a given operating condition, the ECU needs to know the mass flow rate of air entering the engine. The ECU in this application accomplishes this using the speed-density method. This method infers mass flow rate from volumetric efficiency, which is defined by

$$VE \equiv \frac{\dot{m}_{air}}{\rho_{man} V_D {}^{N}/_{n}}$$

where V_D is the engine displacement, N is the engine speed in revolutions per second and n is the number of revolutions per intake stroke. Rearranging this expression, $\dot{m}_{air}$ can be calculated at a particular operating condition if the current values of ρ_{man}, VE, and N are determined, since n and V_D are fixed for a given engine. The ECU uses the ideal gas law to calculate the manifold density (ρ_{man}) from manifold absolute pressure (MAP) and the intake charge air temperature (CAT):

$$\rho_{air} = \frac{p}{RT}$$

where P = MAP, R = gas constant for air, and T = CAT in absolute temperature units. This EMS system retrieves VE from a table as a function of engine speed and MAP. The mass flow rate of air is divided by the target air to fuel (A/F ratio or AFR) in order to determine the mass of fuel to be delivered.

$$\dot{m}_{fuel} = \frac{\dot{m}_{air}}{AFR}$$

The AFR is also retrieved from a table. For our prototype strategy, this is set to 14.6 for all operating conditions. This is the stoichiometric AFR for a gasoline engine. These equations can be combined to give an expression for fuel flow rate

$$\dot{m}_{fuel} = \frac{VE \cdot P \cdot V_D \cdot N}{R \cdot T \cdot n \cdot AFR}$$

The EMS controls the quantity of fuel delivered by adjusting the injector opening time, which is known as the injector pulse width. A given fuel injector will deliver a fuel quantity proportional to its pulse width provided the pressure drop across its exit nozzle is constant and the opening and closing times of the injector solenoid are accounted for. The fuel pressure regulator (see the *Fuel System* subsection below) ensures the pressure drop is constant. Consequently, the flow rate characteristics of the injector can be used to calculate the pulse width required to achieve the fuel flow rate calculated in the above expression. The fuel delivered is related to the pulse width using the expression

$$\dot{m}_{del} = N\, n_p\, \dot{m}_{inj}(t_{PW} - t_{OC})$$

where N is the engine speed in revolutions per second, n_p is the number of injector pulses per revolution, $\dot{m}_{inj}$ is the injector fuel flow rate when the injector is fully opened in mass per second, t_{PW} is the injector pulse width time, and t_{OC} is the pulse width time correction to account for the time to fully open and fully close the injector. Equating this expression to the desired mass flow and rearranging yields the calculated open-loop injector pulse width required to deliver the fuel flow rate expected to result in the desired AFR;

$$t_{PW,ol} = t_{OC} + \frac{V_D VE\, P}{R\, n\, n_p\, \dot{m}_{inj}\, T\;\, AFR}$$

In actual application, this time will be converted to a digital count value, and it can be multiplied by a number of correction factors which compensate for factors such as changes in the battery voltage, below normal engine operating (e.g. during warm up), acceleration, deceleration, among others. If this final digital count value is commanded to the fuel injector directly as calculated, the control strategy is said to be an *open-loop* strategy. In contrast, a *closed-loop* strategy uses a feedback signal to adjust this value to achieve a specific condition. In our case, this feedback signal is output from a binary O_2 switching sensor placed in the exhaust stream. If this sensor signals significant oxygen, the mixture is fuel lean, and if it signals little or no oxygen it is fuel rich. In an O_2 closed loop strategy, the ECU continuously adjusts the calculated pulse width time so the O_2 signal constantly toggles from either rich to lean, insuring a near stoichiometric mixture. The EMS used in this application determines the magnitude of the pulse width adjustment using a proportional-integral (PI) control strategy. Generically, a PI strategy adjusts the control variable with a component proportionally to the magnitude of the deviation from the desired condition (the proportional component) and a second component based on how long the deviation has existed (the integral component). The integral adjustment is continuously incremented until the feedback signal passes through the setpoint value insuring that eventually the desired condition will occur. For fuel control using a binary O_2 feedback, the desired condition is the switching event (rich to lean or lean to rich) and the control variable is the injector pulse width correction to the open-loop value. Therefore, the pulse width command to the injector when operating in closed-loop is given by;

$$t_{pw,cl} = t_{pw,ol} + t_{pw,corr}$$

Both the proportional and integral corrections have gain coefficients that must be adjusted so that the control adjustments make rapid and accurate corrections without making the system go unstable.

<u>EMS System Components and Sensors</u>

Prototype construction consists of installing the EMS system and associated sensors, the electric start system, the fuel system, and the catalyzed muffler and modified exhaust manifold. The function of the EMS is to control ignition timing and fuel delivery based on inputs from the various system sensors. The EMS microprocessor was calibrated for the engine to run at or near stoichiometric air-fuel ratio to maximize the performance of the catalytic converter installed in the muffler. The prototype sensors system and operation are discussed.

<u>The EMS system</u>

This EMS system includes the computer with an integrated MAP sensor and the wiring harness. The ECU microcomputer is physically mounted on an aluminum plate which is fixed to the generator frame as shown in Figure 1. The MAP sensor reads the manifold pressure via a tube which leads to a port installed in the head downstream of the throttle body as shown in Figure 2.

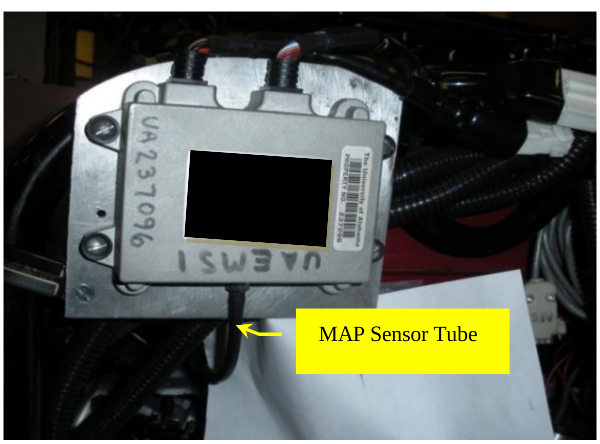

Figure 1: EMS mounted to generator frame

Figure 2: MAP tube port in intake port.

Additionally, there are two EMS sensors for calculating the charge air temperature. The inlet air temperature sensor is located in the air-filter housing and the oil temperature sensor is integrated in the oil drain plug.

Crank Position Sensing System

This crank position sensing system consists of the crank position sensor, toothed wheel and cover. Figure 3 shows the toothed wheel and sensor installed on the prototype. Figure 4 shows the cover separated from the unit. The crank position sensor is an inductive magnetic sensor that produces a voltage proportional to the magnetic flux rate variation in its proximity. The teeth on the toothed wheel pass by the sensor to create this variation, creating a pattern of oscillating voltage peaks which each correspond to 15^o of crank rotation given the 24 (minus 1) teeth on the wheel. One tooth is missing to create a reference for the rotational position of the crank. The EMS delivers fuel and spark at specified crank positions, which it determines by counting the pulses from the missing tooth.

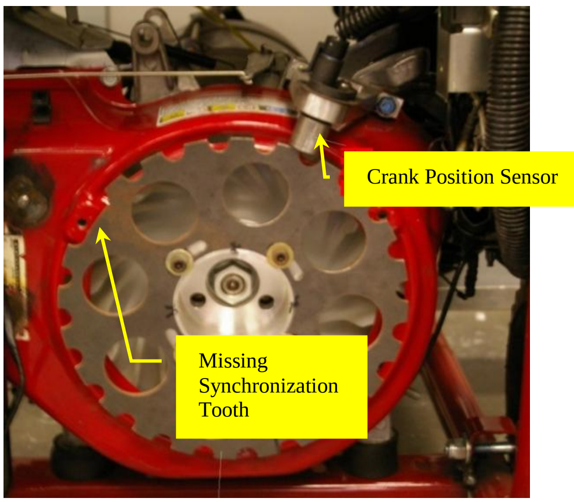

Figure 3: Crank position sensor and toothed wheel.


Figure 4: Crank position toothed wheel cover.

Electric Start System

To ease the adaptation of the crank sensor hardware, an electric start system was incorporated on the engine. The engine can be supplied with or without electric start from the factory. All models have the starter mounting bolt bosses cast in place, but the pull-start models do not have an access hole in the starter mounting flange for the starter nose to pass through to enable the starter gear to engage in the flywheel ring gear. The starter mounting flange is cast into the side of the case that holds the cylinder, therefore requiring the crankshaft, rod and piston assembly to be removed to machine the hole. The engine was disassembled, and the case was machined at the engineering college's machine shop. The engine was cleaned and reassembled with a ring-gear equipped flywheel. The Figure 5 shows the installed starter and the ring-gear equipped flywheel. A 12 volt battery was added to power the starting system as well as the electronic ignition system and fuel pump. The battery charge is maintained by a battery charger that can be connected to the 120V alternator output when the generator is operating. The battery and mounting tray are housed within the generator frame, as shown in Figure 6.

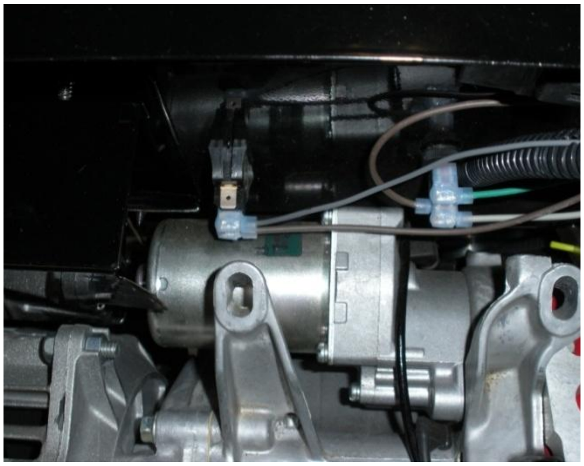

Figure 5: Electric starter motor.

Figure 6: Battery and mounting tray

Fuel System

The fuel system and the throttle body consist of a modified OEM carburetor. The fuel system includes the tank-mounted electric fuel pump and fuel pressure regulator, shown in Figure 7, the fuel line and the fuel injector mounted into the modified throttle body as shown in Figure 8. The regulator is required because the EMS controls fuel delivery based on injector pulse width, which determines the duration the injector is opened to deliver fuel. The fuel system is designed such that the injector will reach full opening in a consistent time, therefore as long as the pressure drop across the injector (fuel delivery pressure minus the manifold pressure) is fixed, the fuel delivered per cycle can be predictably controlled by adjusting the pulse width. In contrast to the carburetor fuel injection system, this EFI system can provide a much more accurate amount of fuel to control the combustion air to fuel ratio and consequently control emissions.

The modifications to the carburetor for use as the prototype throttle body include removal of the fuel bowl and machining the fuel jet port location for mounting of the injector cup. This injector mounting scheme provides fuel delivery at the same location as the original carburetor metering jet. The injection cup is a fuel-rail supply cup. The fuel supply end and the injection end of the injector have identical sized o-rings; therefore, the fuel rail cups make convenient mounting inserts, which are necessary since the carburetor body does not have enough material to machine the necessary mounting shape into it. This cup must be fixed into the body material with adhesive because the body is cast aluminum which cannot be easily welded. Figure 9 shows the modified throttle body and the injector with fuel supply adapter are shown in Figure 10. The adhesive used is JB Weld™ epoxy.

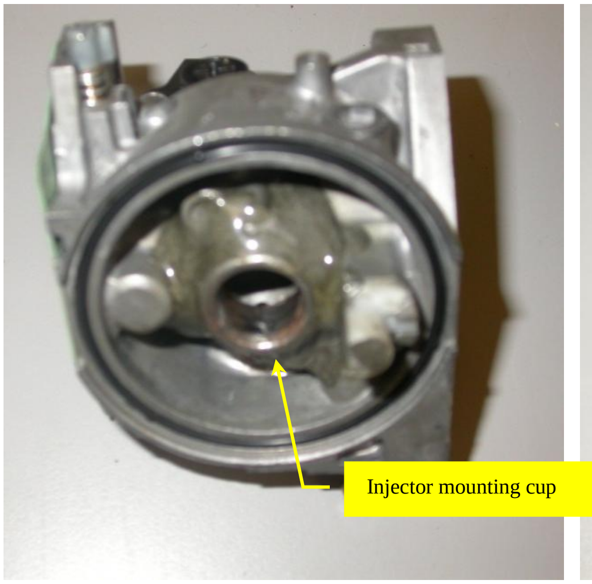

Figure 9: Modified throttle body


Figure 10: Injector with fuel supply line.

<u>Ignition System</u>

This consists of the coil, spark plug wire and spark plug. A three prong connector from the ECU wiring harness to the coil provides the battery power to the ignition primary (low voltage control side) circuit, the timing control signal from the EMS and the ground.

<u>Exhaust System</u>

This system consists of the custom steel tube exhaust pipe, catalyst equipped muffler and heat shroud. The pipe and muffler are shown and Figure 11 and the shroud is shown in Figure 12. The pipe has five ports installed which are used for the O_2 feedback sensor, as well as instrumentation ports to extract emission sample and measurement of temperature, air-fuel ratio and exhaust pressure. The pressure port is not visible in the figure. A flanged tailpipe is welded to the muffler outlet. The flange is used for installation of an exhaust tube used for post catalyst exhaust sampling and for personnel safety to pipe exhaust gasses away from the manned testing area. The tailpipe also includes a temperature instrumentation port. The shroud minimizes exposed surface temperatures. The catalyst cartridge inserted into the muffler’s gas flaw path has a 69 mm diameter and is 50.8 mm long. The metallic catalyst substrate has 400 cells per square inch (cpsi) and is coated with 0, 120 and 4 grams per cubic foot of precious metals platinum palladium, and rhodium, respectively. This formulation was recommended by our catalyst supplier as a solution that would have the necessary CO and HC oxidation conversion to target some of the NOx that was expected to occur due to the stoichiometric 14.6 AFR operation.

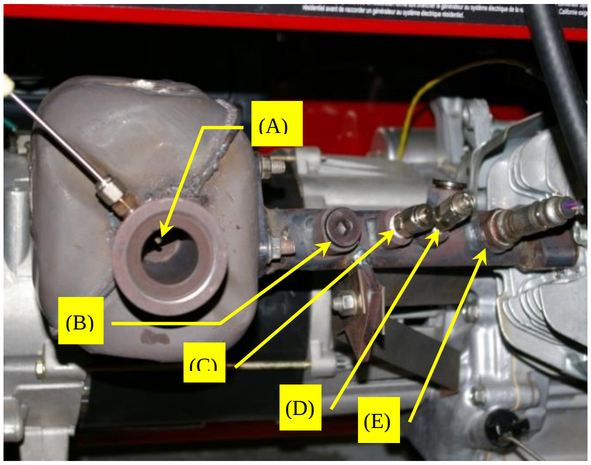

Figure 11: Exhaust pipe and catalyst equipped muffler.
A- Tailpipe with flange and temperature port.
B- Sensor port for wide-range A/F analyzer.
C- Exhaust analysis port.
D- Engine out exhaust temperature port.
E- EMS O_2 sensor port.

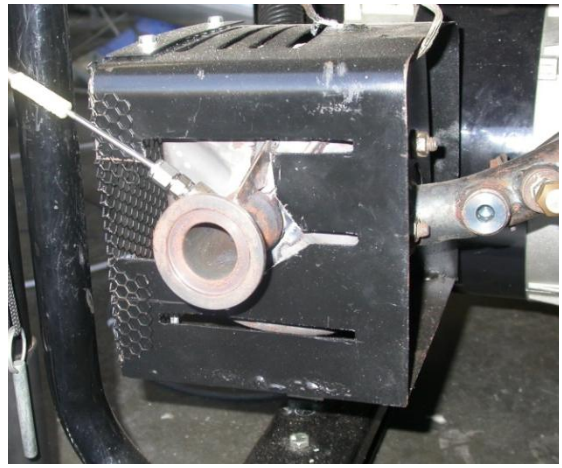

Figure 12: Muffler with shroud installed.

IR photographs of the prototype exhaust system were used to identify the hottest portion of the muffler and muffler shroud surface. These photographs were used to locate the muffler and muffler shroud surface thermocouples such that they represent the maximum temperatures of these surfaces. Figure 13 shows an example taken when the system was operating at maximum load. The figure shows the temperatures profile of the muffler shroud and surrounding areas and indicates the location to which the shroud thermocouple was welded.

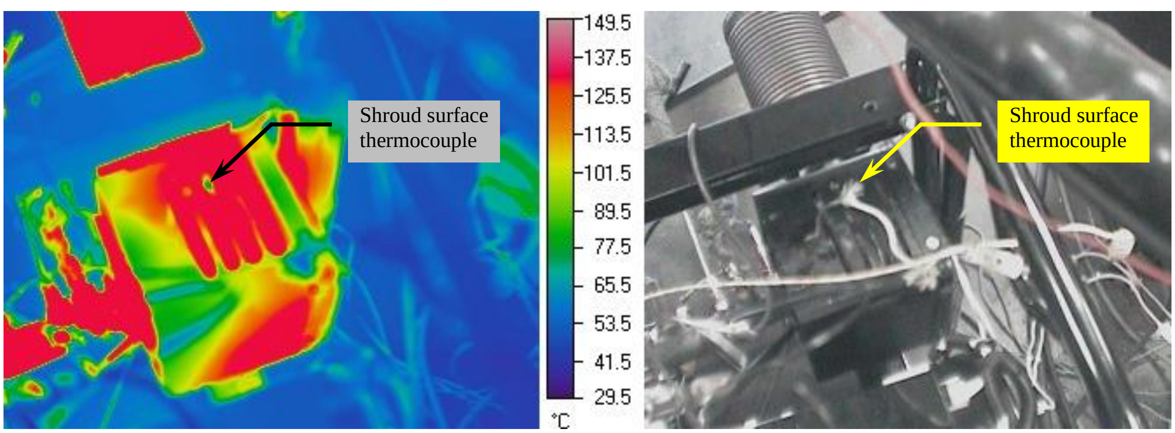

Figure 13: Infrared (IR) and conventional photographs of the exhaust system at mode 1.

Implementation and Tuning

Additional to installation of all the physical components, implementing an EMS on a particular engine application requires properly setting a number of variables describing the engine configuration and the sensor calibrations as well as adjusting the response of several operating condition set-point variables to match the dynamic characteristics of that engine such that its performance is optimized. This subsection describes the optimization of the most significant set-point variables for fuel control and how this optimization is affected by certain aspects particular to this application.

The key set-point variables used to determine fuel pulse width were defined in the *EMS Overview* subsection and include the VE, AFR, and the P and I gain values. Each of these are generally optimized with respect to the engine speed and load, however in this application, AFR was programmed to 14.6 for all conditions. MAP was used as a measure of engine load, since at a given engine speed a higher MAP implies greater air flow into the engine. Therefore while the load is directly controlled by throttle position, it is indicated by the MAP signal. The optimum values of these parameters generally depends non-linearly on speed and load, consequently these values are programmed into tables which have speed and MAP as the independent variables. The ECU constantly interpolates these tables to retrieve the optimum value of the parameters corresponding to the instantaneous value of speed and load. Constructing and adjusting these tables to achieve the desired fuel delivery at each particular operating condition is the core of the EMS calibration process. This calibration information is stored in a calibration (or cal) spreadsheet and downloaded to the ECU from a host PC during the calibration process.

Theoretically, the VE tables could be constructed by simply measuring the air flow at each speed and load and using the definition provided in the overview to calculate the corresponding VE. However, the process is complicated by the measurement of MAP, which considerable intra-cycle variation in a single-cylinder engine due to the strong vacuum pulse which propagates from the cylinder during the intake stroke. During the majority of the cycle when the intake valve is closed, the pressure in the intake tube oscillates around the atmospheric value, even for fairly small throttle angles, however the suction vacuum during intake is strongly affected by throttle position at a given engine speed. The EMS is designed to read the MAP sensor only once per engine cycle. Therefore, to get a measurement representative of load, it must be measured at the minimum value associated with the propagating vacuum pulse to get reliable load resolution. This means that the MAP sensor must be read at a very specific time in the engine cycle, which is defined by the corresponding crank angle (MAP Read Angle). As described in the *Components and Sensors* subsection above, the MAP sensor reads the manifold pressure via a hose which leads to a tube that protrudes into the intake port downstream of the throttle body for measuring static pressure. The length and orientation of this hose distorts and delays the signal at the sensor relative to the instantaneous pressure in the manifold affecting the ability to accurately read and interpret the MAP signal. In this application, the EMS calibration has been specifically performed for a 300 [mm] length tube. As would be expected, the arrival time of the vacuum pulse at the MAP sensor will change depending on speed and load, consequently, MAP Read Angle must be added to the list of variables determined by interpolating a speed-load calibration table. Thus the crank-angle at which MAP is read, (MAP read angle) depends on MAP itself. If the MAP Read Angle is not correctly established, significant misinterpretation of load will result. Furthermore, since the measured MAP doesn't really represent the true pressure in the engine cylinder at BDC, the EMS calibration value of the VE will be significantly different than the value which would result from an engine air-flow measurement.

Another consequence of the flow pulsations is that they can cause fuel accumulation in the MAP sensor tube. Experience with the system revealed the need to have the tube protrude into the port to measure static pressure as opposed to measuring from a port in the wall. The tube should be should be oriented such that gravity tends to empty any accumulation.

As previously explained, the EMS controls the quantity of fuel delivered by adjusting the injector pulse width. A given fuel injector will deliver a fuel quantity proportional to its pulse width provided the pressure drop across its exit nozzle is constant and the opening and closing times of the injector solenoid are accounted for. The fuel pressure regulator (see previous section) ensures the pressure drop is constant. Calculations in the ECU account for the time to fully open and fully close the injector.

When two control mechanisms are present in a single system, in this case the EMS and the independent governor, maintaining stability is complicated by their independent interactions. The mechanical governor and the ECU system may be able to synchronize better with the use of a throttle position sensor, however, this sensor was not recommended, as it may interfere with governor operation. Of the two control systems on the prototype generator, the ECU system has a significantly faster response with stream of input data, faster calculation, feedback, and faster mechanisms to respond to the output.

Accommodating the inter-dependency of the various calibration parameters and unavoidable compromises associated with a low-cost EMS system comprised the majority of the challenges required to implement and tune the EMS for this application. Achieving the desired emission reductions is strongly affected by the ability to maintain the stoichiometric air to fuel ratio set point at which the catalyst is most effective.

Preliminary testing was performed to determine how this EFI strategy could affect generator performance (e.g., maximum sustainable load and engine temperatures). Prototype testing indicated cylinder head temperatures remained within acceptable limits at and near full load, and maximum deliverable generator power was maintained in the prototype configuration.

TEST METHODS AND EQUIPMENT

OVERVIEW

The low CO-emission portable generator program included a durability evaluation with periodic emission tests of the modified prototype and an unmodified baseline unit throughout a 500 hour service period. Five hundred service hours was specified as the engine manufacturer’s rated life for the engines in the generators used in this program. This evaluation investigates the longevity performance of the modified components in the prototype design. In addition, the durability evaluation allows performance comparison between the unmodified baseline generator to the modified prototype unit. The emissions for the engines used on both generator units are regulated by the EPA as directed by The Federal Code of Regulations (CFR) Title 40 Part 90 ‘Control of Emissions from New and In-Use Non-Road Spark-Ignition Engines at or Below 19 Kilowatts’. The test method associated with this regulation is commonly referred to as a six-mode emission test, since it consists of emission measurements made at six specific, steady operating modes. The CFR specifies that a dynamometer be used to apply these engine loads during the test. However, since this program specifically targeted portable generators, the method was adapted to the portable generator program. To achieve the engine loading in the generator application, the dynamometer was substituted with the generator’s alternator, which was loaded using a resistive load bank. The purpose in conducting the durability and periodic emission tests in the generator configuration was to allow the manifestation of any issues that might result from the prototype engine modifications on the end-use consumer product. Such manifestation might otherwise not occur on the dynamometer.

As may be surmised by the use of the generator loading platform, the emission testing performed during the development and durability testing phase described in this report was not intended to be in complete accordance with the EPA small-engine test method, however all efforts were made to reasonably emulate certification-level practice. The emission measurements were made using raw gas sampling method and analyzed by a laboratory grade 5-gas emission bench. The program described here was followed up with full certification testing of the prototype engine performed by an independent laboratory. Those tests included removing the engine from the generator configuration and installing it on an appropriate dynamometer test platform. The results of that testing is described in a separate report.

TEST CONFIGURATION AND EQUIPMENT

Test Configuration

Figure 14 shows a schematic of the setup for the generator emission tests. As indicated above, the emission tests were performed with the engine installed in the generator and loaded with a resistive load bank. The alternator was loaded with an Avtron 10 kW resistive load bank, through the generator’s 240V twist-lock receptacle. As supplied, the load-bank was capable of loads varying from 0 to 10kW with a 1 kW resolution; however additional resistors were installed to improve the resolution to 0.125kW. The applied load was measured using a Fluke model 39 electrical power meter.

The fuel mass flow rate, which is needed for the raw gas sampling method to determine the mass rates of exhaust constituents, was measured gravimetrically during all emission tests. During these tests, the fuel tank was disconnected from the generator frame and placed on a fuel scale. The fuel scale has accuracy greater than 0.1 percent of its 22.5 kg (50 lb) full-scale range and had an analog output proportional to its measured value, which was recorded through the duration of the test.

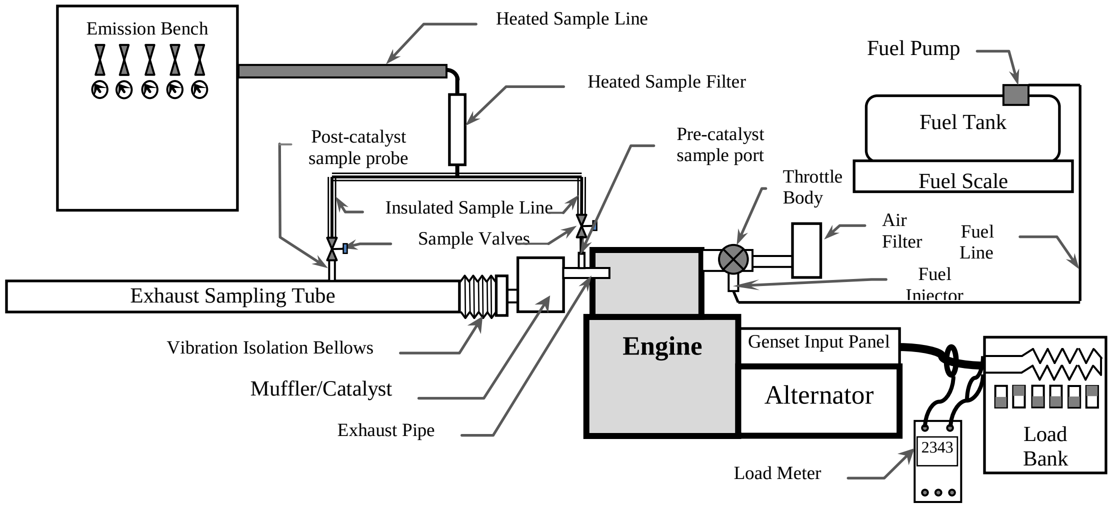

Figure 14: Schematic of test configuration.

The muffler had a flange welded to its outlet to enable attaching an emission sampling tube. The engine side of the sampling tube has a metal bellows section approximately 15 cm (6 in) long which isolates the engine vibration from the tube and generates some turbulence to enhance exhaust gas mixing. The sampling tube, which was 3 m (10 ft) long and 8.5 cm (3.4 in) in diameter, provided the port for mounting the sample probe to draw the exhaust sample for analysis in the emissions bench. The sample port is 70 cm (28 in) from the muffler exit. The exhaust sample is extracted using a 9.5 mm (3/8in) ID sampling probe. This probe penetrates approximately 4 cm (1.5 in) into the sample tube, is capped at the end and has three 4.8 mm (3/16 in) diameter holes drilled facing downstream to extract the gas. The centers of the holes are approximately 6, 16 and 25 mm (1/4, 5/8 and 1 in) from the tube end. This port was used for all the baseline exhaust samples and the post cat samples for the prototypes. Two other ports were drilled through the sampling tube. One port is located 94 cm (37 in) from the muffler exit and was used for mounting the wide band AFR analyzer sensor. The other port was typically unused and plugged.

Exhaust sample was also drawn from the exhaust header tube upstream of the muffler/catalyst in the prototypes. Analysis of this engine-out exhaust gas was used as a reference to the downstream measurements to assess the effectiveness of the catalyst and to estimate the potential results if the stoichiometric AFR strategy were applied without a catalyst-equipped muffler. The samples were not drawn simultaneously from both locations- rather the tests were repeated to acquire pre-cat and post-cat data. High temperature valves were attached to both sampling ports and connected downstream from a T-connector which was attached to the sample filter. These valves were used to direct the desired sample to the emission bench. A probe with the same design used in the sampling tube could not be utilized for this pre-catalyst extraction point because the header pipe is only one inch in diameter, and any adequately sized probe would significantly alter the exhaust flow. Consequently, the exhaust manifold exhaust gas sample is pulled from a port which was flush with the inner diameter of the exhaust manifold pipe. This is an unavoidable deviation from the EPA recommended practice, although the highly unsteady and turbulent flow in this exhaust section insures that the sample will be well mixed.

To eliminate condensation in the sample filter, the filter housing was maintained at 110°C using an electric heater and process controller, and the tubing and valves along the path from the extraction point to the filter tee were insulated. The sample filter was connected to the bench by a flexible heated sample line that is connected to an oven. From the oven, the line is connected to the suction side of sample pump with a heated head. From the pump the line again passes through oven and it is then divided to flow through different analyzers.

Emission Analyzers

The UA emission bench consists of eight separate detectors for measuring five different species in the engine exhaust and a sample handling system to collect and process sample gas and deliver the appropriate sample gas and flow to these analyzers. This bench has four non-dispersive infrared (NDIR) detector units for two separate CO_2 and two separate CO measurements, two chemilluminescent (CLD) sensors for two separate NOx measurements, a flame-ionization detector (FID) to measure unburned hydrocarbons (UHC) and a paramagnetic detector to measure oxygen. These analyzers all output mole fraction which is presented on either a percent (O_2, CO_2) or ppm (NO_x, CO and UHC) basis. The reference used here for the HC output is methane and the entire analyzer and sample path to the analyzer is heated. The NO_x analyzers are partially heated, utilizing the Rosemount 'Wet NO_x' configuration. In this configuration, the NO_x analyzers consist of a heated 'wet NO_x' drier and a dry NO CLD. The sample first enters the heated drier, where it first passes through the thermal NO_2 to NO converter if the system is NO_x mode. After the sample is dried in a chiller, it then flows to the dry CLD where the NO molefraction is measured. This technique is an EPA approved acceptable alternative to using a fully heated analyzer, however since the sample is dried upstream of the CLD, the molefraction is measured on a dry basis in contrast with a fully heated analyzer, which would be on a wet basis. This must be accounted for when converting the mole fractions to a mass emission rate and the equations in 40 CFR Part 90.419 describe how this is done. The detectors are all manufactured by Rosemount Analytical Corporation and the sample handling system construction and sensor integration were performed by Richmond Instruments Corporation (RIC). RIC also integrated data acquisition and control hardware to automate bench operation and sample acquisition and analysis. The analyzer ranges used in this program and the associated linearity specifications are given in Table 2.

Table 2: Analyzer Ranges and Linearity Specifications

Analyzer	CO	CO2	NO	NOx	UHC	O_2
Range 1	0-250 ppm	0-16%	0-900 ppm	0-900 ppm	0 – 1000 ppm	0 – 20%
Range 2	0-3000 ppm	-	0 – 2300 ppm	0 – 2300 ppm	-	-
Linearity	< +/-1% FS	< +/-1% FS	+/-1% FS	+/-1% FS	< +/- 2% R	< +/-1% FS

The sample lines leaving the oven and going to the FID and WNX/CLD analyzers are heated to minimize the condensation in the line while the sample going to the dry analyzers pass through a drier. All heated path temperatures are maintained at 110^{o}C. In the drier the gasses are cooled to temperatures near 3^{o}C so that any water in the sample is condensed. The condensate is separated from the sample by using spiral trap and removed with a peristaltic pump. The dry gas is then sent to the dry analyzers. All the analyzers are connected to a common dump line which is vented to atmosphere.

TEST PROCEDURES

Generator Six-Mode Emission Test

As indicated in the overview, the generator emission tests were performed to emulate the EPA 6-mode engine test procedure specified in 40 CFR Part 90 as close as practically possible while maintaining the engine in the generator and controlling the load using a resistive load bank. To obtain a particular engine operating mode with the engine installed in the generator, the load bank was adjusted until the load measured using a Fluke 39 load meter matched the desired value. Engine torque could not be directly measured since the engine output shaft is inaccessible with the engine coupled to the alternator. The engine output corresponding to the measured alternator load was calculated using alternator efficiencies that were provided by the generator manufacturer. The engine output for the 5 part-load modes in a six mode test are specified as a fraction of the engine's full-load output. 'Full-load' means the maximum power the engine can produce. The EPA test method specifies the full-load point, designated mode 1 of the 6 mode test, to be performed using the dynamometer for speed control. Maximum power is produced when the throttle plate is parallel to the intake flow path, i.e., wide-open. This condition is referred to as wide-open throttle (WOT), and is achieved on a dynamometer test by decoupling the throttle from the engine governor and physically holding it in the WOT position. In contrast, when loading the engine with the alternator and resistive load-bank combination, the generator engine's throttle is modulated by the governor to maintain the set-point speed. Note that while the set-point speed is nominally 3600 RPM the engine speed will always droop below this set-point as the load is increased when using a purely centrifugal mechanical governor such as those used herein. This is because with such a governor, the throttle opening monotonically decreases with engine speed. This means the larger throttle openings needed to sustain higher loads occur at lower engine speeds. Nevertheless, for the governor to successfully maintain this (drooped) speed, it must be able to open the throttle at least slightly beyond the position needed to hold that speed in purely steady state in order to respond to any spontaneous load or engine performance variations. Consequently, tests in the generator application cannot maintain both WOT and the desired engine speed. Therefore the full load point used in this program was performed at a slightly lower power level than what would be achieved in a standard 6-mode test carried out on a dynamometer.

The full load point for this generator program was based on testing of the OEM generator configuration. The generator used in this program had an advertised rated output of 5.0 kW. Through generator applied load testing with a resistive load bank, the unmodified (OEM) generator set was found to be capable of sustaining a deliverable power output of 5.5 kW; the generator circuit breaker would trip at 5.8 kW. From this generator application testing, maximum deliverable generator power output was determined to be 5.5 kW. An associated engine power for this point based on manufacturer-supplied alternator efficiency data was estimated to be 7.6 kW.

All part-load modes (2 through 6) were determined by calculating a percentage of the engine manufacturer's advertised net output of 8.2 kW. Table 3 shows the target engine and generator output power for each mode. Mode 6 represents an idle operation and was achieved by removing the resistive load from the alternator, however the power meter used to set the resistive load points would indicate a residual power of approximately 0.4 kW in this condition. The resolution of the measured generator output power is limited because the resistive load bank has a nominal resolution of 0.125 kW, so the load percentages and target values do not exactly correspond.

Table 3: Loads and Weighting Factors for EPA 6-mode Test

Mode			1	2	3	4	5	6
Load		[%]	Full	75	50	25	10	idle
Weighting			0.09	0.20	0.29	0.30	0.07	0.05
Output Power	Engine	[kW]	7.6	6.2	4.1	2.1	0.82	0.0
	Generator	[kW]	5.50	4.75	3.25	1.50	0.625	0.0

The emission data are taken in mode order (1-6; from full load to idle). Initial warm up is performed by running at mode 3 or greater for a minimum of 20 minutes. The load would then be increased with warm-up ending by running at mode 1 long enough such that engine head and oil temperatures stabilize. Each subsequent mode is preceded by running at the associated mode load long enough for these temperatures to re-stabilize for 5 minutes, whichever is longer. For the catalyst-equipped prototype, three data sets were acquired at each load to estimate catalyst efficiency. These data were gathered in a three separate test sequence each with a minimum two minute sample duration. The first and third tests acquired emission sample upstream of the catalyst (pre-cat) and the second test acquired sample from the sampling tube downstream of the catalyst (post-cat). The pre and post-catalyst tests were necessary since the UA emission bench had only one sample line capable of 5-gas analysis. The third test, which repeated the pre-cat sample, was performed to insure there was no drift in conditions at the load point, however to be consistent with the EPA method, only test 1 (the first pre-catalyst test) and test 2 (the only post-catalyst test) were reported in the results. If the second pre-catalyst test did not match the first, the test was aborted. Each test is separated by a 3-4 minute purge processes which insures the gasses from the previous test are not mixed with the current test. The baseline unit was tested only with a single 3 minute sample at each mode.

<u>Emission Measurement System Calibration</u>

Two levels of analyzer calibration procedures are performed- a periodic detailed calibration and a daily zero/span check. The procedures utilized at UA for these two calibrations are consistent with the specifications in 40 CFR Part 90 Subpart D.

The detailed calibration requires at least six different sample gas concentrations spread over a particular measurement range. For example, if the full scale value for the particular range is 1000 ppm, the minimum requirement for the calibration test would require sample gasses of 0, 200, 400, 600, 800 and 1000 ppm. These gasses could be supplied with separate mixtures or by mixing a single full scale gas (1000 ppm in this case) with a diluent gas using a gas divider. The gas divider technique is used at UA. Calibration checks are made prior to any test sequence anytime the most recent check has been made more than 30 days prior. If any analyzer deviated more than 2% of full scale at any intermediate value, the calibration curve is reconstructed using 11 different mixture concentrations within the range.

The zero/span checks are performed prior to and after each 6-mode emission test. These checks consist simply of injecting a zero gas which, as its name implies, has none of the measured species present and then following that by flowing the full span calibration gas. If the readings deviate from the expected zero and span values, the calibration is linearly adjusted to force the appropriate analyzer response. This procedure is automated by the bench control software.

Test Fuel

The fuel used for the durability program's emission tests was 87 octane non-oxygenated pump gas, which clearly is not an EPA certified test fuel. However, several steps were taken to minimize the impact the fuel would have on emission result through the durability program. First, all the fuel used for the emission tests were acquired at the start of the durability program. Second, the properties of this fuel were analyzed, which verified it to be a non-leaded and non-oxygenated blend of non-remarkable composition. Finally, immediately after purchase, the fuel was transferred into 40 gallon structural steel bottles which were evacuated with a vacuum pump prior to filling and pressurized with 20 psi of helium gas. This was done to minimize compositional changes due to oxidation and evaporation over the duration of the durability program.

The fuel used while simply accumulating hours through the durability program was also locally available pump gas, however it was purchased as needed and no special efforts were made to determine or control its composition.

Measurement and Calculation

The final values for the emission values were computed in accordance with the equations provided in 40 CFR Part 90.419.

Durability

One of the goals of the durability program was to assess the in-use viability of the prototype modifications throughout the engine rated useful life. This was accomplished by running the generators through varying loads over a duration equivalent to the rated service life of the engine supplied with the OEM units. The rated service life of the engines used in this program is 500 hours. The generator load variation pattern consisted of six loads representing the 6 mode emission test. The six mode load profile was applied in descending load order over time periods proportional to the mass-weighted emission average weighting factors. Specifically, these durations were 5.5, 12, 17.5, 18, 4, and 3 minutes for modes 1 (full load) through 6 (idle), respectively. This load profile was applied using automated versions of the same resistive load-bank used in the 6-mode emission tests and repeated continuously until refueling was required, the end of the shift shutdown or if a mechanical issue were to occur. Of particular interest was the prototypes EMS system longevity and catalyst degradation, as well as engine performance degradation and wear, CO emission trends and monitoring that the engines do not exceed applicable EPA HC+NO_x standards, of both the prototype and baseline units over the durability period. These performance outcomes were measured and recorded with the six mode test results at 150 and 250 hours of accumulated service, and ultimately at the end of durability.

A ventilated enclosure was built to hold the units while they ran to protect them from weather and reduce the noise level. This cabinet is pictured in Figure 15. It was equipped with two 1500 standard ft^3/min (scfm) fans in the back and inlet openings in the front. The fans were mounted in boxes to which several snorkels were attached and directed throughout the enclosure so the exhaust air could be pulled uniformly from the unit. The fans exhausted to the back of the mount boxes. The exhaust openings were equipped with louvers to lower sound levels and keep weather out when the unit was not in use.

As indicated in footnote 4, a third generator unit was being used to explore a lean fueling strategy. This unit was at times run in the enclosure with the baseline and prototype units. This third unit is not discussed in any other sections of this report, but is mentioned here to accurately describe the hour accumulation environment. The initial intent was to run all three units in the enclosure simultaneously to insure that the units were being run under the same conditions and similar time schedules. With the shelf installed, the three generators could easily fit in the unit and the ventilation system could keep the oxygen level and temperature reasonably close to atmospheric conditions- nominally within 0.3% and 10^{o}C on the engine air intake. As described below, mechanical, electrical and instrumentation issues made it impractical to do all the hour accumulation simultaneously.

Table 4 shows the various non-scheduled maintenance and repair issues encountered during the durability program. The lean unit issues are included to show the consistency of alternator-related failures. Some of the associated repairs required ordering new parts or machine shop service, which often meant multiple days of down time. To prevent these issues from stacking up sequentially, hour accumulation usually continued on the working units while repairs were made


Figure 15: Photograph of the durability run enclosure

on the disabled unit. Furthermore, although the shelf in the enclosure was statically very rigid, it seemed that under running conditions, the unit operating on the shelf endured some additional vibration that was not present on the bottom shelf. This was concluded after the baseline alternator fan came loose twice within 17 operating hours while it ran on this shelf. Once the shelf was hypothesized to play a role in these issues, it was decided to only run the baseline and primary (stoichiometric strategy) prototype simultaneously in the enclosure. Since the program priority was to compare the prototype using the stoichiometric fuel control strategy to the baseline, they had priority in the enclosure and in repair in maintenance scheduling. The lean prototype was only run when circumstances (weather, surrounding activity) allowed outside of the enclosure or after the durability accumulation was complete for the primary units.

Table 4: Repairs and Non-Scheduled Maintenance During Durability Program

Prototype		
Date	**Problem**	**Hrs**
11/26/2008	Voltage regulator board connector melted. Replaced with wirenuts.[6]	107
2/4/2009	Output panel wiring meltdown. Rewired.	138
7/13/2009	Muffler flange surface cracked. Cracks repaired by welding.	268
8/31/2009	Muffler flange surface cracked. Catalyst removed and installed in new muffler.	300
10/22/2009	Fuel injector loose. Retightened.	435

Baseline		
Date	**Problem**	**Hrs**
1/12/2008	Alternator connector melted, rewired and connector replaced with wire nuts	6
5/6/2009	Alternator fan broken. Rotor circuit capacitors burned. Fan and capacitors replaced.	160
5/19/2009	Head gasket leaking. Replaced.	175
5/21/2009	Alternator fan broken. Alternator stator wiring damaged. Fan and alternator replaced.	177
9/3/2009	Carburetor bowl cracked. Replaced	300

Lean		
Date	**Problem**	**Hrs**
12/13/2008	Output panel connector replaced	38
1/29/2009	Exhaust studs broken. Replaced	82
2/25/2009	Circuit breaker melted. Replaced.	113
8/20/2009	Exhaust studs broken. Replaced	273
3/20/2009	Valve cover stud loosened. Repaired thread and reinstalled.	340
3/25/2010	Alternator to output panel wiring melted. Replaced.	
4/2/2010	Alternator fan broken. Alternator wiring failure. Fan and alternator replaced.	380

[6] More details concerning the voltage regular and associated alternator connectors are provided in Appendix A. As indicated, this loose connector and wiring issue with the voltage regulator occurred with both the baseline and prototype generators and were discovered after the zero hour emission testing. The situation is believed to have skewed the zero hour emission tests results for the prototype and baselines at some unknown but slightly lower loading profile.

The net effect of the repair issues and down-time associated with the 150 and 250 hour emission tests was that the baseline and stoichiometric strategy prototypes ran simultaneously in the enclosure for 270 of the 500 durability hours, or 54% of the time. While the balance of the hours did not occur exactly simultaneously, the environmental variation during the remaining 46% of the time was limited to the random variations in day to day weather that occur over a week or two week period during any given season.

The actual hour accumulation patterns varied from day to day depending on staffing and the mechanical and emission testing status discussed above. The units were only run if a project team member was available to monitor the operation. Most of the time, these team members were students whose schedules were not necessarily conducive to long consecutive hour runs. Nevertheless, there were occasions where it could be arranged to run the units for 12 or more hours per day and there were other days where the units ran for only two or three hours. The monitor was responsible for refueling and periodically checking to insure no problems were present. The amount of fuel consumed was logged with each refilling. As indicated above, the fuel used was local 87 octane pump gas, which was acquired and stored 40 to 50 gallons at a time as needed.

As Table 4 illustrates, the mechanical issues were dominated by failures of the alternators and associated wiring. *These issues were not engine related*. Similar problems occurred in both the unmodified and modified generators, e.g., alternator fan. These failures suggest such failures would occur anyway and is not due to the EFI conversion. These were present in all three units and as described in the appendix were concluded to be due to electrical components under-designed for the load capabilities of these generator sets. The only issues that arose specific to the hardware added to the prototype units were the broken exhaust studs on the lean unit at 82 and 273 hours, and the loose fuel injector at 435 hours and the cracked muffler flanges at 268 and 300 hours on the prototype. The first instance of these muffler cracks was repaired by welding. The reappearance of these cracks less than 40 hours later indicates that the weld repair was not adequate under these test circumstances. After the second instance, the catalyst was removed and integrated into a new muffler. Including post durability investigations, this new muffler was run for at least 300 hours with no evidence of impending failure. These flange failures can be attributed to at least four factors, three of which would not be present in an OEM version of the prototype. First, the mufflers on the prototypes were hanging from the end of their fabricated exhaust header pipes, which were necessarily considerably longer than the baseline cast iron pipes to facilitate instrumentation access. Second, as described in the prototype development section, integrating the catalyst into the OEM baseline muffler was deemed impossible, so a muffler of a different configuration had to be used. The configuration of this muffler and the added length of the exhaust pipe made it impossible to support the muffler to the alternator housing as securely as was done in the baseline unit. These first two factors led to significantly increased vibration stress at the flange, which was where the muffler mounted to the exhaust pipe. Third, the muffler had to be cut in half and re-welded to integrate the catalyst, which may have pre-stressed the flange upon reassembly. Finally, the prototype exhaust temperature was somewhat higher than the baseline unit, which could have led to increased thermal fatigue. The vibration issues described in factors one and two were also the likely cause of the exhaust stud failures in the lean unit.

DURABILITY TEST RESULTS

OVERVIEW

Upon completion of development and construction of the prototype generator, the durability program with periodic emission testing was carried out to evaluate the long term effectiveness of the EMS and the addition of the catalyst muffler and any effect on generator longevity. The prototype generator was specifically developed to demonstrate the reduction of CO while maintaining no increased HC + NOx emission levels. This durability test provides an endurance evaluation and performance comparison of the unmodified OEM baseline generator to the prototype generator with the emission control technologies. The procedures of this durability program, including how the emissions test results presented in this section were determined, are detailed in the *Test Methods and Equipment* section. Briefly, the baseline and prototype generator were cyclically loaded through a full-to-no-load profile for 500 engine hours, which is the rated useful life of the engine. The primary focus of the durability test was to evaluate the effects of wear on the baseline and prototype generator unit from the beginning of the test program (zero hours) to the end of the engine's rated useful life (500 hours). Emission tests were conducted at 150 and 250 hours for some performance record at intermediate useful life.

This section presents the results of the durability program. First, a comparison is presented between the zero hour 'as delivered' performance of the baseline and pre-mod[7] prototype units. Next, the combined weighted mass-emission results (composite results) acquired at the 0, 150, 250 and end of life (500 engine hours) milestone points are presented and discussed as they relate to program objectives. Finally, the 500 hour individual modal data is presented to provide insight to how the prototype modifications affected performance and emissions as a function of load. In the section subsequent to this one, the post-durability wear analysis and comparison of the baseline and the prototype generators are described. The complete durability emission test results and associated engine data of the unmodified and prototype generator at the 0, 150, 250, and 500 hour emission tests are presented in the appendices.

UNMODIFIED GENERATOR PERFORMANCE COMPARISON

To establish the exhaust emission profile and engine performance measurements on the original OEM equipment, the unmodified generator units were subjected to the six mode generator emission tests that included measuring the engine performance parameters such as AFR, cylinder head, exhaust manifold, and muffler surface temperatures. This section presents the characterization of the OEM baseline and pre-mod prototype generators. Of particular interest was the unit to unit variation of maximum temperatures for the cylinder

[7] The generator which was used to produce the prototype was tested in two configurations: (1) prior to any modification and (2) after prototype modifications. The tests performed prior to modifications are referred to as 'pre-mod prototype' and the tests after modification are referred to simply as 'prototype'.

head and exhaust components and to establish an initial acceptable performance of each OEM unit. It should be emphasized that each load was run until the engine temperatures could stabilize and reach approximate equilibrium.

The two OEM generators were operationally checked and then emission tested with approximately zero engine hours. It should be noted that there are two initial generator emission tests for the prototype generator unit. The first one was in the pre-mod condition at which time, the unit had approximately zero engine hours. The second emission test was after the prototype modifications were made. The unit had been run for approximately 25 hours at the time of this second test. The hour counts referred to in the durability results for the prototype are relative to the initial test in the modified condition. Therefore, the service hour accumulation on the prototype was actually 25 hours greater than these hour counts.

Cylinder Head Temperatures

The maximum sustainable delivered power output from the generators was determined to be 5.5 kW, as discussed in the *Test Methods and Equipment* section. In this full load condition, the baseline generator AFR was 12.8. In contrast, the pre-mod prototype generator when operated at full load condition had an AFR of 14.0. Significant variations in the AFR exist in the other modes as well. Notably, the trends with both units show that the AFR *decreases* with decreasing load.

These AFR variations affect all engine operating temperatures. At this maximum 5.5 kW generator load, the 14.0 AFR on the pre-modified prototype generator was associated with a cylinder head temperatures of 227°C. At this same full load, the 12.8 AFR on the baseline generator measured cylinder head temperatures of 203°C. Table 5 shows the variation of AFR and associated cylinder head and oil temperatures from the OEM generators and the prototype over the generator six-mode load profile.

Table 5: AFR and Temperatures with OEM Generator Units

	OEM Baseline Generator				Pre-mod Prototype Generator			
MODE	AFR	Cyl. Head °C	Oil °C	Fuel Rate (kg/hr)	AFR	Cyl. Head °C	Oil °C	Fuel Rate (kg/hr)
1	12.82	203	108	2.40	13.98	227	115	2.36
2	12.38	195	104	2.28	13.72	220	113	2.53
3	12.49	180	97	2.00	13.80	208	107	1.80
4	11.09	154	86	1.54	11.29	172	93	1.42
5	10.90	143	81	1.25	11.31	162	89	1.31
6	10.80	136	79	1.21	11.26	157	86	1.23

The AFR values of both units in carbureted form were leanest at full load and became progressively richer with decreasing load. Of particular significance is the 14.0 AFR of the pre-modified prototype, which is only 0.6 AFR from the stoichiometric value. The premodified prototype was leaner than the baseline at each individual mode. The biggest difference was at full load (mode 1) where the baseline was nearly 1.2 AFR richer at 12.8, and the smallest difference was at mode 4 where the baseline was only 0.2 AFR richer at 11.1. The average AFR over all 6 modes was 0.8 AFR richer for the baseline than the pre-modified prototype

These AFR variations between the OEM are likely primarily due to manufacturing variations in the carburetors. This unit-to-unit AFR causes measurable temperature differences and fuel efficiency. Variations in the electrical loading demand from the alternator unit, thermal losses, and voltage regulator performance could also be a contributor to the AFR differences, since these variations would alter the alternator efficiency and result in different engine outputs for a given electrical load.

Figure 16 graphically contrasts the cylinder head temperatures of the two units. The unit to unit cylinder head variation is approximately 20°C over the entire loading profile.

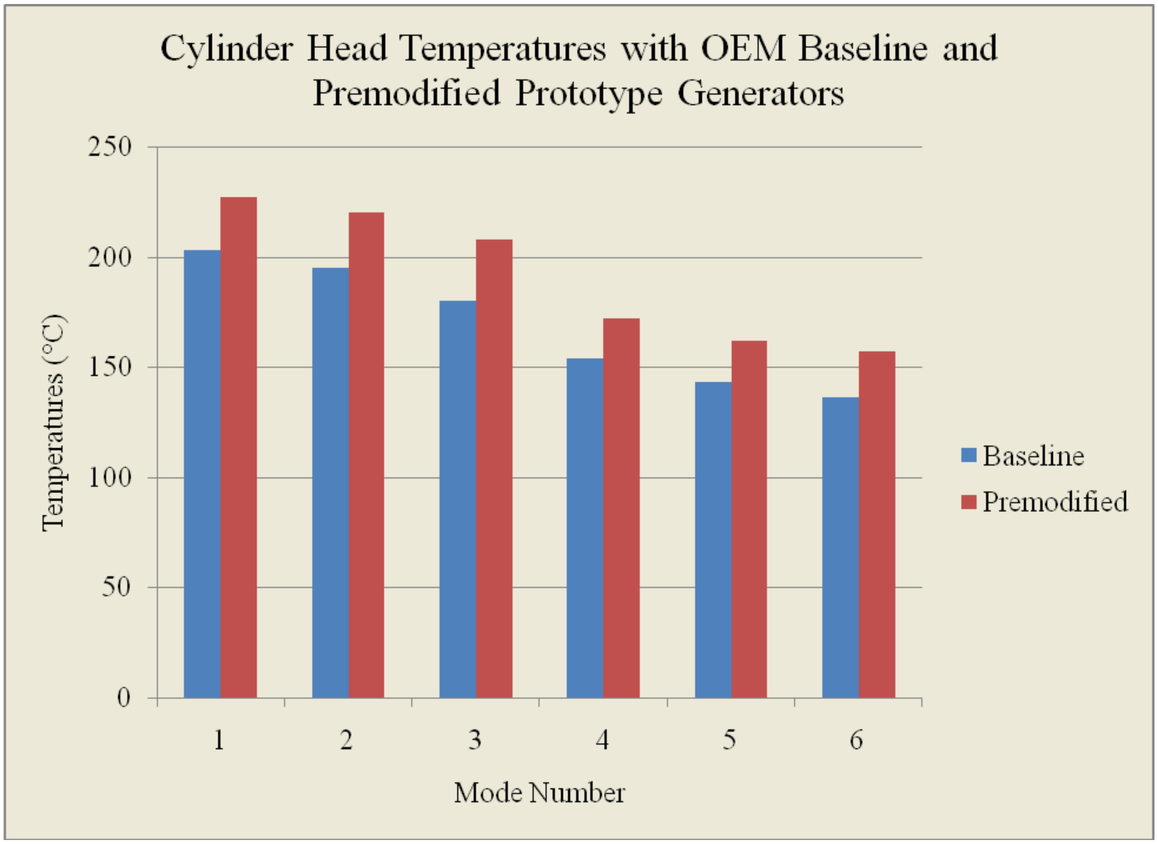

Figure 16: Comparison of Premodified OEM Generators Cylinder Head Temperatures

<u>Exhaust System Temperatures</u>

The exhaust gas temperatures were measured at the tailpipe and downstream of the muffler on the two OEM generators. At 5.5kW, the maximum exhaust gas temperatures were 579°C for the baseline generator and 597°C for the pre-modified prototype generator. These gas temperatures are consistent with the cylinder head temperatures, and are also attributable to the near stoichiometric AFR in the premodified prototype at full load. At this load, the muffler surface temperature of the OEM configurations were approximately 441°C for the baseline unit and 456°C for the prototype unit prior to modification. The pre-modified prototype and baseline generators came equipped with same OEM muffler design with intricate baffling that was advertised as a quiet muffler.

COMBINED WEIGHTED EMISSION RESULTS

To demonstrate the performance of the prototype compared to the baseline, generator emission tests were planned for the zero[8], 150, 250, and 500 hours of accumulation. The subsequent charts and tables show the summaries for the weighted mass-emission results for the baseline and the prototype generator at these 0, 150, 250 and 500 hour milestones during the durability program. The values reported in this section are a weighted mean of all six modes using the weighting factors prescribed by the EPA for a six mode test. These factors are 0.09, 0.20, 0.29, 0.30, 0.07 and 0.05 for modes one through six respectively. Further details regarding measurement and computation of these values are provided in the *Testing Methods and Equipment* section. Tables 6 and 7 show the CO and HC + NOx emission levels, respectively, of the baseline generator compared to the prototype generator. The direct comparisons between the two are shown in the column labeled percent reduction (or Δ%).   The EPA Phase Two and Phase Three emission limit for CO is 610 g/kW-hr. The Phase 2 emission limit for HC + NO_x is 12.1 g/kW-hr and Phase 3 emission limit is 8 g/kW-hr.

CO Results

Table 6 shows the durability program combined weighted CO results of the baseline generator compared to the prototype emissions at locations upstream and downstream of the catalyst, labeled pre (for pre-catalyst) and post (for post-catalyst), respectively. Generator emission test results are presented at the beginning (0 hour), intermediate (150 hour and 250 hour), and end (500 hour) of the generators' rated useful life.   The column labeled percent reduction (or Δ%) is that of the prototype generator compared to the baseline generator. For reference, the EPA Phase Two and Phase Three emission limit for CO is 610 g/kW-hr.

Program success is demonstrated by the combined weighted CO emission rates that are considerably lower than the 30 g/kW-hr target. The prototype generator pre-catalyst data show CO reductions relative to the baseline ranging from 90 to 94.5%. This pre-catalyst data give an indication of what could be expected by simply controlling AFR near 14.6 rather than running the engine in the 10.5 to 13.5[9] AFR range as in the baseline

[8] Note that the loads on the generators at the zero hour emission test were at some unknown but slightly lower loading value due to thermal losses and eventual melting of alternator wiring and mating connector issues. This loose connector and wiring issue with the voltage regulator occurred with both the baseline and prototype generators after the zero hour emission testing.   A detailed discussion of this connector wiring and other failures during durability are discussed in section the *Test Methods and Equipment* section and in Appendix A.

[9] The baseline AFR did not exactly repeat at each individual mode over the 500 hour program, although the trend for AFR decreasing with load did. This range reflects the variations over the loads for the full program and is therefore larger than the range reported at zero hours in Table 5.

carbureted engine. This 14.6 AFR strategy provides the engine power required for the generator application without the excessive CO formation from richer operations where there is insufficient oxygen to chemically convert the gasoline composition. With the post-catalyst emissions, the prototype CO reduction improves from 93.3 to 99.4%.

Table 6: Combined Weighted CO Results of Baseline and Prototype Generators

Engine Hours	Baseline CO emissions (g/kW-hr)	Prototype CO emissions			
		Pre	Post	Pre	Post
		g/kW-hr	g/kW-hr	Δ%	Δ%
0	282	19	2.42	**93.1**	**99.1**
150	316	16.7	1.76	**94.5**	**99.4**
250	239	26.4	8.05	**90**	**96.6**
500	260	22.8	17.51	**91.2**	**93.3**

Figure 17 provides a graphical view of the prototype generators capacity to sustain low CO emissions and a comparison to the baseline generator. This results display the EFI technology reducing the majority of CO emissions and the catalyst improving the CO reduction by approximately an additional 5 to 6%.

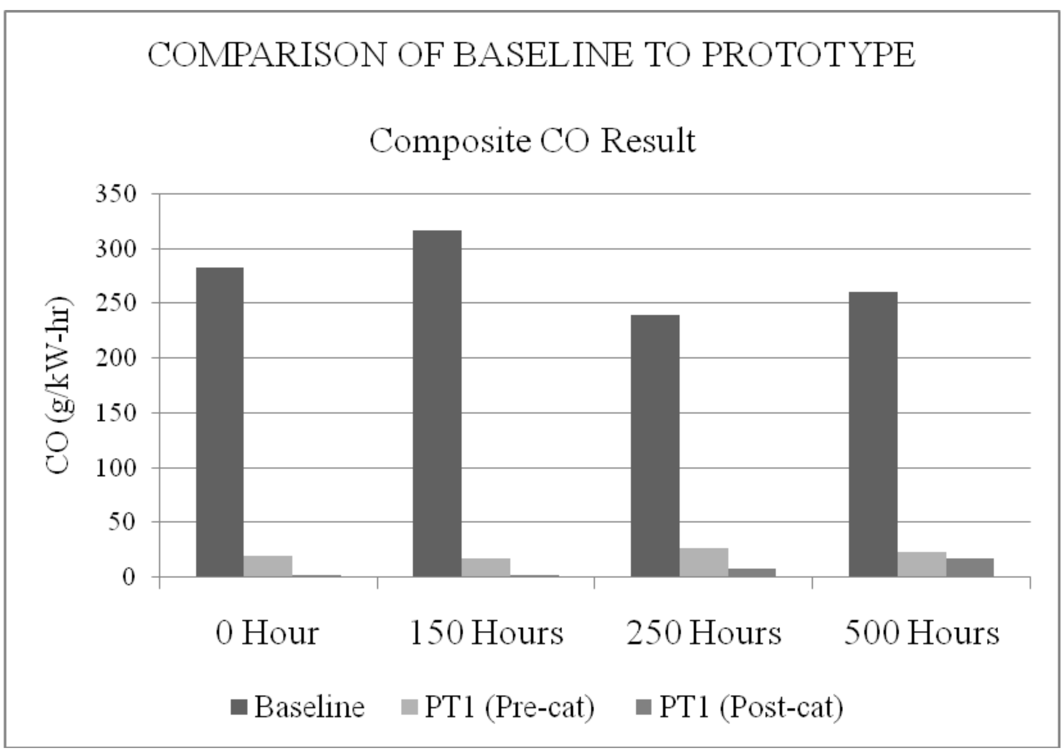

Figure 17: Durability CO Emission Test Results of the Prototype and Baseline Generators

The durability tested prototype engine demonstrated at least a 90% reduction in CO emission levels with EFI controls and at least 93% reduction CO emission levels when considering the EFI and catalyst technologies.

HC + NOx Results

Table 7 shows the durability program combined weighted HC+NO_x results of the baseline generator compared to the prototype emissions measured at pre-cat and post-cat locations. For reference, the Phase 2 emission limit for HC+NO_x is 12.1 g/kW-hr and Phase 3 emission limit is 8 g/kW-hr. The column labeled percent reduction (or Δ%) is that of the prototype generator compared to the baseline generator. These data are also shown graphically in Figure 18.

As shown in Figure 18, the baseline generator HC+NOx appears to increase linearly with hour accumulation through durability, whereas PT1 does not seem to have any trend.

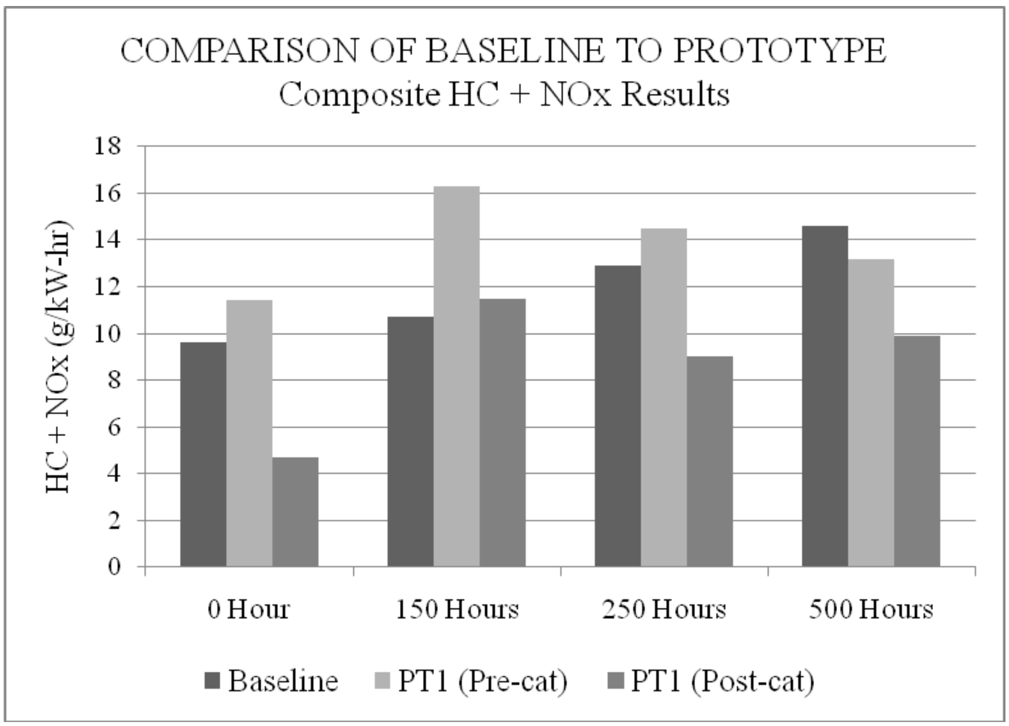

Figure 18: Durability HC + NOx Emission Test Results of the Prototype and Baseline Generators

Compared to the baseline, the prototype emissions after the catalyst (post-catalyst) showed lowered HC + NOx emissions at every emission test except for the 150 hour emission test. All post catalyst test results suggest levels below the EPA Phase 2 regulation limit for HC + NOx. In addition, the prototype generator post catalyst appears to comply with the EPA Phase 3 regulation of 8 g/kW-hr at the 0 hour; exceeds 8 g/kW-hr by 1 g/kW-hr at 250 and 500 hour marks and is 1.5 times greater than the regulation at the 150 hour mark. These results can be seen in Table 7. At 500 hours, the prototype HC + NOx levels (pre and post catalyst) decreased relative to the baseline.

Table 7: HC + NOx Results in the Baseline and Prototype Generators

Hour	Unburned HC (Hydrocarbons) [g/kW-hr] except %				NOx [g/kW-hr] except %				HC+NOx [g/kW-hr] except %				
	Baseline	Prototype			Baseline	Prototype			Baseline	Prototype		% Reduction	
		Pre	Post	%Conv		Pre	Post	%Conv		Pre	Post	Pre	Post
0	5.05	0.73	0.15	79.5	4.55	10.7	4.55	57.5	9.6	11.4	4.7	-18.8	51
150	5.88	0.96	0.23	76.0	4.83	15.3	11.3	26.4	10.7	16.3	11.5	-52.2	-7.3
250	5.38	1.21	0.32	73.6	7.48	13.3	8.71	34.5	12.9	14.5	9.03	-12.8	29.8
500	6.57	0.90	1.03	-14.4	8.04	12.3	8.86	27.9	14.6	13.2	9.89	9.5	32.2

The prototype design with the EFI controller sustains an AFR of 14.6 (stoichiometric) compared to the richer mixtures of the carburetor engines. This reduces CO and HC, however, the tradeoff for operations at 14.6 AFR is that engine-out NO_x emissions will increase. The prototype design intended to address any elevation in NOx emission through catalyst reduction process. Preliminary prototype testing indicated emission levels within CO goals and below HC+NOx standards, however the three-way catalyst was included since the effects of engine wear on emissions could not be predicted in this particular application. Efficient conversion with the three way catalyst requires stoichiometric operation. The best case oxidation (CO and HC) and reduction (NOx) catalyst conversion compromise occurs with controlled rich and lean excursions through stoichiometric AFR. Such excursions take advantage of the non-linear effect that AFR has on catalyst conversion efficiencies. Specifically, during an EFI oscillation to a lean excursion, CO and HC’s are very effectively oxidized in the catalyst and engine out NO_x is higher. Then, during the ensuing rich EFI excursion, the adsorbed NOx combines with the CO from the rich feed gas and is reduced to CO_2 and N_2. Given the limitations of the EMS and the time limitations for the prototype development, the AFR oscillations were not optimized in such a manner for this application. Consequently NOx conversion was less than ideal and varied somewhat during the durability program. However, the stoichiometric strategy implemented here based on the program’s focus on CO reduction caused corresponding reduction in unburned HC emissions. This HC reduction coupled with the limited NOx conversion efficiency was sufficient to maintain HC + NOx levels comparable to the baseline and appear to be below the engine’s originally certified Phase 2 limits. Had the EFI controller been able to optimize the rich to lean excursions to the point to achieve 50% NO_x catalyst conversion efficiencies, it is believed that the prototype post-catalyst emissions would have been below Phase 3 HC + NO_x levels at all the durability milestone tests.

Fuel Consumption Improvements

Improvements in fuel-consumption are a significant benefit to the stoichiometric engine-control strategy implemented on the prototype generator. In Table 8, the fuel consumption values are presented as weighted brake-specific fuel mass flow rate, kg/kW-hr. The factors used to calculate the weighted average emissions were used for fuel consumption here. The fuel mass flow rate was measured from the fuel scale that supported the raw gas sampling emission tests. This generator six-mode emission test procedure, including a fuel scale description and calculated engine power outputs, are described in *Test Methods and Equipment*. In comparing the baseline and prototype generator weighted brake specific fuel consumption (BSFC), the prototype design shows a decrease in fuel consumption ranging from 15 to 28% over the zero, 150, 250, and 500 hour durability emission tests. The average improvement of fuel consumption over these four tests was approximately 22%. Using the weighted BSFC numbers, the baseline unit would use approximately 60 gallons of additional fuel during the 500 hour service life of the engine compared to that of the prototype generator.

Table 8: Prototype Generator Fuel Consumption Improvements

Weighted Brake –Specific Fuel Consumption			
Hour	Baseline	Prototype	Δ %
	kg / kW- hour		[-]
Zero	0.50	0.36	28.0
150.0	0.49	0.38	22.4
250.0	0.48	0.41	14.6
500.0	0.48	0.41	14.6

500-HR EMISSION TEST MODAL DATA SUMMARY

The individual six mode data at 500 hours are presented in Tables 9 and 10 and are discussed in this subsection to provide additional detail on the end of life modal performance. Table 10C provides a summary of the 500 hour combined weighted (composite) emission results for a convenient reference and comparison to the modal results. The emission levels, catalyst performance, temperatures, fuel consumption, and AFR are presented. The interrelationship of these parameters and trends with respect to load are discussed where relevant. The prototype generator program success with maintaining below 30 g/kW-hr during the four durability milestone emission testing was presented in the previous subsection. The highlights here are the significantly reduced CO emission rates and decreased fuel consumption associated with the stoichiometric fuel control strategy on the prototype which is consistent with the combined weighted average results. Also of note is that the engine temperatures remain within acceptable ranges even without the cooling effect of the considerably richer AFRs found in the baseline configuration.

Table 9: 500 Hour Milestone Baseline Modal Data

Engine Modal Data									Emission rate unweighted (g/hr)		
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Manifold Exhaust Gas Temp °C	Tailpipe Exhaust Gas Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx
1	13.1	7.6	196	101	647	631	434	2.4	27.3	826.1	82.4
2	12.4	6.2	183	96	612	589	403	2.3	28.4	1101.3	55.2
3	12.4	4.1	166	87	575	527	362	1.9	24.7	870.5	34.4
4	11.4	2.1	142	76	521	441	302	1.6	25.3	1113.0	6.7
5	11.4	0.8	136	72	513	414	285	1.3	19.2	937.4	2.6
6	11.2	0.4	128	69	496	384	266	1.2	17.0	896.4	1.9

Table 10: Prototype Generator at 500 Hour

A. Precatalyst / Premuffler Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)		
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Manifold Exhaust Gas Temp °C	Tailpipe Exhaust Gas Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx
1	14.5	7.6	220	117	799	664	479	110	2.1	7.2	148.1	95.3
2	14.6	6.2	211	114	789	637	471	100	2.0	6.3	116.4	90.0
3	14.5	4.1	190	100	766	634	424	79	1.5	3.1	79.4	51.1
4	14.5	2.1	168	90	741	559	373	65	1.2	1.6	72.7	17.1
5	14.5	0.8	163	86	748	566	344	57	1.0	0.5	51.4	4.9
6	14.5	0.4	156	82	758	580	329	53	0.9	0.2	40.5	2.8

B. Post Catalyst Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)		
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Manifold Exhaust Gas Temp °C	Tailpipe Exhaust Gas Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx
1	14.5	7.6	220	117	797	669	484	110	2.2	1.1	36.6	83.1
2	14.5	6.2	212	113	788	646	479	101	2.1	0.9	28.8	75.0
3	14.5	4.1	191	101	765	645	430	80	1.6	0.6	15.6	34.7
4	14.7	2.1	164	88	714	592	385	66	1.3	11.6	175.0	3.5
5	14.5	0.8	162	86	747	590	352	58	1.1	0.1	7.2	2.3
6	14.5	0.4	156	82	759	613	338	54	0.9	0.0	5.9	1.3

C. 500 Hour Combined Weighted Emission Summary

	HC (g/kW-hr)	CO (g/kW-hr)	NOx (g/kW-hr)	HC+NOx (g/kW-hr)
Baseline	6.6	259.5	8.0	14.6
Prototype (Pre Catalyst)	0.9	22.8	12.3	13.2
Prototype (Post Catalyst)	1.0	17.5	8.9	9.9

The tables support that the engine parameters of interest are most strongly affected by load and AFR. The prototype maintained an average near the stoichiometric value of 14.6, but the baseline values were all rich starting at 13.1 for mode 1 and becoming progressively richer as load is decreased.

The mode-by-mode fuel consumption results support the observations made from the weighted brake specific fuel consumption. The prototype shows lower fuel consumption at each mode. The largest improvements were at the lower load modes, with mode 5 showing the biggest improvement of 27%. Mode 1 had the smallest improvement at 11%. For both the prototype and the baseline generator, the fuel consumption was lowest (highest efficiency) at the highest load and increased with decreasing load. This load-efficiency trend is typical for a homogeneous-charge spark-ignited engine running at constant speed and AFR in the absence of abnormalities such as knock or preignition. The trend is exacerbated in the baseline unit where the AFR becomes richer as load is decreased. Peak efficiency in such engines typically occurs somewhat lean of stoichiometric AFR. The baseline AFR trend, running leanest at mode 1 and most rich at modes 4, 5 and 6 explains why the highest efficiency improvements in the prototype occurred at lower loads. It also counters expectations since the extra fuel associated with the carbureted AFR strategy in air-cooled engines is typically used for engine cooling and to limit NO_x formation, which is most severe at the highest loads. With cylinder head temperatures well below acceptable values at all modes in the prototype running stoichiometric AFR and, as will be shown below, very low NOx production, there seems to be no reason to run rich at modes 4, 5 or 6.

Figure 19 compares CO emissions of the baseline to the prototype's when sampling both upstream of the catalyst (pre catalyst) and post catalyst (post catalyst). Consistent with the weighted CO emission results, the individual modal data shows substantial reductions in CO from the prototype where the CO emission rates tracked proportionately with fuel flow, except at the mode 4 post catalyst point which is discussed below. The lower fuel consumption rates equate to lower carbon flow through the engine, so all else being equal, in particular AFR, it is expected that the CO rates would be lowest at light loads. However this is not the case with the baseline generator unit, as the carburetor delivered the richest AFR and the largest CO emission rate at mode 4. In contrast, the prototype's AFR was maintained near 14.6 AFR at all loads, so the pre catalyst CO emission rate decreased monotonically with load. Figure 19 shows overall 80 to 97% CO emission rate reductions when comparing *pre-catalyst* prototype generator results to those of the baseline unit. Comparing the prototype CO emissions rate post catalyst to the baseline generator, the CO emission rates are reduced 84 to 99% compared to the baseline.

The relative decrease in CO emission from pre to post catalyst ranged from 75 to 86 %, when disregarding mode 4 where the catalyst out CO was substantially higher than the engine out value. This anomaly is discussed below. The reduction (not considering mode 4) generally increased as load decreased. The trend might be expected if the AFRs over all modes are very constant, since as long as the temperatures are adequate, the longer residence times in the catalyst at lower loads should translate to improved conversion.

As described in the *Test Procedures* section, pre-cat and post-cat were acquired in separate tests performed consecutively. Two separate tests were necessary because the emission bench could only analyze one sample stream at a time. Generally, there were no obvious significant deviations in engine and EMS performance between the two tests, so the emission results can be used to indicate catalyst efficiency. However, during the post catalyst test at mode 4, the AFR variations were more than normal. At approximately 250 hours, there were some instances where the prototype mode 4 AFR excursions were observed to be larger compared to the other modes, which in the worst cases caused an associated engine-speed variation. This speed variation was only severe enough to substantially affect results during the post-catalyst test at the 500 hour milestone, however it was occasionally observed during the hour accumulation operation leading up to 500 hours. In some cases the variation occurred directly after the transition from mode 3 to mode 4 and in others it would occur after extended operation. It was also observed to spontaneously stabilize after running for some time as well. A similar variation was observed after extended operation at mode 1 which required small decreases (~0.25 kW) in the load bank setting in order to sustain load during the milestone emission tests. Since the CO results were still well within the program targets despite the noted AFR and speed variation, and since the intent was to complete the durability program with only maintenance repairs, it was decided to complete the durability program without making any changes to the prototype to address these issues. The effort to explore and, as appropriate, address their causes was reserved for a post-durability investigation which included certification testing of the prototype at an independent test facility. This post-durability investigation, which is described later in this results section, revealed that these variations were caused by incomplete calibration of the EMS. As the generators progressed through durability, the alternator degraded and the governor mechanisms experienced normal wear. This wear and degradation was believed to cause the prototype engine to operate into areas of the calibration tables which were not initially well mapped. The larger AFR excursions at mode 4 caused by these unmapped operating points caused corresponding increased CO and HC emissions. The effect of this calibration issue can first be seen with the 250 hour mode 4 data, which is available for review in the appendix. Most significant however is that once correcting this incomplete calibration, the prototype, having accumulated well over 550 hours, performed exceptionally well during the certification tests performed by an independent test facility.[10]

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[10] The certification test results are described in http://www.cpsc.gov/library/foia/foia11/os/intertek2010.pdf.

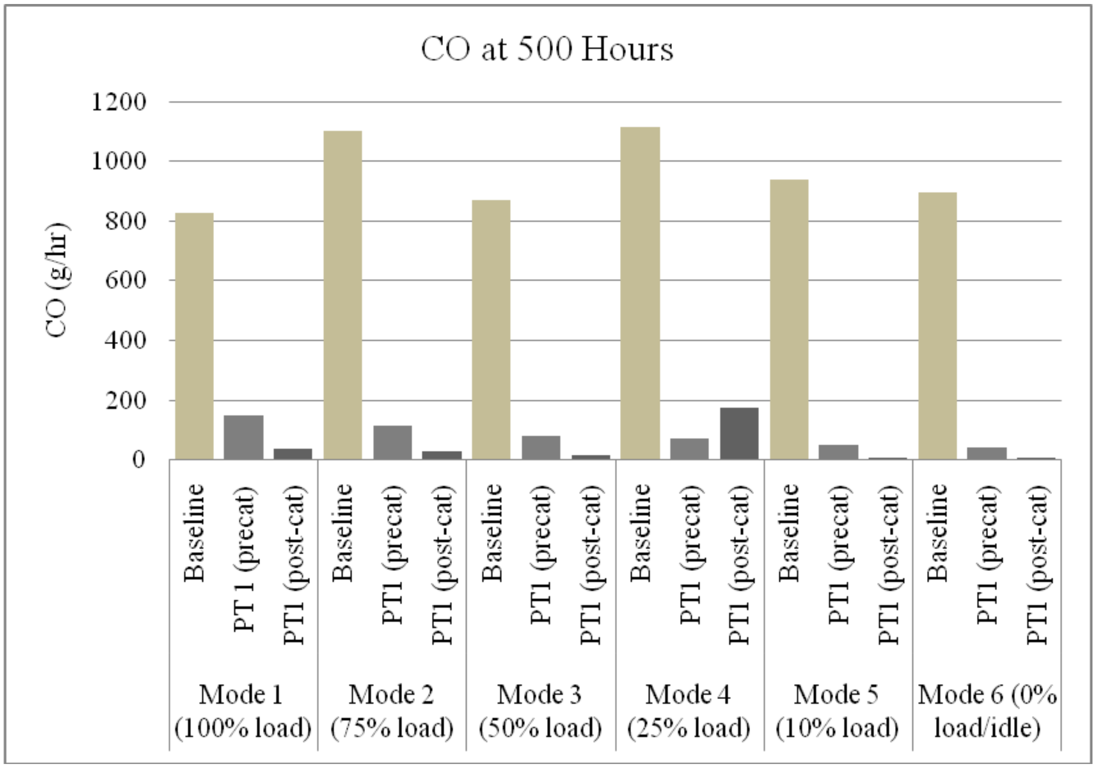


Figure 19: Modal CO Emission Data for the Prototype and Baseline Generators

Figure 20 shows the 500- hour six mode $HC+NO_x$ emission data for both the baseline and prototype generator units. The darker lower bars represent the HC contribution and the lighter upper bars represent the NO_x contribution. In contrast to the Phase 2 and Phase 3 CO limits, the $HC+NO_x$ allowable emission levels are relatively stringent and are decreased in the Phase 3 regulation (from 12.1 to 8.0 g/(kW-hr)). As such, the target levels for the prototype performance was to remain below the regulated limits[3] for Phase 2 given the expected NO_x increase associated with the stoichiometric AFR strategy while significantly reducing the CO emissions. As can be seen in the figure, the $HC+NO_X$ is highest for both the baseline and prototype at mode 1, and decreases monotonically with load. For all modes, both the pre and post catalyst prototype $HC+NO_X$ total is dominated by the NO_X contribution except with the mode 4 post catalyst data where the increased AFR variations affected the results, In fact the HC is essentially insignificant in the post cat data. At mode 4, it is interesting to note that the post cat NO_x was actually significantly lower than in the precatalyst data, while the HC was significantly higher. This suggests that the AFR was rich during the higher load portions and lean during the lower load portions of the load transients associated with the speed variations during the test. The lower NO_X at mode 4 explains the lower $HC+NO_x$ weighted value despite the less than ideal AFR control at mode 4. For the baseline unit, NO_X was the dominant contributor at modes 1 and 2, but HC was similar to NO_x at mode 3 and dominant at modes 4, 5 and 6. This is fully consistent with the effect of load and AFR on NO_x and HC production. The only data point where the prototype demonstrated higher $HC+NO_x$ emission than the baseline was the precatalyst data acquired at mode 2.

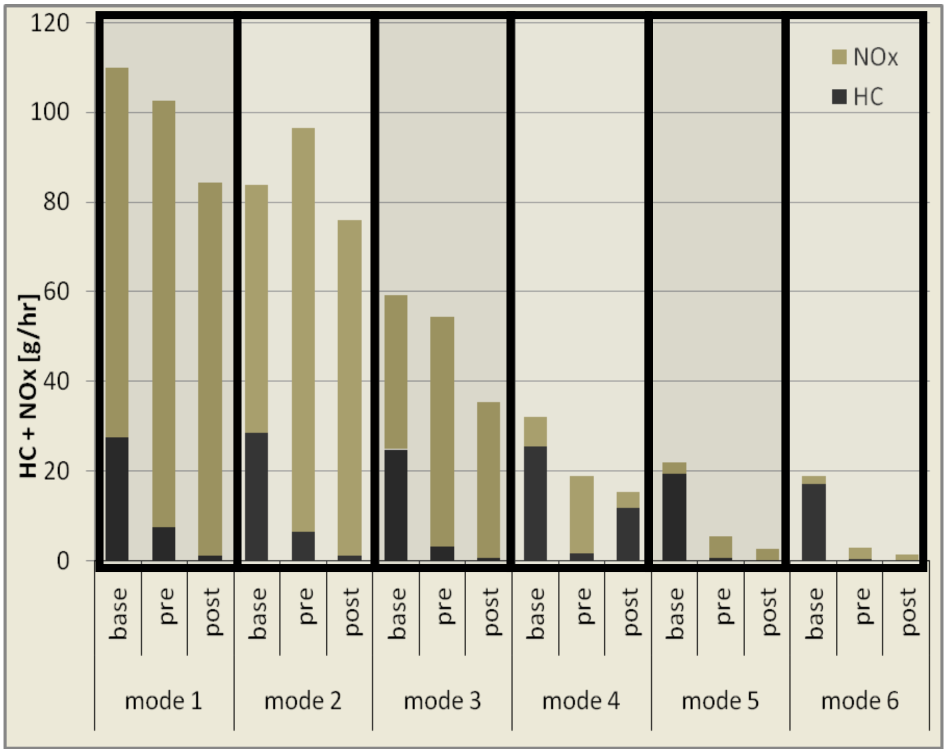


Figure 20: Modal HC+NO_x Emission Data for the Prototype and Baseline Generators

Discounting mode 4, the HC conversion efficiencies ranged from 80 to 99%. NO_x conversion was not as effective, ranging from 13 to 53%. This efficiency increased monotonically as load decreased. This is likely related to the effect of AFR excursions discussed in the mean weighted results section above, however it could also indicate a larger catalyst volume is required for effective NO_x reduction for this application, particularly since the lowest conversion efficiencies occurred at the highest loads.
The AFR has a predictable effect on the engine temperatures. The concerns in this program were with how the 14.6 AFR strategy would affect engine head and oil temperatures at maximum load, and how the AFR and the addition of a catalyst would affect muffler surface and exhaust temperatures. A discussion with the engine manufacturer was initiated to establish the maximum allowable head and oil temperatures prior the start of the durability program. The manufacturer recommended that these temperatures not exceed 270°C and 140°C for the cylinder head and oil, respectively. For this 500 hour testing and all previous testing, the prototype cylinder head and oil temperatures were substantially below these limits.

At low loads, temperatures are not a significant issue. At full load, the head temperature for the prototype was 220°C, which was an increase of 24^{o}C relative to the baseline. Compared to the *premodified* prototype tests reported at the beginning of this section, the cylinder head temperature was about 6^{o}C *cooler* at mode 1 during the 500 hour milestone test than at mode 1 during the zero hour test performed prior to any modifications. While it is somewhat unexpected for the stoichiometric strategy using the EMS to produce lower head temperatures on the same engine when using a carburetor producing a rich

AFR, several factors may explain this condition. Clearly, the previously noted degradation in the alternator through the 500 hour program caused some uncertainty in the engine load required to meet the measured electrical load, and the measured electrical load at mode 1 was about 0.25 kW lower at 500 hours compared to 150, so it is possible that the engine load at mode 1 500 hours was slightly lower than at zero hours. However, recall the premodified carbureted prototype had an AFR value (14.0) much closer to stoichiometric than the baseline unit did at mode 1 (13.1). That coupled with differences in the combustion behavior influenced by the intake and fuel delivery and ignition system modifications likely were just as, or possibly even more significant than the minor load uncertainty. Finally, it should be reiterated that the prototype cylinder head temperatures are far below the manufacturer's recommended limits.

The prototype engine-out exhaust gas temperatures operated between approximately 715 to 800°C, while the baseline range was 500 to 650^{o}C. The higher exhaust temperatures are consistent with the fueling strategies of the two units. The prototype engine out exhaust temperature was within the catalyst manufacturer's recommended optimum operating range of 600 – 900°C.

The OEM muffler model that was installed on the unmodified generators was not used on the prototype generator design because the extensive baffling in this muffler prevented the insertion of the catalytic converter. The engine manufacturer uses several muffler designs for OEM applications; the one selected for integration of the catalyst on the prototype generator came from the OEM suite. While the geometric configuration of the mufflers and the exhaust gas path flow with the two styles of mufflers can impact the muffler surface temperatures, the major factor for the increased muffler surface temperatures was the higher engine out exhaust temperatures as discussed above. At mode 1 the prototype muffler surface was approximately 45^{o}C higher than the baseline, which had a value of 434^{o}C. The higher muffler surface temperatures associated with prototype were mitigated by the muffler shroud which dramatically reduced the exposed surface temperature to 110°C at Mode 1 during the 500 hour milestone test.

POST_DURABILITY ANALYSES

Several analyses were performed after the durability program was complete to gain further insight on the prototype modifications and ultimately to have a certification level 6-mode emission test performed by an independent laboratory. This certification test was done following all EPA procedures using a dynamometer. Prior to the dynamometer test, the certification lab performed a modified 6-mode test using the generator configuration loaded with a resistive load bank. This generator configuration test was similar to the milestone emission tests performed during the durability program. The result and details of these independent emission tests are published in a separate report. This section presents a mechanical wear analysis and an investigation into the causes of the increased AFR variability observed at mode 4.

WEAR ANALYSIS

The wear analysis consisted of dimensional measurements of the key engine components and a qualitative visual assessment. This subsection is presented in two parts: first, the dimensional results are presented in tabular form and the measurements techniques are described, and second the dimensional results and visual inspections are discussed. As indicated in the *Durability Test Results* section, the prototype was run for approximately 25 hours to perform the pre-modified zero-hour emission testing and the EMS development. To accommodate post durability testing conducted by an independent certification laboratory and the post-durability calibration analysis, the prototype (PT1) was run for an estimated 60 hours after the conclusion of the durability program. Consequently, the prototype had accumulated approximately 85 hours more than the baseline unit at the time of the wear analysis.

Methods and Results

The dimensional results are shown in Table 11, which summarizes the piston, cylinder and crankshaft measurements and Table 12 which summarizes the valve train component measurements. The outer-diameter measurements were made with a Chicago Brand micrometer set with a vernier scale calibrated to the nearest 0.0001 in, and the inner-diameter measurements were made with a Mitutoyo bore gauge set using a dial indicator gauge with dial marks each 0.0001 in. The piston ring width was measured using a digital caliper, which had readout resolution of 0.0005 in.

The micrometer set was calibrated using gauge rods machined to one-inch increments. Repeated measurements of the gauge rod were made to assess the repeatability of the micrometer measurement process. Six measurements were made and analyzed. The six measurements were all within a range of 1.5 ten-thousandths of an inch, and had a sample standard deviation of 0.61 ten thousandths of an inch. The associated interval for 95% confidence is ± 1.56 and ± 0.64 ten thousandths for a single measurement and the mean (of 6 measurements), respectively. This interval can be completely attributed to the micrometer itself, and is caused by slight variations in orientation and variations in the clutch release of the rotating barrel.

The uncertainty of the actual part dimension measurements depended on the OD of the part. The repeatability of smaller parts such as the valve stems and lifters was similar to that experienced with the gauge rods; however the piston diameter measurements demonstrated larger precision error. These variations are primarily due to measurement-to-measurement variation in the micrometer orientation and location. Slight changes in the vertical or radial position lead to variations in the measured diameter since the piston skirt has slight taper and is not perfectly round. The 95% confidence intervals (accounting for both the part and instrument) of the mean values of these measurements were from ±0.8 to ±2.3 ten thousandths of an inch.

The bore gauges were calibrated (zeroed) using a fixed micrometer setting, so the reading on the dial indicator provided the difference between the micrometer setting and the measured inside diameter (ID). This calibration (zeroing) process leads to potential error, as it depends on finding the minimum measured distance between the micrometer surfaces and setting the dial zero position, however this error is believed to be less than 1.5 ten thousandths. To get the best relative bore comparison measurements, the bore gauge was zeroed once for the bore diameter measurements of both the prototype and baseline engines, so initial bore gauge setting errors would not cause any relative differences between measurements from engine-to-engine. Bore gauge measurements were generally repeatable to within the one ten-thousandth dial marker resolution, so no additional uncertainty information is provided.

Table 11: Piston, Cylinder and Crankshaft Measurements (All measurements in inches)

	Piston			Bore			Clearance		
	PT 1	PT 2	Base	PT 1	PT 2	Base	PT 1	PT 2	Base
Top	3.4601	3.4592	3.4608	3.4662	3.4659	3.4664	0.0061	0.0067	0.0055
Middle	3.4631	3.4627	3.4635	3.4667	3.4662	3.4670	0.0035	0.0035	0.0035
Bottom	3.4635	3.4624	3.4634	3.4668	3.4661	3.4671	0.0032	0.0037	0.0037
Reference				3.4660	3.4658	3.4661			
	30^o from gap			180^o from gap			330^o from gap		
Ring	PT 1	PT 2	Base	PT 1	PT 2	Base	PT 1	PT 2	Base
Width	0.1478		0.1421	0.1466		0.1422	0.1481		0.1418
	PT 1						Baseline		
Gap	0.018						0.022		
	Rod Big End			Journal			Clearance		
	PT 1	PT 2	Base	PT 1	PT 2	Base	PT 1	PT 2	Base
Thrust	1.4202	1.4191	1.4190	1.4165	1.4167	1.4164	0.0037	0.0024	0.0026
	Rod Small End			Piston Pin			Clearance		
	PT 1	PT 2	Base	PT 1	PT 2	Base	PT 1	PT 2	Base
Thrust	0.7889	0.7888	0.7887	0.7878	0.7878	0.7878	0.0011	0.0010	0.0009
	Piston Pin Bore			Piston Pin			Clearance		
	PT 1	PT 2	Base	PT 1	PT 2	Base	PT 1	PT 2	Base
Side 1	0.7881	0.7881	0.7882	0.7878	0.7878	0.7878	0.0003	0.0003	0.0004
Side 2	0.7881	0.7882	0.7882	0.7878	0.7878	0.7878	0.0003	0.0004	0.0004

Table 12: Valve Train Component Measurements (All measurements in inches)

	Intake			Exhaust		
	PT 1	PT 2	Base	PT 1	PT 2	Base
Valve Stem Diameter	0.2590	0.2590	0.2590	0.2577	0.2575	0.2575
Lifter Diameter	0.3535	0.3534	0.3537	0.3535	0.3434	0.3536

A calibration exercise similar to that used for the micrometer was used for the digital caliper. There was one difference in that the zero value can be tared when the caliper is closed. A one-inch gauge block was used to check the repeatability. After 15 repeated measurements, the values ranged from 0.9980 to 1.0000 and the standard deviation was 0.6 thousandths. Consequently, for a sample of six measurements the 95% confidence interval for the mean value was 0.57 thousandths. Similar to the discussion regarding the micrometer, this characterized the uncertainty of the micrometer alone. When measuring the ring widths, there was additional variation due to variations in orientation and location of the measurement. The largest 95% confidence interval for the mean of six measurements was 1.4 thousandth.

Discussion

The pistons were measured at 3 locations on the skirt. The bores were measured in four locations. Three of these were on diameters perpendicular to the piston pin axis, which is the anticipated wear surface, on three vertical positions. The highest measurement position was approximately 0.5 inch below the deck surface, which corresponded to the oil-ring position at top dead center (TDC). The lowest of the three measurements made on the wear surface was approximately 0.25 inches above the top compression ring location at bottom dead center (BDC), and the middle position was 1.5 inches below the deck. A fourth measurement was made low in the bore, below the oil ring location at BDC and parallel to the piston pin. This area should not have been subjected to any significant wear and in-fact had a surface feel of a newly-honed cylinder. This measurement would indicate the original bore diameter if the cylinder was initially perfectly round and straight. The baseline and prototype values for these measurements are within one ten-thousandth indicating the two engines effectively had identical initial bore diameters. The baseline bore diameters on the wear areas were 2 to 3 ten-thousandths larger than the prototype though. The only piston diameter measurements which had a difference in baseline and prototype values larger than the estimated measurement uncertainty was at the top of the skirt where the prototype piston was 0.7 thousandths of an inch smaller than the baseline. This indicates that the prototype experienced small, but measureable increased wear near the top of the piston as compared to the baseline. This would be expected given the increased temperatures encountered with the stoichiometric fuel strategy for the prototype; however as the temperature ranges stayed within the manufacturer's limits, the additional wear was very small and only amounted to 0.6 thousandths additional piston to wall clearance just below the ring wear surface at TDC. The clearances at the lower positions were the same at middle position and 0.5 thousandth less for the prototype at the bottom position.

The reduced wear for the prototype compared to the baseline at the bottom of the cylinder could possibly be attributed to less dissolution of the cylinder wall oil film for the prototype case. The excess fuel in the rich mixture present in the baseline engine could have dissolved some fraction of the oil film and caused increased wear in locations where temperature differences were not the dominant wear factor. The piston ring measurements support this as, on average, the ring width of the baseline was 5.5 thousandths narrower than the prototype, and the end gap was 3.5 thousandths greater for the baseline.

The connecting rod of the prototype ended its post durability testing with 1.1 thousandth additional crank-to-rod clearance than the baseline engine. The connecting rod bore diameter was measured along the rod thrust axis, as this was anticipated to experience the maximum wear. The crankshaft rod journal diameters were almost identical for the two engines, so the additional crank-to-rod clearance in the prototype could be entirely attributed to additional connecting rod wear in the prototype. The majority of the wear would be expected in the rod since the rods were manufactured from aluminum and the crank is cast iron. The additional wear in the prototype could partially be attributed to the additional run time it experienced prior to the wear analysis, but the majority was likely due to the higher oil temperatures which resulted from the stoichiometric fueling strategy. The appearance of the rod and crank wear surfaces showed some minor galling in the prototype that was not present on the baseline parts. The connecting rod to piston interface showed no substantial measured or visual differences between the two engines. The visual appearances of the two engine's internal components were also consistent with their respective fueling strategies. The prototype's combustion chamber surfaces on the cylinder head and piston have significantly less carbon accumulation; however there are more deposits on the prototype intake valve compared to the baseline. Any homogeneous charge combustion chamber with excess fuel will accumulate deposits such as those seen in the photographs of the baseline engine. Apparently however, the cooler baseline combustion temperatures resulted in intake valve temperatures that were not high enough to cause deposit accumulation. The higher prototype temperatures are apparent in the piston coloration. The ring land areas on the prototype are blackened. The annular area between the piston and cylinder are known to be quench areas in which combustion is extinguished. In the hotter prototype piston, the unburned fuel and oil film are baked onto the surface, whereas in the cooler baseline piston, no coking is present despite the presence of significantly more fuel in the charge mixture. Furthermore, the copper coloring below the rings indicates the prototype piston was hotter than the baseline.

In contrast to the intake valves, the baseline exhaust valve showed significantly higher carbon deposits than those on the prototype. Clearly, the exhaust valve temperatures would be hot enough for deposit formation in either case, but only the baseline fueling strategy had enough unburned fuel in the exhaust to actually accumulate.

The valve train component measurements did not indicate any significant differences between the baseline and prototype. The valve guide diameters were too small for the available bore gauge set, so the stem to guide wear measurements were limited to the stem alone. Typically, valve stem wear will be greatest at the top and bottom of the stem, so the difference between these measurements and the measurement made at the middle indicates valve stem wear. The lifters and lifter bores were essentially identical.

In summary, all the dimensional data and visual observations suggest that the prototype fuel control strategy did not significantly alter the wear of the engine relative to the baseline. The prototype demonstrated some increased wear at the top of the piston and at the connecting rod to crankshaft interface; however, the piston ring and cylinder wear was less on the prototype than on the baseline.

Baseline	Prototype

Figure 21: Photographs of pistons after program completion.

Baseline	Prototype

Figure 22: Photographs of cylinder heads after program completion.

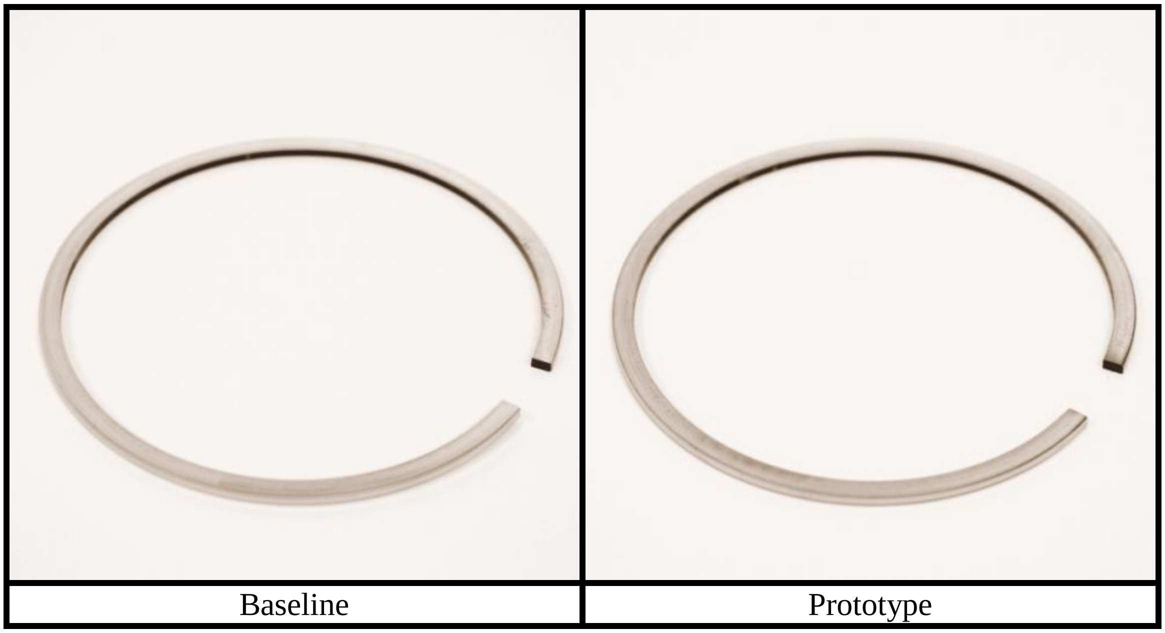


Figure 23: Photographs of piston rings after program completion.

Figure 24: Photographs of intake valves after program completion.

Figure 25: Photographs of exhaust valves after program completion.

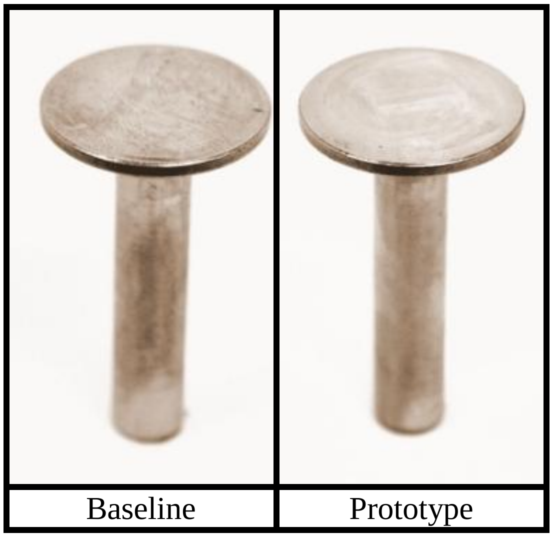


Figure 26: Photographs of intake valve lifters after program completion.

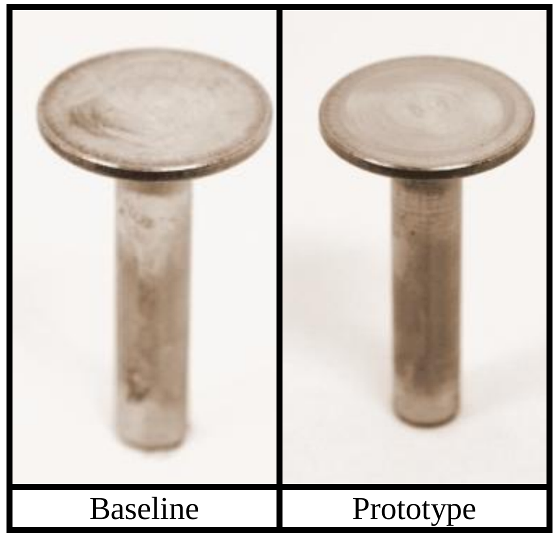


Figure 27: Photographs of exhaust valve lifters after program completion.

EMS CALIBRATION INVESTIGATION

The emission and engine performance of the prototype generator were presented in the *Durability Test Results* sections. The emission test results showed prototype program success by reducing CO emissions by more than 90% after implementing the stoichiometric fuel control strategy and exhaust aftertreatment with a three-way catalyst. As discussed in the results section, the stoichiometric 14.6 AFR was generally maintained with average AFR oscillations held to within ±0.2 throughout the durability program except for during mode 4 operation in the 250 and 500 hour emission tests. During these tests, the mode 4 loading point showed larger AFR oscillations than typical, and during the 500 hour test, caused corresponding variation in engine speed. While the overall performance at the 250 hour and 500 hour tests met program goals, results could be considerably better if the mode 4 performance could be made consistent with the other modes. Furthermore, uncovering the cause of the increased AFR variations was considered an important contribution to the technology demonstration. This section describes the effort to explain and improve the AFR control at mode 4.

Overview

Even under "steady state" conditions, the engine-speed governor on any throttle-controlled engine is constantly making small throttle-angle adjustments to accommodate small imbalances between applied load and engine output. These small throttle angle changes cause small variations in the AFR since neither carbureted nor electronically-controlled fuel systems respond instantaneously or perfectly proportionately to air-flow changes. One of the causes for this in electronic fuel control systems such as the one used in this program is that the calibration tables from which the fuel setpoint variables are obtained have finite resolution. These setpoint variables consist of all the quantities required to determine the fuel-injector pulse width as discussed in the *Prototype*

Development section. Recall these variables are nonlinear functions of engine speed and load, which is indicated by manifold pressure, and they are linearly interpolated from their corresponding calibration tables. If the calibration were perfectly performed, the tables had infinite resolution, all the sensors had infinite frequency response and all the acquisitions, calculations and actuations were performed instantly, the AFR would be constantly maintained at the desired value- in this case a stoichiometric value of 14.6. Since this is not the case, the AFR will deviate somewhat from stoichiometric as the speed and load vary. Consequently, the pulsewidth correction term based on the O_2 sensor feedback will constantly adjust itself to try to correct this deviation. As described in the Prototype Development section, the EMS uses a proportional-integral (P-I) control loop algorithm to calculate the correction. Under steady-state conditions, the integral term will insure that the correction will eventually be large enough to achieve the desired AFR value, however, it will also insure that the correction will overshoot this value at least slightly. The important implication of this control-loop functional review is that the AFR will constantly vary along with the throttle position even when a ‘steady’ load is applied to the generator set. The experience in this program was these variations as indicated by a wide-band AFR meter where approximately ±0.2 AFR at all operating points, except at mode 4.

Simultaneous observation of the wide-band AFR analyzer and the mechanical governor during the post-test investigation revealed that the engine AFR would become excessively lean upon throttle opening while operating at mode 4. It is apparent that as the engine and alternator wore through the durability program, the speed-MAP operating points changed from those originally encountered during calibration. These previously unencountered operating points were not thoroughly calibrated, and the consequence was the increased AFR variation which caused the degraded performance at mode 4 . The paragraphs that follow first explain the circumstances which led to the incomplete initial calibration, then provide a more detailed description of how the increased AFR variation developed, and finally illustrate the improvements of an expanded calibration that was performed post durability.

Calibration Limitations with the Engine Installed in the Generator

It was decided during the prototype development phase to calibrate the EMS system in the generator loaded with the resistive load bank rather than removing the engine and doing the calibration work on a dynamometer. In hindsight, this was not the best course of action for long term durability performance. The main issue is the limited speed-load operating points that were achievable in the generator configuration compared to virtually any speed-load combination that can be obtained using a dynamometer.

The calibration limitations when performed in the generator are primarily due to two factors: (1) the mechanical limitations of the governor and (2) the current limitations of the alternator. For a given governor setting, the engine speed naturally droops as the load bank resistance is increased on the alternator, giving a specific relationship between speed and load when testing the generator-load-bank combination. This means that at any particular engine speed, only one corresponding load (indicated by MAP) can be calibrated in steady state for the particular governor setting. This could be expanded to the extent of the generator adjustment physical limitations, provided the alternator current remain consistent. The current was an issue due to the speed-voltage characteristic of the alternator, the voltage regulator component, and the relationship between current, voltage and power when loading the generator. The load bank power absorption is given by

$$P_{absorbed} = V \cdot i = \frac{V^2}{R_{load}} = i^2 R_{load}$$

where V is the load bank voltage, i is the load bank current and R_{load} is the loadbank resistance. The last two equalities are obtained by application of Ohm's Law. The alternator voltage is proportional to the rotor speed, therefore current must be increased (by reducing the load-bank resistance) to achieve a given load as the rotational speed decreases. The alternator used in this program had a current limit of 25 amps. This current limit restricts the ability to load the unit at low engine speeds, which were not required to accurately establish the calibration parameter values at the initial generator calibration conditions. While it could be verified that the unit would stabilize normally during load transients when the unit was new, these transients could not be thoroughly optimized. These limitations were exacerbated in the mode 4 operations of the prototype 250 and 500 hour emission test when the engine encountered uncalibrated speed-load combinations as it wore and the loading characteristics of the alternator changed (see Appendix A) through the durability effort.

Therefore, in the 250 and 500 hour emission test when the engine would encounter these points under transient conditions, the calibration values for MAP Read Angle, Volumetric Efficiency and the P-I loop parameters were inevitably off and the O_2 feedback would have to compensate for these errors. If the errors are small and the feedback correction could keep up with the transient, the engine would run acceptably. If the error was too big for the feedback correction factor to overcome, the air-fuel ratio would deviate substantially around stoichiometric. The deviations at mode 4 could create momentary AFR values of 14.6 +/- 4.0, which would then be corrected and dampened by the feedback controls.

Consequence of the Limited Calibration Table

The performance of the prototype at mode 4 in the 250 and 500 hour durability test was related to the calibration of the EFI tables within the generator configuration. The following explains the operating assumption from observation and discusses the conditions where the mode 4 EFI values were outside of the calibrated portions of the EFI tables.

A transient increase in throttle opening angle naturally increases (leans) the AFR because the higher manifold pressure causes a larger percentage of delivered fuel to condense on the port walls. At the time of initial calibration, the leaning associated with this phenomenon was not significant enough to cause any noticeable instability. However, as the condition of the engine, governor and alternator changed over the 500 hour program, the speed and manifold pressures experienced while the generator system was producing mode 4 power had drifted from the original values during the initial calibration process. This means that the open-loop setpoint values used to calculate open-loop base pulse width as well as the P and I controller constants for the feedback correction term are being extracted from uncalibrated regions of their associated look-up tables. Recall from the *Prototype Development* section, that when using a closed loop fuel injection control, the final injector pulse width is comprised of an open-loop term and a closed loop correction term which is constantly adjusted by the P-I controller logic to drive the O_2 feedback signal toward stoichiometric. Apparently, beginning around the 250 hour state, the mode 4 calibration point produced leaning in addition to the natural amount caused by the increased MAP associated with throttle opening. This was verified by manually manipulating the throttle while running at mode 4 with the feedback control turned off. In fact while running in closed loop, the compounded affect seemed to have resulted in a severe enough increase in AFR (leaning) such that the engine output *decreased* with the throttle opening rather than increased. This is similar to the stumble sometimes experienced when the accelerator is depressed in a vehicle that is not properly tuned. Since the engine output decreased, the speed falls further, causing the governor to open the throttle even more. This speed decrease continues until the engine output equals (or exceeds) the load-bank's power demand, which can happen if the engine output increases or the demand decreases. As indicated above, the alternator voltage is proportional to speed. The load bank resistance at a given mode is constant, therefore it can be seen from the equation above that the power drops with the square of the voltage. As long as the engine continues to run, the loadbank power demand eventually will fall below the engine power output. The engine power, however, will simultaneously increase, since the closed loop injector pulse correction will continue to increase as long as the O_2 sensor indicates a lean condition. The combination of the decreasing demand and the rapidly increasing engine output will lead to a condition where the engine output exceeds demand and the engine will accelerate the shaft speed. This speed change can be rather rapid and cause the engine to over-speed past the nominal no-load position. It should be kept in mind that the throttle position maintained by the centrifugal governor is purely related to engine speed. Therefore, when the speed exceeds the no-load value, the throttle closes against the idle-stop regardless of the load balance between the generator and the load bank. Now the engine is at a high-speed condition with the throttle closed or nearly closed. In contrast to the low-speed, high-load points, which were restricted by maximum alternator current, high-speed, low-load operating points were generally reachable in steady state when calibrating in the generator configuration with a simple governor adjustment (at least to the physical limitation of the adjustment screw), so the open loop pulse-width is likely close to the value necessary for stoichiometric operation at this over-speed condition. This means the residual pulse-width correction value which had enriched the low-speed, high-load, erroneously-calibrated-lean open-loop setting causes over fueling at the current high-speed, low-load condition that was otherwise properly calibrated. The feedback correction begins adjustment to return the pulse-width correction factor toward a neutral value and thereby moving the rich AFR toward stoichiometric. However, the over-speed condition causes the voltage and consequently the load to increase above the value required to maintain this speed and MAP at steady state. Consequently, the engine decelerates while the pulse width correction leans out. If the engine speed falls back down to the leaned out under-speed that occurred at the beginning of this sequence, the process repeats itself and the engine speed fluctuates. Under these conditions emissions are can be high and efficiency is poor. Whether this fluctuation is indefinite or temporary depends on if the AFR deviations continue to be as severe as those which started the process. The inter-relationship between the governor, the engine controller and the engine is relatively complex, so the phasing of the AFR excursions with governor position tend to not be highly repetitive. Consequently, the fluctuations can manifest and vanish spontaneously if the conditions support this. Such fluctuation existed to some extent at both the 250 and 500 hour mode 4 tests, however it was only severe enough to markedly affect results at 500 hours. During the 500 hour tests, the speed and AFR were normal during the pre-catalyst portion of the test, but a speed fluctuation condition persisted for approximately 30 seconds during the post-catalyst portion and caused a correspondingly high post-catalyst CO emission result.

Performance Improvements Following Post Durability Calibration

After the completion of the durability test, the EMS was recalibrated and the prototype performance was investigated by an independent certification laboratory. That investigation consisted of emission testing in both the generator configuration (loaded with the resistive load bank) and engine certification testing with the engine removed from the generator and loaded with a dynamometer. While the recalibration was still performed in the generator configuration, a much larger operating range was calibrated by making the largest possible governor adjustments and running the current to the breaker trip limit. With this calibration, mode 4 AFR operation was substantially improved. These improvements at mode 4 are evident in Figure 28, where the variation in base pulse width was substantially reduced in the post durability data. In order to verify that the new calibration would have been effective throughout the engine's life and was not just a calibration adjustment specific to engine wear, a brand new engine was installed in the generator and run with the new calibration. AFR and engine speed stability were confirmed with this new engine, indicating this calibration would work with an engine from initial break-in to beyond rated service life. Figure 28 shows that once the engine was calibrated on a dynamometer, the error range was comparable to those of all the "normal" ranges in other modes and also prior to midlife service hour accumulation.

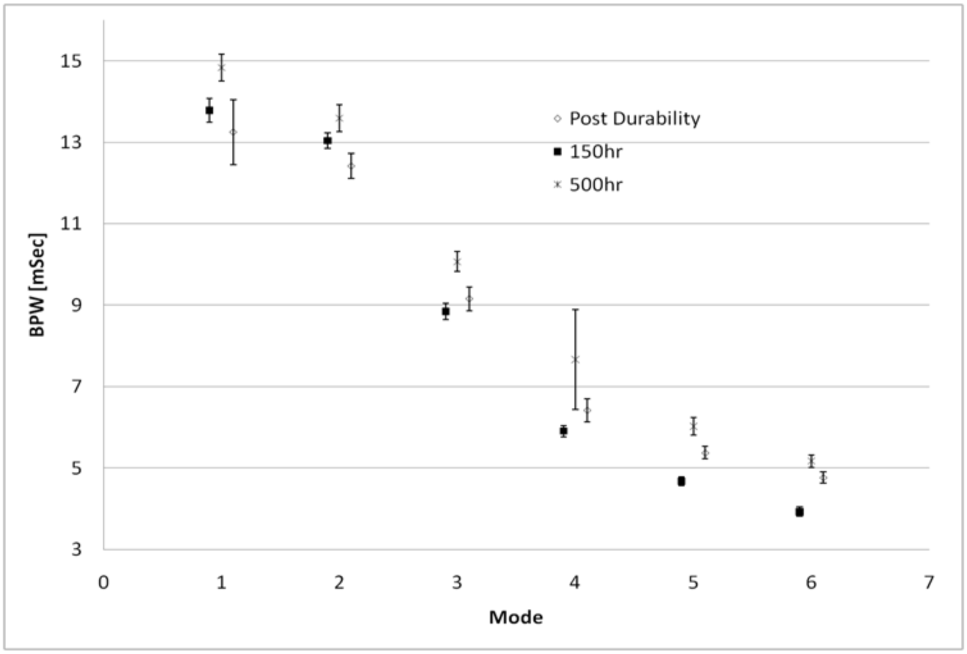


Figure 28: Average and variation of base pulse width through durability as a function of mode. Note 150 hours and post durability data offset respectively to the left and right of the mode number to enhance clarity of variation lines.

ADDITIONAL PROTOTYPES BUILT FOR CPSC STAFF

CPSC contracted for the construction and delivery of two additional prototype units, with the same fuel control strategy and catalyst as the durability-tested prototype. Both units were designated for testing, under an agreement between CPSC and the National Institute for Standards and Technology (NIST), in a series of tests while operating in the garage attached to NIST's double-wide manufactured test house in scenarios typical of those that cause consumer fatalities. This house is a facility designed for conducting residential indoor air quality (IAQ) studies and the results provide empirical data on the CO generation and infiltration into the house. CPSC staff will perform health effects analyses on these test results to assess the efficacy of the prototype design in reducing the CO poisoning hazard.

The first of these two prototypes was physically identical to that of the durability-tested prototype, using the same model generator, including the engine, as well as the EMS and its associated sensors and components. The six-mode generator emission test procedure described previously was performed on it in its as-purchased, unmodified configuration, which NIST referred to as unmod Gen X, after NIST conducted an initial series of tests with it. It was then modified into the prototype configuration, calibrated, and emission tested again. In this configuration, NIST referred to it as mod Gen X. Mod Gen X was then shipped back to NIST for performing a comparative series of tests in the prototype configuration.

The second unit, referred to as SO1, was constructed to address CPSC's concern that the prototype engine's CO emission rate may increase when operated in a confined space, in which the engine consumes the confined space's oxygen at a rate faster than the air exchange through it can sustain. There was uncertainty about the minimum oxygen level in the intake air necessary to maintain adequate combustion and, correspondingly, maintain the target CO emission rate. Thus, a task order was added for the development and implementation of an algorithm that would be programmed into the ECU on this second prototype generator for detecting confined space operation and shutting off the fuel injection. CPSC staff specifically directed that the algorithm not rely on any additional sensors beyond those already integral to the existing EMS so as to serve as a supplementary approach to further reducing the risk of CO poisoning associated with the prototype generator without adding any additional component cost. CPSC also specified that the algorithm have the ability to be disabled for testing and evaluation purposes.

While it was preferred to use the same model generator for SO1 as that of the baseline, durability-tested prototype, and Gen X, that model was no longer available by the time this task order was added. The OEM generator used for SO1 used the same engine but had a different alternator with an advertised continuous output rating of 7 kW. The ECU that was previously used on the durability-tested prototype and mod Gen X was no longer supported so an upgraded version provided by the same manufacturer was used. The recent model ECU offered several improved features over the previous model. One improvement is that it used an external MAP sensor that was placed directly at the intake manifold, minimizing the tube loss and acoustic delays discussed previously that were associated with the MAP sensor integral to the previous model ECU. This close placement also reduced the likelihood of gas condensing in the tube or being trapped in the transducer cavity and distorting the MAP signal, lending to more accurate fueling parameter calculations.

In addition to the external MAP sensor, the upgraded ECU has a feature to program the lines in the calibration look-up tables to cover the nominal range of MAP values expected during engine operation in the generator application with higher resolution than the hard-coded tables of the previous ECU. The upgraded ECU also included a more robust block learn memory (BLM) feature which compensates for long-term variations in engine operating conditions, thus removing some of the control force requirements from the closed-loop controller. It also included programming to prevent closed loop operation until the oil temperature rose above approximately 60 $^{\circ}$C. Additionally, this model ECU used a heated switching oxygen sensor, which is more durable and precise than the unheated switching sensor employed by the previous model ECU. Aside from these differences, the other hardware used in the construction of the SO1 prototype was identical to those components used on the durability-tested prototype and mod Gen X.

After SO1 was modified into the prototype configuration, it was calibrated and emission tested. This unit was then shipped to NIST for testing in the same series of tests as unmod Gen X and mod Gen X. The results from testing unmod Gen X, mod Gen X, and SO1 at NIST are documented in a pending report from NIST to CPSC. The tests reported in this NIST report that were performed with SO1 were conducted with the initial algorithm programmed into the ECU but switched to the disabled mode so that SO1 would operate until the test operator manually shut the engine off. A complete description of the development, implementation, testing of the initial algorithm, and some subsequent work on an alternative algorithm strategy will be provided in a separate, future UA report.

The generator emission test results for unmod Gen X, mod Gen X, and SO1 are provided in Appendix C.

CONCLUSIONS

The objective was to reduce the engine's CO emissions to the lowest possible level without negatively impacting power output, engine durability, maintainability, fuel economy, and risk of fire and burn, while not increasing HC+NOx emissions at end of useful life. CPSC staff specified an initial target CO emission rate at or below 30 g/kW-hr.

- The maximum combined weighted CO value throughout the durability program for the prototype generator was 26.4 g/kW-hr without catalyst and 17.51 g/kW-hr with the catalyst. The prototype generator pre catalyst data show CO reductions relative to the baseline ranging from 90 to 94.5%. With the prototype post-catalyst emissions, this CO reduction improves further to 93.3 to 99.4%.
- The maximum power output of the prototype unit was comparable to that of the original carburetor generator unit. These generators delivered a maximum of 5.5 kW of electrical power output. There was some uncertainty in the exact engine output for a given electrical load due to degradation of alternator components and the associated effect on alternator efficiencies in both the baseline and prototype units, however rated power capability of the prototype engine was confirmed at the conclusion of the program in certification testing performed by an independent laboratory. (Those results were documented in a separate report which was cited in footnote 10.)
- The prototype and unmodified generators sustained the 500 hour durability test cycle. Based on visual observations and component measurements, the wear between the two units was comparable. At the end of the durability program, the prototype demonstrated an approximate 32% reduction of HC+NOx emission rate as compared to the unmodified unit.
- The fuel injection and AFR strategy associated with the prototype generator improves the fuel consumption from the unmodified carburetor engine by approximately 15 to 28%.
- Muffler surface temperatures of the prototype were a maximum of 90 degrees Celsius higher when compared to the OEM design. The prototype's muffler shroud temperatures were approximately 165 deg Celsius or less over the range of deliverable power. There was no shrouding with the unmodified generator. The maximum tailpipe exhaust gas temperature for the prototype was approximately 30 degrees Celsius hotter than the baseline.

- Routine maintenance actions that were taken throughout the durability program with the prototype and unmodified generator units were comparable. The majority of repair actions associated with the generators involved non-engine components, such as the voltage regulator and its connectors.
- The integrity of the EMS system was maintained throughout the durability test program. The adapted technology of the EMS controller with associated sensors, fuel regulation, and catalyst demonstrated longevity by performing as designed throughout the durability cyclic hour accumulation and maintaining program target emission results in the end of life testing.

APPENDICES

Appendix A: Analysis of Alternator Connection Failures.

Appendix B: Generator Durability Emission Test Results

Appendix C: Generator 6-Mode Data Tables for Unmod Gen X, Mod Gen X, and SO1

APPENDIX A

ANALYSIS OF ALTERNATOR ELECTRICAL CONNECTION FAILURES

Early in the course of the durability testing, degradation in the alternator wiring was found to affect the test power output level. This was discovered during some intermediate verification tests on PT1 performed between the zero and 150 hour 6 mode tests. The load in our tests was controlled using a resistive load bank. With the load bank connected to the generator, the total load on the alternator consists of the external load applied by the load bank and the internal load created from the resistance of the alternator windings and interconnection wiring. The alternator and its associated loads can be represented as shown in Figure A-1. The load bank, represented by R_2, in fact contains a number of resistors particularly selected such that they can be switched in and out to create loads in 0.125 [W] increments when the alternator is operating at 240 [V]. The load bank switch settings were verified using a Fluke Model 39 power meter during initial calibration tests. Once having established these, the loads for all tests up until and including the zero hour tests were set using the calibrated switch settings without the load meter.

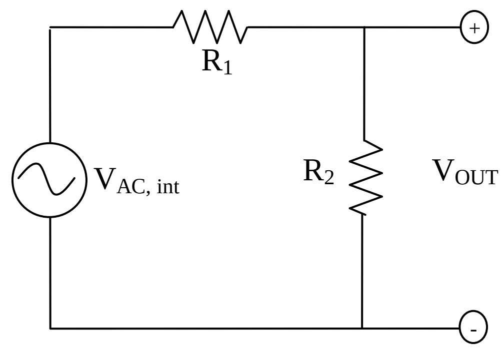


Figure A-1: Circuit model for illustrating affect of resistance on alternator load and voltage

The loads applied in the intermediate tests performed after zero hour however were verified with the power meter, which revealed that the measured power output was considerably less than original values corresponding to the associated switch settings. The load bank resistance values were checked and found to be essentially unchanged, therefore attention was shifted to the alternator.

Figure A-2 shows the condition of the primary power connector between the stator winding on the synchronous generator and the electronics box containing the voltage regulator board discovered during this inspection. The connector and several inches of wire had been melted and burned, with the connector as the center point of the damage. Two hot legs and two neutral legs are terminated through this connection. Post-mortem analysis of the connector indicates that the failed pins were not adequately mated. Figure A-3(a) illustrates a single pin connection that is properly mated. Figure A-3(b) illustrates an improperly mated connection. In Figure A-3(a), the cross sectional area of the connection is large compared to that in Figure A-3(b). Thus, the current density and the resistance in the connection are much lower than that of the connection in Figure A-3(b). Consequently for a given power level, the resistive losses in the connection are significantly higher in magnitude and more concentrated spatially in the improper connection. Thus, more heating occurs with an associated rise in conductor temperature, which then further increases resistance. This results in a thermal runaway that eventually leads to the failure seen in Figure A-2. Eventually, similar failures arose in both prototypes as well as the baseline unit.

Given our mode 1 load of 5.5 [kW] is above the 5.0 [kW] continuous rating of the generator, it is apparent that the electronics are not capable of withstanding extended periods of operation as little as 10% over the rated output. This seems like a significant design flaw given that the testing at UA shows the engine and alternator are obviously capable of maintaining such loads. Good design practice would dictate component selection with at least a factor of safety of 2 or more over the *capability* of the unit (as opposed to its rating) given the consequences of failure could easily lead to a fire. When repaired with hard connections, i.e. wire nuts, the units functioned properly for extended periods of time with no pursuant similar failures verifying the conclusion that the wiring and connectors were inadequate for this application.

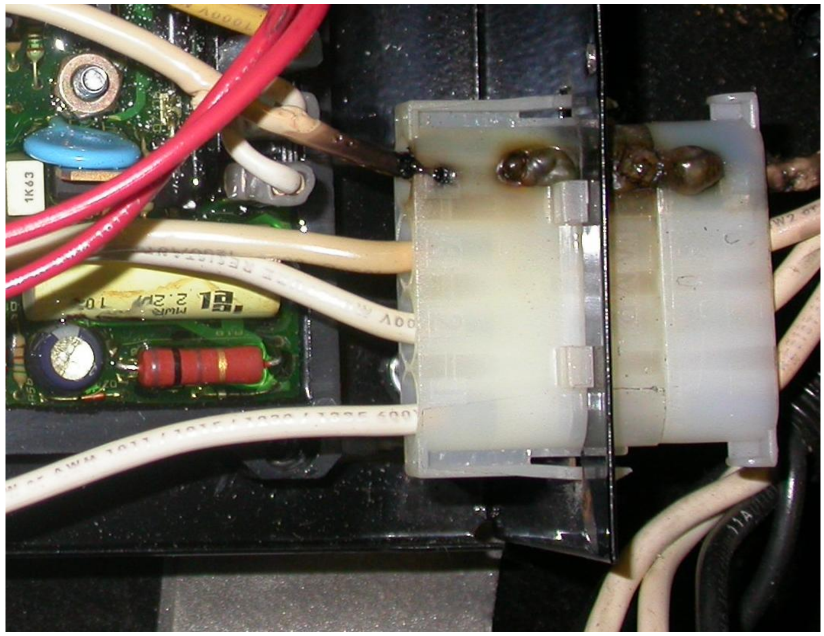


Figure A-2: Melted primary power connector between alternator and voltage regulator.

In the failure process, the net impedance of the generator is increased, and the voltage and power output of the generator will be affected. The impact on the output is further complicated since the failure electrically imbalances the generator, which has much more significant consequences as the power level is increased.

To illustrate the impact of resistance variation, consider the system presented in Figure A-1. Assume $R_2 = 12\ \Omega$ and $R_1 = 1\ \Omega$ represent the total external load and internal resistance on the synchronous generator. These values are reasonable for the voltage and power levels under consideration. Further, consider that the source voltage ($V_{AC,\ int}$) magnitude is 260 V. This too is reasonable for a 240 V alternator considering internal impedance. Using Ohm's law and the relationship for electrical power, equations 1 and 2

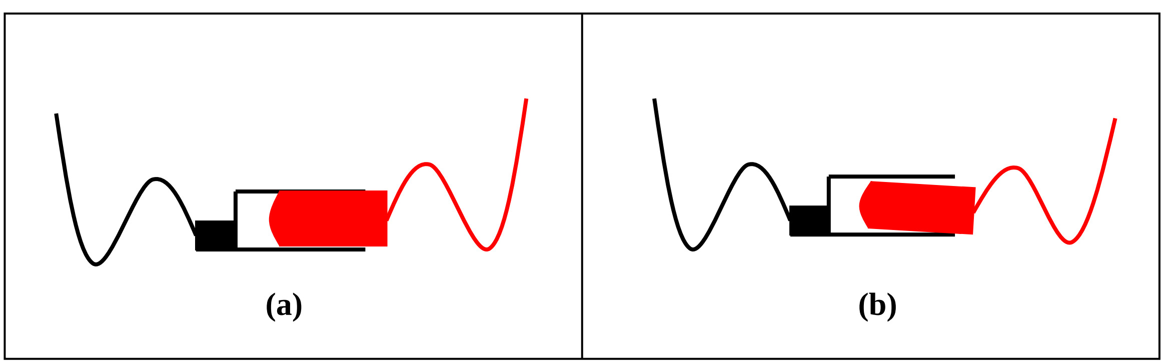


Figure A-3: Illustration of properly (a) and improperly (b) mated connectors.

respectively, the effect of a change on external resistance, R_1, can be found on the external voltage and power output of the alternator system

$$V_R = i\ R \qquad \textbf{Eqn. 1}$$

$$P = V\ i \qquad \textbf{Eqn. 2}$$

Figure A-4 displays the percent of nominal power output to R_2 and the output voltage across R_2 versus the percentage increase in R_1 on the left and right axes respectively. This increase in R_1 is intended to represent the potential effect of the connector degradation. The graph shows that doubling the internal resistance reduces the available power almost 15% and reduces the output voltage from 240 [V] to just over 220. This voltage reduction is consistent with what was measured at the alternator output when the unit was tested in the verification tests prior to repair of the wiring.

Overall, the connector failure explains output voltage and power variations due to the variation in internal impedance. The impact of the failure on the control mechanism and the resulting effects on output would require much more detailed data on the generator and control system. In the general sense, though, it is clear that correcting the connection issues is the solution to the problem.

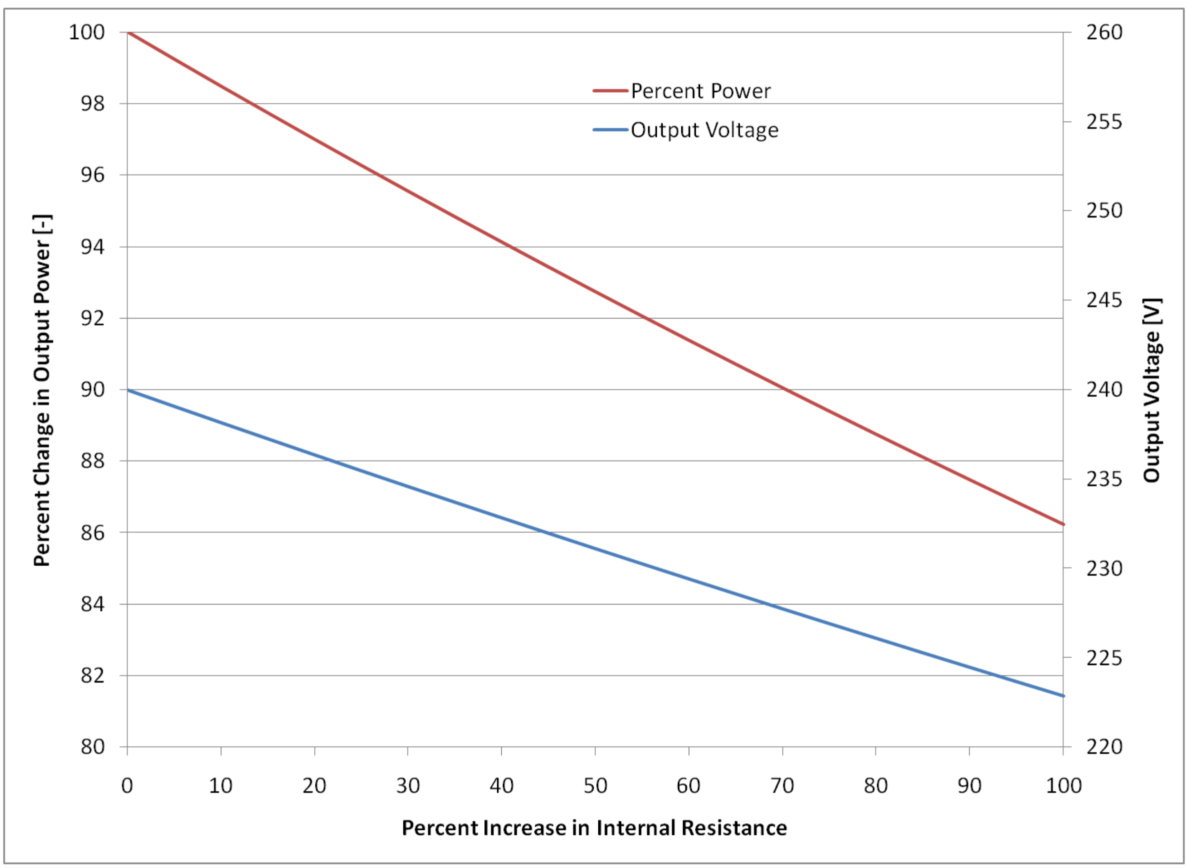


Figure A-4: Percent change in output power and output voltage as a function in percent increase in internal resistance.

APPENDIX B

GENERATOR DURABILITY EMISSION TEST RESULTS

At the zero, 150, 250, and 500 hour of the engine durability test, generator six mode emission tests were performed on the prototype and baseline generators. The durability hour accumulation load profile followed a full to no load cycle, which was meant to replicate the industry rated speed test cycle for engine applications in products like portable generators. The applied load to the generators during durability service accumulation was based on predetermined load bank resistance settings, which were automatically cycled. This allowed the service accumulation cycles to occur without personnel adjusting the load bank setting. The generator six mode emission tests followed this cyclic load profile. More details on the emission test can be found in the *Test Procedures* section. This appendix tables the measured modal generator emission and engine parameters. Discussions on these results can be found in the *Durability Test Results* Section.

This appendix presents the zero, 150, 250, and 500 engine hour durability emission test results for both the prototype and baseline generators.

<u>Prototype and Baseline Generator at Zero Hour Engine Emission Test</u>

Baseline Generator at 0 Engine Hours

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	12.8	7.6	202.8	108.0	760.0	578.0	441.0	2.4	20.5	974.6	56.2	5.1	282.6	4.5	9.6
2	12.4	6.2	194.8	104.2	740.0	549.0	420.0	2.3	20.6	1147.4	25.2				
3	12.5	4.1	180.0	96.6	717.0	495.0	379.0	2.0	19.4	938.6	20.7				
4	11.1	2.1	154.4	86.4	653.0	398.0	313.0	1.5	18.5	1212.7	3.3				
5	10.9	0.8	142.9	81.3	637.0	356.0	286.0	1.3	17.7	1067.4	2.0				
6	10.8	0.4	136.2	78.9	629.0	332.0	269.0	1.2	19.1	1031.0	1.6				

Prototype Generator at 0 Engine Hours

1. Precatalyst / Premuffler Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	225	117	700	587	436	88	1.9	6.6	102.2	100.9	0.7	19.6	10.9	11.6
2	14.6	6.2	217	113	694	568	421	84	1.8	4.7	87.1	78.0				
3	14.6	4.1	201	105	672	518	389	75	1.5	3.0	88.2	45.0				
4	14.6	2.1	181	96	655	439	339	66	1.1	1.1	59.1	11.1				
5	14.6	0.8	170	91	651	396	305	61	0.9	0.5	45.0	5.0				
6	14.7	0.4	164	89	655	375	290	60	0.8	0.2	36.1	3.0				

2. Postcatalyst Emissions Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	226	117	698	597	440	89	1.9	1.1	13.5	43.1	0.1	2.4	4.6	4.7
2	14.7	6.2	217	113	690	578	425	85	1.8	0.9	9.4	47.0				
3	14.6	4.1	201	105	670	532	394	76	1.5	0.7	11.4	11.3				
4	14.5	2.1	181	96	652	455	345	67	1.1	0.3	8.5	2.3				
5	14.6	0.8	170	91	648	416	315	62	0.9	0.1	3.1	1.7				
6	14.6	0.4	163	88	652	394	299	60	0.9	0.0	2.1	1.4				

Prototype and Baseline Generator at 150 Hour Engine Emission Test

Baseline Generator at 150 Engine Hours

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	12.4	7.6	210	113	739	589	412	2.5	24.8	1337.1	38.5	5.9	318.2	4.8	10.7
2	12.4	6.2	201	108	739	574	404	2.4	24.1	1218.6	39.6				
3	12.1	4.1	180	96	696	499	354	1.9	21.3	1090.6	19.1				
4	11.1	2.1	155	86	641	414	303	1.6	22.2	1296.1	4.2				
5	10.7	0.8	143	80	620	372	279	1.4	21.5	1269.5	2.2				
6	10.5	0.4	136	78	607	346	265	1.2	21.0	1153.3	1.6				

Prototype Generator at 150 Engine Hours

1. Precatalyst / Premuffler Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.5	7.6	240	124	716	605	482	105	2.1	9.5	103.4	149.0	1.0	17.4	15.6	16.6
2	14.6	6.2	228	121	712	584	462	98	2.0	8.1	83.1	127.6				
3	14.5	4.1	203	107	689	511	409	82	1.5	3.4	70.3	54.8				
4	14.5	2.1	180	97	669	417	344	70	1.2	1.0	50.2	14.0				
5	14.4	0.8	168	91	662	375	311	65	0.9	0.5	44.4	4.9				
6	14.4	0.4	161	90	661	348	293	62	0.8	0.2	36.1	2.7				

2. Postcatalyst Emissions Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.5	7.6	241	126	714	614	487	106	2.0	1.9	13.5	97.0	0.2	1.8	11.3	11.5
2	14.6	6.2	230	121	710	592	465	99	2.0	1.7	10.1	104.7				
3	14.5	4.1	203	107	685	523	415	83	1.5	1.0	7.5	37.5				
4	14.5	2.1	180	97	667	436	355	71	1.0	0.2	3.2	7.9				
5	14.4	0.8	168	91	659	395	323	66	0.9	0.1	3.7	0.6				
6	14.4	0.4	161	89	659	367	304	63	0.8	0.0	2.3	0.6				

Prototype and Baseline Generator at 250 Hour Engine Emission Test

Baseline Generator at 250 Engine Hours

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	13.4	7.6	196.6	96	665	644	422	2.4	22.3	645.9	80.0	5.7	248.9	7.7	13.3
2	13.4	6.2	187.4	93	651	625	412	2.3	20.8	651.2	71.9				
3	12.4	4.1	168.1	85	585	538	355	1.8	21.0	881.3	21.1				
4	11.2	2.1	146.2	78	521	445	292	1.5	22.4	1207.5	4.5				
5	10.9	0.8	137.3	74	502	411	264	1.4	21.3	1203.9	2.5				
6	10.5	0.4	129.9	72	480	381	242	1.3	22.4	1206.6	1.8				

Prototype Generator at 250 Engine Hours

1. Precatalyst / Premuffler Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.5	7.6	230	115	725	624	507	158	2.2	8.6	126.6	104.4	1.0	23.8	13.0	14.0
2	14.5	6.2	223	114	733	606	494	129	2.1	8.0	110.8	95.7				
3	14.5	4.1	204	105	713	533	443	126	1.6	3.4	79.2	59.9				
4	14.3	2.1	183	97	693	447	387	105	1.1	1.7	95.1	10.3				
5	14.5	0.8	173	91	686	407	353	94	1.0	0.7	58.5	5.2				
6	14.5	0.4	168	90	686	382	332	93	0.8	0.1	37.4	3.0				

2. Postcatalyst Emissions Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	231	116	724	632	511	165	2.2	1.5	22.9	91.6	0.3	8.1	8.5	8.8
2	14.6	6.2	224	114	731	613	497	146	2.1	1.4	20.6	82.1				
3	14.6	4.1	204	104	708	546	448	125	1.6	0.7	10.7	24.1				
4	14.3	2.1	182	97	691	466	397	106	1.1	2.0	67.9	1.7				
5	14.6	0.8	173	92	683	435	372	100	1.1	0.2	13.6	1.6				
6	14.6	0.4	168	90	684	400	342	95	0.9	0.0	3.2	1.6				

Prototype and Baseline Generator at 500 Hour Engine Emission Test

Baseline Generator at 500 Engine Hours

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	13.1	7.6	196	101	647	631	434	2.4	27.3	826.1	82.4	6.6	259.5	8.0	14.6
2	12.4	6.2	183	96	612	589	403	2.3	28.4	1101.3	55.2				
3	12.4	4.1	166	87	575	527	362	1.9	24.7	870.5	34.4				
4	11.4	2.1	142	76	521	441	302	1.6	25.3	1113.0	6.7				
5	11.4	0.8	136	72	513	414	285	1.3	19.2	937.4	2.6				
6	11.2	0.4	128	69	496	384	266	1.2	17.0	896.4	1.9				

Prototype Generator at 500 Engine Hours

1. Precatalyst / Premuffler Emission Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.5	7.6	220	117	799	664	479	110	2.1	7.2	148.1	95.3	0.9	22.8	12.3	13.2
2	14.6	6.2	211	114	789	637	471	100	2.0	6.3	116.4	90.0				
3	14.5	4.1	190	100	766	634	424	79	1.5	3.1	79.4	51.1				
4	14.5	2.1	168	90	741	559	373	65	1.2	1.6	72.7	17.1				
5	14.5	0.8	163	86	748	566	344	57	1.0	0.5	51.4	4.9				
6	14.5	0.4	156	82	758	580	329	53	0.9	0.2	40.5	2.8				

2. Postcatalyst Emissions Test

Engine Modal Data										Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Muffler Shroud Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	220	117	797	669	484	110	2.2	1.1	36.6	83.1	1.0	17.5	8.9	9.9
2	14.6	6.2	212	113	788	646	479	101	2.1	0.9	28.8	75.0				
3	14.5	4.1	191	101	765	645	430	80	1.6	0.6	15.6	34.7				
4	14.4	2.1	164	88	714	592	385	66	1.3	11.6	175.0	3.5				
5	14.5	0.8	162	86	747	590	352	58	1.1	0.1	7.2	2.3				
6	14.5	0.4	156	82	759	613	338	54	0.9	0.0	5.9	1.3				

APPENDIX C:

GENERATOR 6-MODE EMISSION TEST RESULTS FOR UNMOD GEN X (PERFORMED AFTER APPROXIMATELY 60 HOURS OF PRIOR OPERATION AT NIST)

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	12.6	7.6	191	101	740.55	545.95	416.25	2.27	21.49	1000.6	41.94	4.8	225.8	5.236	10.07
2	13.0	6.2	182	97	734.89	519.42	399.33	2.00	18.90	671.16	42.73				
3	12.8	4.1	169	90	714.10	476.43	370.29	1.74	17.36	697.54	23.09				
4	11.1	2.1	142	80	649.49	376.51	297.94	1.41	18.66	1075.6	2.69				
5	10.8	0.8	131	77	630.35	337.16	272.18	1.15	18.17	971.04	1.53				
6	10.9	0.4	128	75	625.06	329.25	265.95	1.12	17.55	911.78	1.49				

GENERATOR 6-MODE EMISSION TEST RESULTS FOR MOD GEN X (PERFORMED AFTER APPROXIMATELY 70 HOURS OF PRIOR OPERATION IN UNMOD GEN X CONFIGURATION)

1. Pre catalyst

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	227	113	766	590	**	1.98	3.90	73.71	58.87	0.43	15.6	6.72	7.15
2	14.6	6.2	221	111	763	572	**	1.88	3.07	72.25	46.94				
3	14.7	4.1	205	103	748	524	**	1.65	1.60	62.19	27.98				
4	14.6	2.1	185	95	729	434	**	1.21	0.55	50.02	8.25				
5	14.6	0.8	174	89	721	392	**	1.03	0.45	48.04	3.98				
6	14.7	0.4	169	86	725	371	**	0.96	0.27	43.86	2.74				

2. Post catalyst

Engine Modal Data									Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Muffler Surface Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	227	114	761	595	**	1.98	0.57	6.99	51.08	0.07	1.36	5.65	5.71
2	14.6	6.2	221	111	760	583	**	1.94	0.50	6.95	41.78				
3	14.6	4.1	205	103	746	538	**	1.62	0.30	5.36	22.82				
4	14.7	2.1	186	94	727	452	**	1.22	0.04	4.001	5.93				
5	14.6	0.8	174	88	718	408	**	1.03	0.00	4.54	1.79				
6	14.7	0.4	168	85	721	387	**	0.95	0.00	2.38	1.82				

Note: ** Not measured.

GENERATOR 6-MODE EMISSION TEST RESULTS FOR GEN SO1 (PERFORMED AFTER APPROXIMATELY 175 HOURS OF PRIOR OPERATION FOR ALGORITHM DEVELOPMENT TESTING)

1. Pre catalyst

Engine Modal Data								Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.6	7.6	214	105	636	579	2.06	14.91	94.02	100.2	1.79	18.3	13.04	14.83
2	14.6	6.2	207	107	631	560	1.96	13.60	103.45	93.19				
3	14.6	4.1	186	102	602	491	1.50	6.86	68.12	63.36				
4	14.6	2.1	165	92	580	410	1.14	2.31	50.70	11.08				
5	14.6	0.8	155	84	577	375	0.90	1.01	47.99	4.44				
6	14.6	0.4	148	80	578	354	0.82	0.82	49.36	2.83				

2. Post catalyst

Engine Modal Data								Emission rate unweighted (g/hr)			Combined Weighted Emission Rates (g/kW-hr)			
Mode	AFR	Est Eng Power (kW)	Cyl. Head Temp °C	Oil Temp °C	Exhaust Gas In Temp °C	Exhaust Gas Out Temp °C	Fuel Rate kg/hr	HC	CO	NOx	HC	CO	NOx	HC + NOx
1	14.7	7.6	215	108	633	586	2.04	2.51	11.34	95.19	0.43	6.37	4.19	4.62
2	14.6	6.2	207	106	627	571	1.96	2.65	21.89	22.45				
3	14.5	4.1	184	98	595	497	1.49	2.10	34.81	7.74				
4	14.5	2.1	164	89	573	415	1.11	0.84	25.70	1.75				
5	14.6	0.8	154	83	573	389	1.00	0.27	10.22	1.96				
6	14.6	0.4	149	79	574	374	0.85	0.15	8.59	0.47				

TAB D

Engines

- Research
  - Combustion
  - Emissions
  - Heat Rejection
  - Friction
  - Analysis
- Development
  - Testing
  - Durability
  - Mapping
  - Emissions

Emissions

- Research
- Development
  - Deterioration Factors
- Certification
- Audit
- Compliance

Chemistry

- Research
- Development
- Unregulated Emissions
- GC/Mass Spec.

Services

- Support
- Consulting

July 30, 2010

Janet Buyer and Susan Bathalon
jbuyer@cpsc.gov and sbathalon@cpsc.gov
U.S. Consumer Product Safety Commission
4330 East West Hwy, Room 611
Bethesda, MD 20814

Subject: CPSC-Q-10-0069, "Test and Provide Laboratory Exhaust Emission Testing Results for a Prototype Generator Engine Designed for Low Carbon Monoxide (CO) Emission Rates and EPA Phase 2 Emission Standards for Nonroad Small Spark-Ignited (SI) Nonhandheld Engines" Report

Dear Ms. Buyer and Ms. Bathalon,

Thank you for your interest in Intertek Carnot Emission Services' (Intertek CES) engine emission testing services. This report and included test sheets detail the laboratory exhaust emission testing for a prototype generator engine designed for low carbon monoxide (CO) emission rates and EPA Phase 2 emission standards for nonroad small spark-ignition (SI) nonhandheld engines. The objective of this test program was to conduct triplicate 6 load points on the prototype engine with an aged catalyst and triplicate with a non-catalyst OEM muffler while the engine was installed in a generator using a resistive load bank. The engine was then uninstalled from the generator and tested in triplicate 6 mode emission tests on a prototype engine with an aged catalyst and in triplicate with a non-catalyst OEM muffler while installed on a AC dynamometer.

If there are any questions, I can be reached at (210) 928-2230, or via FAX at (210) 928-1233, or via email at tim.griffin@intertek.com.

Approved by:

Steven E. Griffin
General Manager
Intertek CES

Sincerely,

Timothy Griffin
Lab Operations Manager
Intertek CES

Test and Provide Laboratory Exhaust Emission Testing Results for a Prototype Generator Engine Designed for Low Carbon Monoxide (CO) Emission Rates and EPA Phase 2 Emission Standards for Nonroad Small Spark-Ignited (SI) Nonhandheld Engines

Project CPSC-Q-10-0069

CONDUCTED FOR:

U.S. Consumer Product Safety Commission
4330 East West Hwy, Room 611
Bethesda, MD 20814

SUBMITED BY:

Timothy Griffin
Lab Operations Manager
Intertek Carnot Emission Services

In my opinion, this testing was conducted in a valid manner according to the test method listed.
The results provided on this report relate only to the items tested.

Report History:

Revision A	Initial Release	July 30, 2010

INTRODUCTION

This report documents Intertek Carnot Emission Services' (Intertek CES) recent testing of [redacted] 389cc small offroad engine (SORE) with serial number GCANK-1254782. Intertek CES conducted emission testing that meets applicable CARB regulations and test procedures conforming to the California Code of Regulations, Title 13, Sections 2400-2409, as well as the 40 CFR Part 90, 1054, and 1065 for EPA. 40 CFR Part 90 regulates SORE Class II (≥225cc) for Phase II through 2010 while 40 CFR Part 1054 covers SORE Class II for Phase III for 2011+. 40 CFR Part 1065 is EPA's overall regulation covering test procedures. CCR 2400-2409 is the California Air Resource Boards equivalent of 40 CFR Parts 90 and1054. A summary of the work for this engine test program is shown in Table 1. Tests were first conducted on a load bank with the engine installed in the generator in triplicate with the catalyst and in triplicate without the catalyst according to the load points provided by CPSC (5.5 kW, 4.7 kW, 3.2 kW, 1.5 kW, 0.6 kW, and no load). The engine was then removed from the generator and installed on a test stand to be tested on a dynamometer in triplicate with the catalyst and in triplicate without the catalyst according to an EPA B cycle as shown in Table 2.

TABLE 1. General Program Tasks

Task	Description
A	**Conduct engine emission testing using the prescribed regulations and test methods conforming to 40 CFR 90 and 1065.**
A.1	Conduct engine emission testing with aged catalyst installed at 6 resistive load points (5.5 kW, 4.7 kW, 3.2 kW, 1.5 kW, 0.6 kW, and no load) applied to the generator through its 240-volt receptacle using load bank. The applied loads will be measured, verified, and recorded using a power-meter. Process data and determine test results based on efficiency data correlation between generator and engine power supplied by CPSC. A minimum of three tests will be conducted.
A.2	Conduct engine emission testing without catalyst (OEM muffler) at 6 resistive load points (5.5 kW, 4.7 kW, 3.2 kW, 1.5 kW, 0.6 kW, and no load) applied to the generator through its 240-volt receptacle using load bank. The applied loads will be measured, verified, and recorded using a power-meter. Process data and determine test results based on efficiency data correlation between generator and engine power supplied by CPSC. A minimum of three tests will be conducted.
B	**Disassemble engine shaft from brushless alternator rotors in generator unit for dynamometer testing.**
C	**Conduct dynamometer engine emission testing using the prescribed regulations and test methods conforming to 40 CFR 90 and 1065.**
C.1	Install engine on dynamometer, verify engine performance and conduct power/torque curve.
C.2	Conduct 6 mode B cycle weighted cycle emission test on dynamometer with aged catalyst installed. Process data and determine test results. A minimum of three tests will be conducted.
C.3	Conduct 6 mode B cycle weighted cycle emission test on dynamometer without catalyst (OEM muffler). Process data and determine test results. A minimum of three tests will be conducted.
D	**Prepare and submit deliverables.**

TEST FACILITIES

Intertek is a leading provider of quality and safety solutions serving a wide range of industries around the world. From auditing and inspection, to testing, quality assurance and certification, Intertek people are dedicated to adding value to customers' products and processes, supporting their success in the global marketplace.

Our services take us into almost every field imaginable, such as textiles, toys, electronics, building, heating, pharmaceuticals, petroleum, food and cargo scanning. We operate a global network of more than 400 laboratories and offices and over 21,000 people in 110 countries around the world. Customers of Intertek include some of the world's leading brands, major global and local companies and governments.

Intertek provides laboratory testing, laboratory outsourcing, consulting, cargo inspection and certification services for clients in a wide range of industries, on a global basis. Industrial and commercial organizations choose Intertek as their preferred partner across the world for quality, professionalism, performance and solutions.

Intertek CES is a branch of Intertek and is a research and development facility specializing in the offroad engine industry. The offroad engine industry produces exhaust emissions that are regulated by the Environmental Protection Agency (EPA) and California Air Resources Board (CARB). Reductions of exhaust and evaporative emissions require extensive engine research, development, testing, durability, and certification services to meet both government and consumer needs. The offroad industry typically includes gasoline (SI), diesel (CI), liquefied-petroleum gas (LPG), or natural gas (NG) powered, two or four stroke, water or air-cooled, and vertical or horizontal shaft engines used in numerous applications ranging from small offroad engines (SORE), large spark ignited (LSI) engines, to stationary spark ignition internal combustion engines and marine engines.

Intertek CES is located at KellyUSA, in a 29,500 ft^2 facility. Ten test cells, most with multiple test stands, are used for conducting a wide range of engine tests and measurements. The test cells are equipped with AC dynamometers using in-line torque meters for the highest accuracy and motoring capabilities. Emission measurements are available using PDP CVS full flow dilute sampling, and have been used for lab-to-lab correlation with EPA and other major OEM's. Standard emission sampling includes particulate matter (PM), hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO), and carbon dioxide (CO_2). Measurements of nonmethane hydrocarbons (NMHC), volatile organic compounds (VOCs), oxygen (O_2), and intake CO_2 for determining exhaust gas recirculation (EGR) are also available.

Emission equipment used for the testing includes an Emerson Rosemount set of analyzers packaged by Richmond Instruments. The analyzers include NGA 2000 series heated flame ionization detector, wet NOx and chemiluminescense detector (CLD), and infrared (MLT) detectors for CO and CO_2. Calibrations are made with span gases that have 1% accuracy, and are traceable to a NIST standard reference material (SRM).

Data acquisition is monitored and recorded with an HP 34970A unit, and National Instruments LabVIEW software integrated with a 6031E Series card. ICES maintains and calibrates all equipment used for certification testing in compliance with the schedules and standards specified by the Code of Federal Regulations and California Code of Regulations.

The exhaust gas sampling system conforms to §86.1310, and §89.308, §90.420, and §1065. The design of the system used at Intertek CES is depicted in Figure 1.

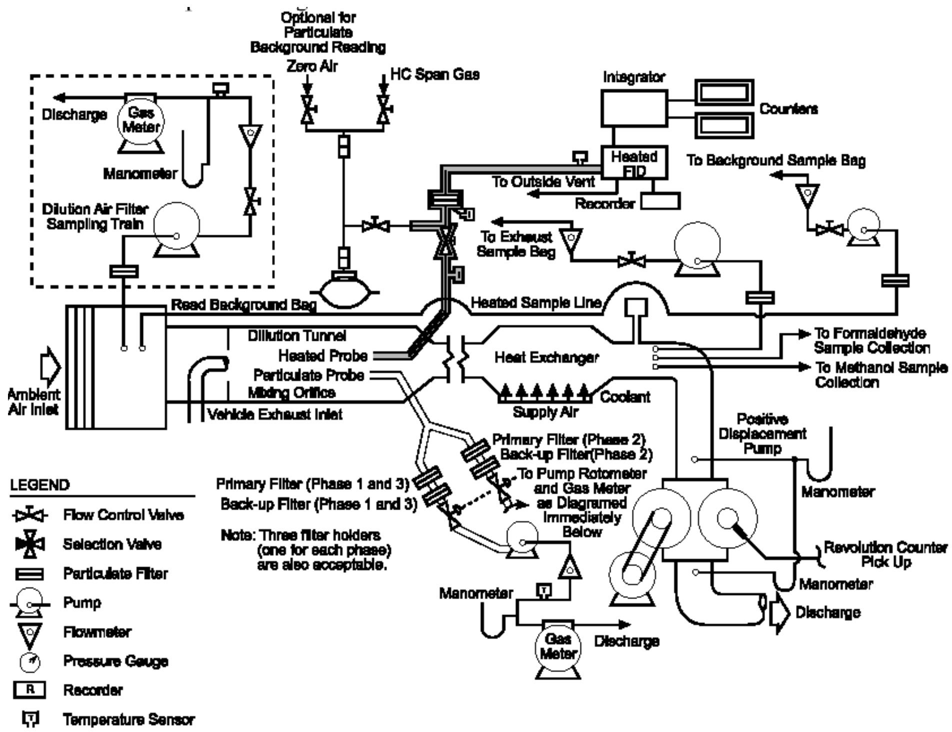


Figure 1 - Gaseous and Particulate Emissions Sampling System (PDP-CVS)

The exhaust gas measurement system conforms to §86.1310, §89.309, §89.421, and §1065. The configuration that is used at Intertek CES is represented in Figure 2.

Dilution tunnel calibrations are performed with a Meriam Instruments LFE for both the primary and secondary dilution tunnels. Monthly propane recovery checks are also performed on the dilution tunnels using a Horiba single CFO.

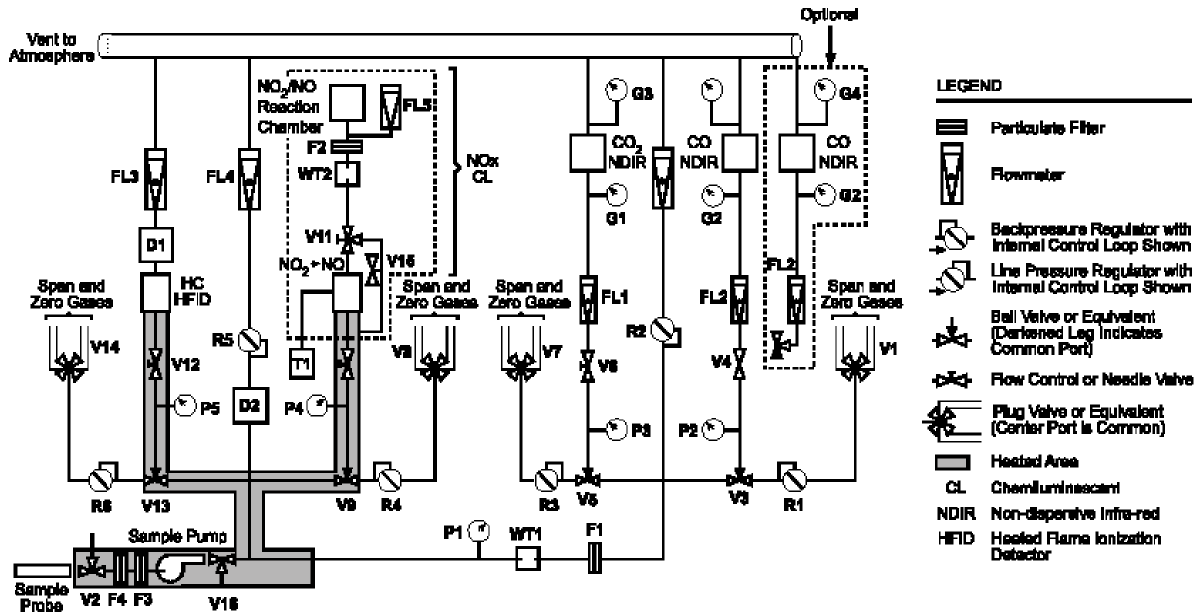
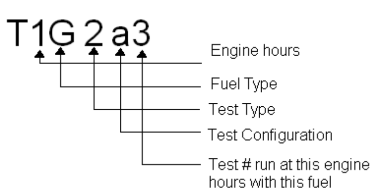


Figure 2 - Exhaust Gas Sampling and Analytical Train

INSTALLATION & PERFORMANCE VERIFICATION

The engine/generator configuration was installed in Test Cell #1 on July 19. 2010. The engine was removed from the generator and installed on the dynamometer on stand B in Test Cell #1 on July 22, 2010. After installation (Figure 3) Intertek CES conducted a power curve with the governor enabled on the engine. The power curve results can be found in Figure 4. Overall results from the power and torque curves are in the summary Table 2. Engine testing nomenclature, task, or performance identification is as follows:



Fuel Type Code:

- ***G- Gasoline***
- L- LPG
- D- Diesel
- C- Compressed Natural Gas
- E- Ethanol
- O- Other

Test Type Code:

- 1- LSI Transients
- 2- LSI C2 Constant Speed 7Mode
- 3- LSI C1 LSI Diesel 8Mode
- ***4- SORE A-Cycle 6Mode***
- ***5- SORE B-Cycle 6Mode***
- ***6- SORE C-Cycle 2Mode***
- 7- LSI D2 Constant Speed 5Mode
- 8- Marine E1 5Mode
- 9- Marine E2 4Mode
- 0- Power Curves or Other Manufacturer Tests

Test Configuration Code:

- ***A- Genset testing with Catalyst***
- ***B- Genset testing witout Catalyst***
- ***C - Dynamometer testing without Catalyst***
- ***D - Dynamometer testing with Catalyst***

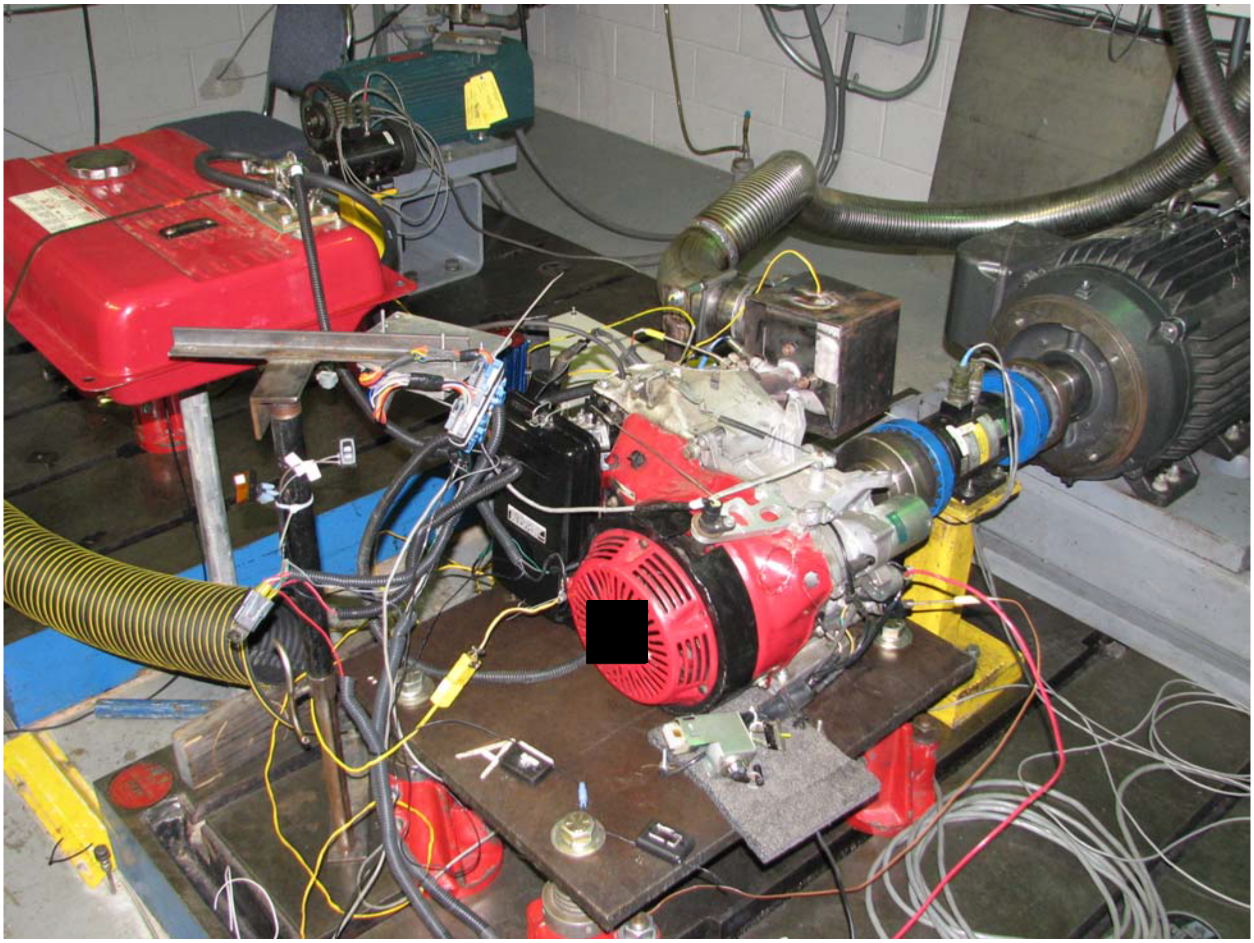


FIGURE 3. Installation Photo

TABLE 2. Governor Enabled Power Curve Results

Test	Engine	Rated T_{Test} Power	T_{Test} Torque
T1G0A1	GCANK-1254782	7.4 kW @ 3163 rpm	22.2 N-m @ 3163 rpm

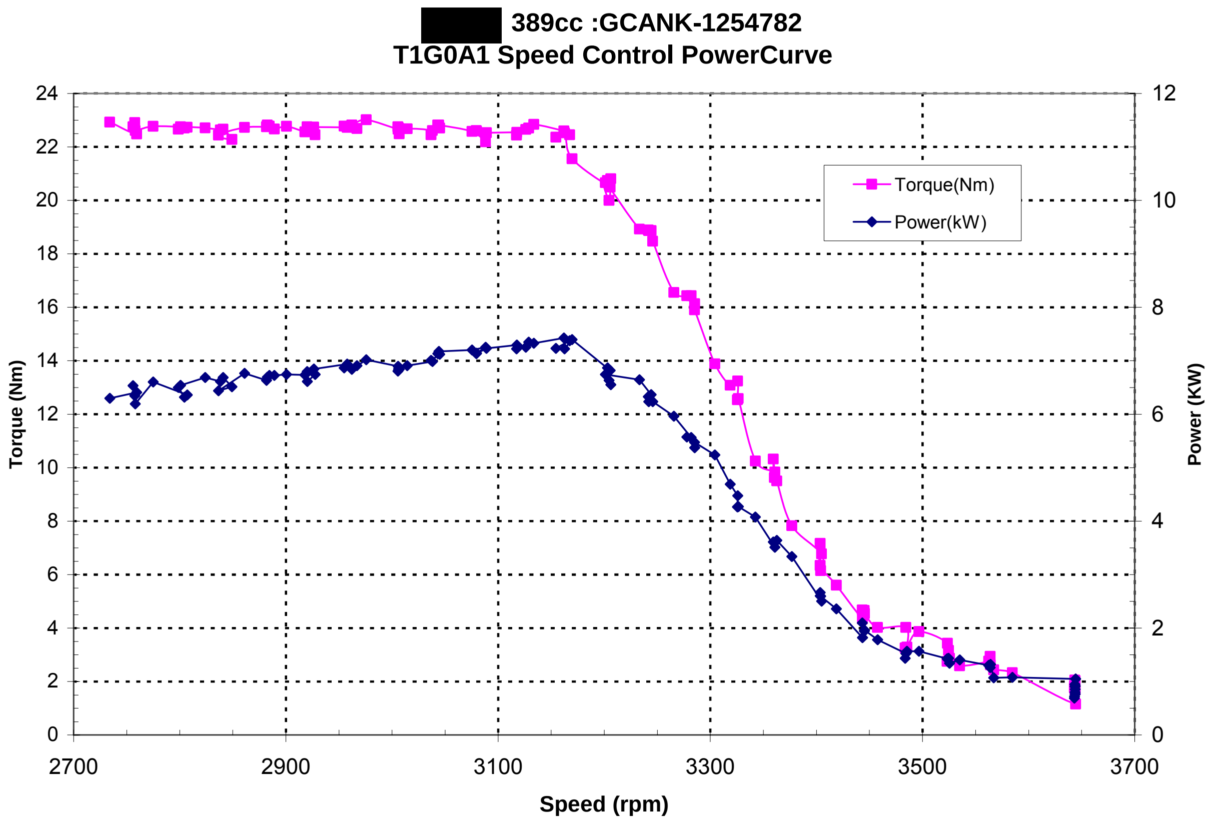


FIGURE 4. Speed Control Power Curve

TESTING

Testing was conducted on the engine while installed in the generator using a resistive load bank at 6 resistive load points applied to the generator through its 240-volt receptacle. The planned targeted load points were 5.5 kW, 4.7 kW, 3.2 kW, 1.5 kW, 0.6 kW, and no load while the actual load points were ~4.9 kW, ~4.7 kW, ~3.2 kW, ~1.5 kW, ~0.6 kW, and no load. Triplicate emission tests were conducted both with and without the catalyst installed on the engine. The mode 1 load points were reduced due to the generator circuitry that either melted wires or tripped breakers. Minor mapping was performed at Intertek Carnot prior to performing the tests.

After the generator based testing was concluded, the engine was removed from the generator and installed on a dynamometer.

Dynamometer testing included triplicate, full EPA B-Cycle steady-state emission tests on the engine both with and without the catalyst installed. The EPA approved B-cycle is a 6-mode test cycle and is shown in Table 3. Table 4 shows the current and future Class II emission standards. The test fuel used is a Chevron-Phillips Unleaded Test Gasoline (UTG) that is compliant with 40 CFR 1065.710 general testing (Table 5).

TABLE 3. ISO 8178-G2 (B) Test Cycle

Mode	1	2	3	4	5	6
Speed	Rated	Rated	Rated	Rated	Rated	Low/High Idle
Load (%)	100	75	50	25	10	N/A
Weight (%)	9	20	29	30	7	5

TABLE 4. Class II Emission Standards

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

TABLE 5. 40 CFR 1065.710 Gasoline Test Fuel Specifications

Item	Units	General testing	Low-temperature testing	Reference procedure[1]
Distillation Range:				
Initial boiling point	°C	24–35[2]	24–36	
10% point	°C	49–57	37–48	ASTM D86–07a.
50% point	°C	93–110	82–101	
90% point	°C	149–163	158–174	
End point	°C	Maximum, 213	Maximum, 212	
Hydrocarbon composition:				
Olefins	m^3/m^3	Maximum, 0.10	Maximum, 0.175	ASTM D1319–03.
Aromatics		Maximum, 0.35	Maximum, 0.304	
Saturates		Remainder	Remainder	
Lead (organic)	g/liter	Maximum, 0.013	Maximum, 0.013	ASTM D3237–06e01.
Phosphorous	g/liter	Maximum, 0.0013	Maximum, 0.005	ASTM D3231–07.
Total sulfur	mg/kg	Maximum, 80	Maximum, 80	ASTM D2622–07.
Volatility (Reid Vapor Pressure)	kPa	60.0–63.4[2,3]	77.2–81.4	ASTM D5191–07.

RESULTS

A summary of the results from each test are shown in Table 6 along with averages, standard deviation and coefficient of variance for each triplicate set of tests. The averages, standard deviation and coefficient of variance is also shown for all the testing in the generator and all the testing on the dynamometer. Full test result sheets are available in Appendices A through D.

Genset Testing with Catalyst (g/kw-hr)

Test	CO	HC	NOx	HC + Nox
T1G0A1	6.09	0.36	6.60	6.96
T1G0A2	6.77	0.39	7.19	7.58
T1G0A3	5.06	0.38	7.40	7.78
Average	5.98	0.38	7.06	7.44
StDev	0.86	0.01	0.42	0.43
COV	**14.4%**	**3.6%**	**5.9%**	**5.7%**

Dynamometer Testing without Catalyst (B-cycle)

Test	CO	HC	NOx	HC + Nox
T1G5C1	28.12	1.38	11.63	13.01
T1G5C2	26.06	1.37	11.54	12.91
T1G5C3	26.40	1.31	11.33	12.64
Average	26.86	1.35	11.50	12.85
StDev	1.10	0.04	0.15	0.19
COV	**4.1%**	**2.9%**	**1.3%**	**1.5%**

Genset Testing without Catalyst (g/kw-hr)

Test	CO	HC	NOx	HC + Nox
T1G0B1	24.15	1.16	11.91	13.08
T1G0B2	23.88	1.17	12.16	13.33
T1G0B3	23.42	1.20	12.15	13.34
Average	23.82	1.17	12.07	13.25
StDev	0.37	0.02	0.14	0.15
COV	**1.6%**	**1.5%**	**1.2%**	**1.1%**

Dynamometer Testing with Catalyst (B-cycle)

Test	CO	HC	NOx	HC + Nox
T1G5D1	5.96	0.42	6.25	6.67
T1G5D2	5.68	0.41	6.26	6.66
T1G5D3	5.42	0.40	6.43	6.83
Average	5.68	0.41	6.31	6.72
StDev	0.27	0.01	0.10	0.09
COV	**4.8%**	**2.6%**	**1.6%**	**1.4%**

All Testing without Catalyst (g/kw-hr) / **All Testing with Catalyst**

Test	CO	HC	NOx	HC + Nox		Test	CO	HC	NOx	HC + Nox
T1G0B1	24.15	1.16	11.91	13.08		T1G0A1	6.09	0.36	6.60	6.96
T1G0B2	23.88	1.17	12.16	13.33	◄Genset Tests►	T1G0A2	6.77	0.39	7.19	7.58
T1G0B3	23.42	1.20	12.15	13.34		T1G0A3	5.06	0.38	7.40	7.78
T1G5C1	28.12	1.38	11.63	13.01		T1G5D1	5.96	0.42	6.25	6.67
T1G5C2	26.06	1.37	11.54	12.91	◄ B Cycle Tests►	T1G5D2	5.68	0.41	6.26	6.66
T1G5C3	26.40	1.31	11.33	12.64		T1G5D3	5.42	0.40	6.43	6.83
Average	25.34	1.26	11.79	13.05		Average	5.83	0.39	6.69	7.08
StDev	1.82	0.10	0.34	0.27		StDev	0.59	0.02	0.49	0.48
COV	**7.2%**	**8.0%**	**2.9%**	**2.0%**		**COV**	**10.2%**	**5.3%**	**7.4%**	**6.8%**

TABLE 6. EPA B-Cycle Steady-State and Genset Emission Results
Mode 1 of B-Cycle Tests were conducted at 3600 rpm and WOT.
Mode 1 of Genset Tests were set to highest load prior to breaker tripping.

For calculating the generator based testing composite brake emissions, the electrical motor efficiency table supplied by CPSC was originally utilized. After further review of the high calculated torques during test groups A and B, Fuel flow versus Power was plotted (Figure 5) from the T1G5C1 Dynamometer test. The high torque calculated from the generator based tests led us to believe that the electrical motor efficiencies were too low so that when plotted together, the genset fuel economy was below the dyno economy. By forcing the motor efficiencies from groups A and B to fit the T1G5C1 Fuel Flow vs. Power curve for the generator based tests we were able to determine that the efficiency of the electrical motor should be adjusted in test groups A and B from about 75% at modes 1 and 2 to 80%. Idle efficiency remained the same.

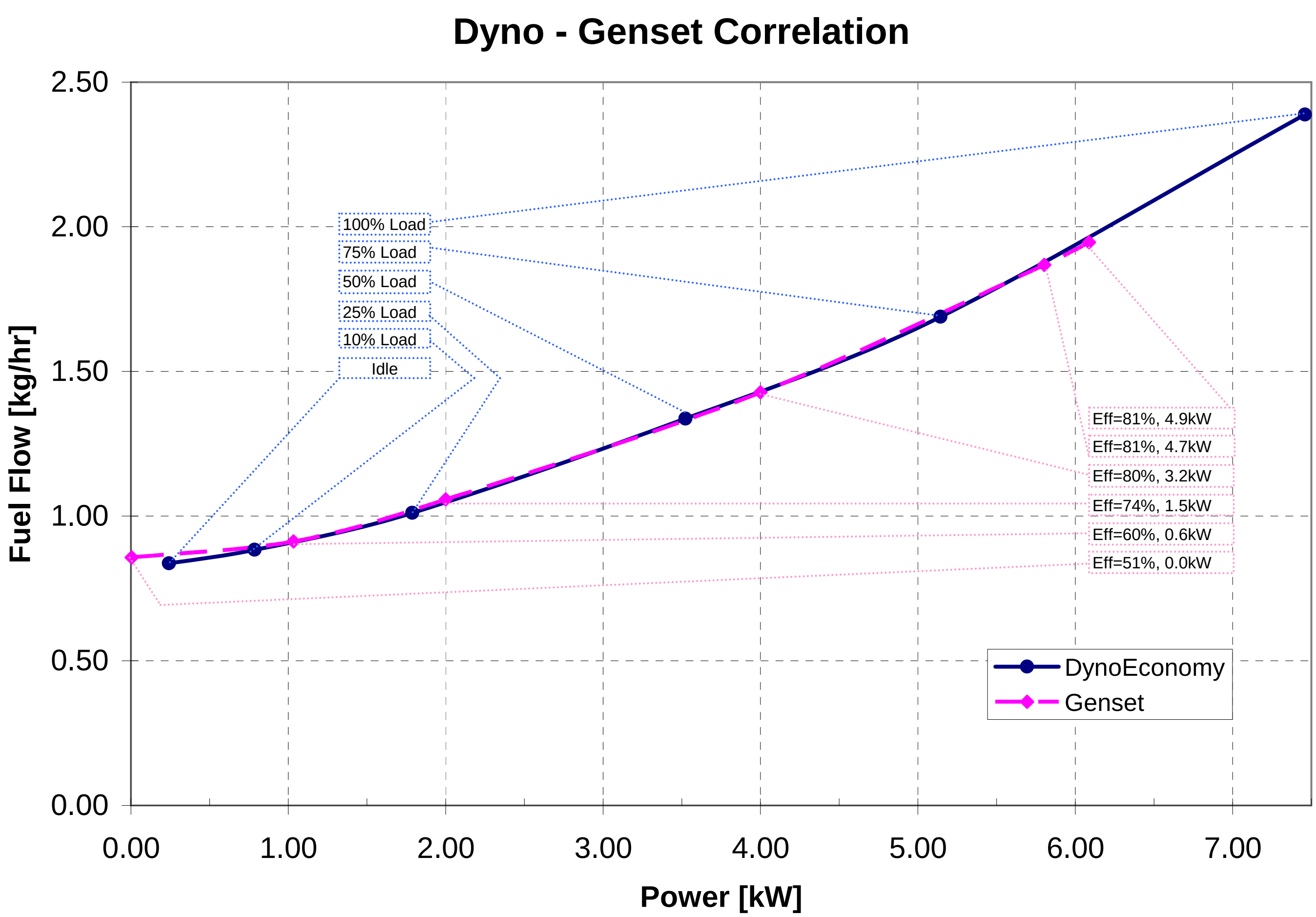


FIGURE 5. Fuel Flow vs. Power

CLOSURE

Intertek Carnot Emission Services continuously works toward improvements that benefit our quality and performance. Our sincere hope is that our engineering services benefit your test programs and core business. If you have any questions, comments, or feedback regarding the testing and/or reporting on this program, we would be happy to discuss those items at any time. We can be reached at (210) 928-1724, or via FAX at (210) 928-1233 if you have any questions.

Approved by:

Steven E. Griffin
General Manager
Intertek CES

Sincerely,

Timothy Griffin
Lab Operations Manager
Intertek CES

APPENDIX A

[redacted]
sn GCANK-1254872

Summary Test Result Sheets
Generator Testing with Resistive Load Bank
Catalyst Installed

INTERTEK CARNOT EMISSION SERVICES

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	8:15:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0A1	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank with Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	5.0	120.0	3340	17.76	0.81	2.05	23.1	21.6	99.083	0.993	1.090	113.54	1.021
2	3600	75	4.7	120.0	3340	16.59	0.81	1.94	23.7	21.0	99.081	0.994	1.081	109.42	1.021
3	3600	50	3.2	120.0	3395	11.25	0.80	1.48	23.0	18.5	99.084	0.996	1.046	94.08	1.016
4	3600	25	1.5	120.0	3475	5.57	0.74	1.09	22.9	17.5	99.082	0.998	1.033	88.35	1.015
5	3600	10	0.6	120.0	3550	2.78	0.60	0.94	22.6	16.9	99.088	0.998	1.024	84.54	1.013
6	3600	0	0.0	120.0	3660	0.01	0.51	0.88	22.2	16.2	99.091	0.999	1.017	81.12	1.011

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.21	135.76	1.07	13.41	88.11			11.98	225.0	51.82	6398.3	2.53	60.21		
2	5.80	92.55	1.02	13.95	84.17			12.54	225.3	35.18	6093.5	2.62	56.78		
3	4.00	65.71	0.78	8.11	35.27			16.26	225.2	25.03	4647.6	1.53	23.07		
4	2.03	32.77	0.57	3.03	8.21			21.77	225.4	12.56	3432.3	0.58	5.34		
5	1.03	17.33	0.49	1.52	5.14			25.03	225.4	6.68	2976.3	0.29	3.33		
6	0.00	14.47	0.46	0.91	3.55			26.77	225.4	5.60	2774.0	0.17	2.29		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	4.66	575.8	0.23	5.42			0.56
2	0.20	7.04	1218.7	0.52	11.36			1.16
3	0.29	7.26	1347.8	0.44	6.69			1.16
4	0.30	3.77	1029.7	0.17	1.60			0.61
5	0.07	0.47	208.3	0.02	0.23			0.07
6	0.05	0.28	138.7	0.01	0.11			0.00
SUM	1.00	23.47	4519.1	1.40	25.42			3.56

COMPOSITE BRAKE EMISSIONS

BSCO	=	4.92	g/hp-hr	=	6.59	g/kW-hr
BSCO2	=	946.61	g/hp-hr	=	1269.4	g/kW-hr
BSTHC	=	0.29	g/hp-hr	=	0.39	g/kW-hr
BSNOx	=	5.32	g/hp-hr	=	7.14	g/kW-hr
BS(THC+NOx)	=	5.62	g/hp-hr	=	7.53	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.664	lb/hp-hr	=	0.404	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	19.9%	12.7%	16.3%	21.3%	21.1%			14.420	43.48	210.29	217.05	648.7	357.4	35.9	124.4
2	30.0%	27.0%	37.5%	44.7%	44.3%			14.421	40.96	210.38	209.18	642.5	345.3	36.3	131.5
3	30.9%	29.8%	31.7%	26.3%	26.6%			14.437	39.51	191.39	174.44	608.2	287.0	34.3	120.8
4	16.1%	22.8%	12.4%	6.3%	6.6%			14.381	39.72	172.61	145.80	586.0	239.6	33.1	109.0
5	2.0%	4.6%	1.5%	0.9%	0.9%			14.394	40.75	162.99	131.55	585.6	218.3	31.8	100.3
6	1.2%	3.1%	0.6%	0.5%	0.5%			14.405	40.64	156.96	126.76	594.1	211.2	31.2	95.0

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0253	6.40

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

Intertek

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	9:40:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0A2	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank with Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	5.0	120.0	3310	17.92	0.81	2.04	29.2	19.6	99.087	0.993	1.061	100.60	1.032
2	3600	75	4.7	120.0	3340	16.59	0.81	1.93	29.5	20.9	99.084	0.994	1.080	109.03	1.035
3	3600	50	3.2	120.0	3400	11.24	0.80	1.47	29.0	19.7	99.079	0.996	1.062	101.20	1.032
4	3600	25	1.5	120.0	3460	5.60	0.74	1.07	28.4	18.7	99.073	0.998	1.048	95.22	1.029
5	3600	10	0.6	120.0	3530	2.80	0.60	0.93	27.9	17.9	99.081	0.998	1.038	90.64	1.027
6	3600	0	0.0	120.0	3660	0.01	0.51	0.87	27.5	17.7	99.083	0.999	1.036	89.50	1.026

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.21	282.71	1.05	21.00	83.01			12.03	224.9	107.91	6279.5	3.97	55.20		
2	5.80	82.20	1.02	12.80	96.99			12.62	225.3	31.27	6068.4	2.41	65.44		
3	4.00	53.30	0.77	7.98	39.92			16.40	225.3	20.31	4619.0	1.51	26.54		
4	2.03	30.70	0.56	3.40	8.18			22.13	225.4	11.77	3377.1	0.65	5.40		
5	1.03	16.41	0.49	1.82	4.95			25.36	225.4	6.33	2943.7	0.35	3.26		
6	0.00	13.86	0.45	1.03	3.42			27.05	225.4	5.36	2747.7	0.20	2.25		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	9.71	565.2	0.36	4.97			0.56
2	0.20	6.25	1213.7	0.48	13.09			1.16
3	0.29	5.89	1339.5	0.44	7.70			1.16
4	0.30	3.53	1013.1	0.19	1.62			0.61
5	0.07	0.44	206.1	0.02	0.23			0.07
6	0.05	0.27	137.4	0.01	0.11			0.00
SUM	1.00	26.10	4474.9	1.50	27.71			3.56

COMPOSITE BRAKE EMISSIONS

BSCO	=	5.47	g/hp-hr	=	7.33	g/kW-hr
BSCO2	=	937.36	g/hp-hr	=	1257.0	g/kW-hr
BSTHC	=	0.32	g/hp-hr	=	0.42	g/kW-hr
BSNOx	=	5.80	g/hp-hr	=	7.78	g/kW-hr
BS(THC+NOx)	=	6.12	g/hp-hr	=	8.21	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.658	lb/hp-hr	=	0.400	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	37.2%	12.6%	23.7%	17.9%	18.2%			14.363	37.60	213.88	216.31	645.1	355.7	36.4	127.4
2	24.0%	27.1%	32.1%	47.2%	46.4%			14.455	37.57	215.14	210.53	642.7	345.1	37.9	135.0
3	22.6%	29.9%	29.0%	27.8%	27.8%			14.435	38.82	195.41	174.95	607.8	285.5	35.9	125.2
4	13.5%	22.6%	12.9%	5.8%	6.2%			14.378	40.53	174.75	144.91	583.5	236.9	34.0	111.5
5	1.7%	4.6%	1.6%	0.8%	0.9%			14.345	41.43	164.70	132.19	583.5	217.6	32.8	101.8
6	1.0%	3.1%	0.7%	0.4%	0.4%			14.383	41.73	159.63	127.77	594.0	211.6	32.4	97.2

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0493	6.57

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

Intertek

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INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	10:56:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0A3	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank with Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	4.9	120.0	3320	17.51	0.81	2.01	26.5	19.8	99.075	0.993	1.063	101.70	1.026
2	3600	75	4.7	120.0	3340	16.42	0.81	1.90	26.7	19.2	99.074	0.994	1.055	98.05	1.026
3	3600	50	3.2	120.0	3400	11.24	0.80	1.46	26.3	18.9	99.060	0.996	1.051	96.23	1.025
4	3600	25	1.5	120.0	3460	5.60	0.74	1.08	25.6	17.5	99.049	0.998	1.033	88.16	1.021
5	3600	10	0.6	120.0	3550	2.78	0.60	0.94	25.2	17.2	99.044	0.998	1.029	86.46	1.020
6	3600	0	0.0	120.0	3660	0.01	0.51	0.88	24.9	17.1	99.035	0.999	1.028	86.15	1.019

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.09	107.57	1.05	13.80	100.08			12.18	224.9	40.99	6302.9	2.60	66.59		
2	5.74	76.91	1.00	13.48	94.29			12.85	225.4	29.29	5975.9	2.54	62.21		
3	4.00	50.86	0.77	8.63	41.14			16.53	225.4	19.42	4601.3	1.63	27.12		
4	2.03	29.83	0.56	3.40	8.60			22.09	225.5	11.46	3403.9	0.65	5.60		
5	1.03	18.41	0.49	1.76	5.04			25.28	225.5	7.11	2956.2	0.34	3.29		
6	0.00	13.60	0.46	1.08	3.56			26.99	225.5	5.27	2769.5	0.21	2.33		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	3.69	567.3	0.23	5.99			0.55
2	0.20	5.86	1195.2	0.51	12.44			1.15
3	0.29	5.63	1334.4	0.47	7.86			1.16
4	0.30	3.44	1021.2	0.19	1.68			0.61
5	0.07	0.50	206.9	0.02	0.23			0.07
6	0.05	0.26	138.5	0.01	0.12			0.00
SUM	1.00	19.38	4463.4	1.44	28.33			3.54

COMPOSITE BRAKE EMISSIONS

BSCO	=	4.09	g/hp-hr	=	5.48	g/kW-hr
BSCO2	=	941.17	g/hp-hr	=	1262.1	g/kW-hr
BSTHC	=	0.30	g/hp-hr	=	0.41	g/kW-hr
BSNOx	=	5.97	g/hp-hr	=	8.01	g/kW-hr
BS(THC+NOx)	=	6.28	g/hp-hr	=	8.42	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.659	lb/hp-hr	=	0.401	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	19.0%	12.7%	16.2%	21.2%	20.9%			14.401	37.00	214.89	214.58	645.5	353.3	36.9	132.3
2	30.2%	26.8%	35.2%	43.9%	43.5%			14.444	35.78	211.56	206.68	637.6	340.3	36.8	131.8
3	29.1%	29.9%	32.8%	27.8%	28.0%			14.473	37.12	191.83	172.21	605.8	283.3	35.8	119.7
4	17.7%	22.9%	13.4%	5.9%	6.3%			14.402	38.48	171.77	144.08	585.2	236.8	33.6	106.6
5	2.6%	4.6%	1.6%	0.8%	0.9%			14.402	39.05	163.01	132.36	585.6	218.5	33.0	99.5
6	1.4%	3.1%	0.7%	0.4%	0.4%			14.405	40.12	157.68	127.25	593.9	212.1	32.4	94.7

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0381	6.36

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

APPENDIX B

[redacted]
sn GCANK-1254872

Summary Test Result Sheets
Generator Testing with Resistive Load Bank
Without Catalyst Installed

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	14:12:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0B1	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank without Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	4.9	120.0	3340	17.40	0.81	1.95	25.9	20.4	98.931	0.994	1.073	105.96	1.027
2	3600	75	4.7	120.0	3340	16.59	0.81	1.87	26.2	19.6	98.921	0.995	1.061	100.73	1.027
3	3600	50	3.2	120.0	3390	11.27	0.80	1.43	25.3	18.5	98.895	0.997	1.046	94.08	1.024
4	3600	25	1.5	120.0	3450	5.54	0.74	1.06	24.8	17.4	98.891	0.998	1.031	87.42	1.021
5	3600	10	0.6	120.0	3500	2.82	0.60	0.91	24.9	17.7	98.876	0.999	1.035	89.17	1.022
6	3600	0	0.0	120.0	3640	0.01	0.51	0.86	24.5	17.4	98.872	0.999	1.031	87.36	1.020

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.09	369.61	0.90	39.65	141.22			13.63	247.8	153.74	5905.7	8.17	103.54		
2	5.80	303.95	0.88	38.21	137.88			14.13	248.2	126.01	5702.9	7.84	99.65		
3	4.00	222.86	0.67	23.99	61.96			18.30	248.4	92.86	4366.5	4.95	44.37		
4	2.00	167.80	0.49	10.26	14.35			24.24	248.5	70.26	3239.1	2.13	10.18		
5	1.03	115.85	0.43	4.03	6.55			27.90	248.6	48.75	2815.8	0.84	4.69		
6	0.00	98.07	0.40	1.76	4.19			29.67	248.7	41.35	2653.4	0.37	2.99		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	13.84	531.5	0.73	9.32			0.55
2	0.20	25.20	1140.6	1.57	19.93			1.16
3	0.29	26.93	1266.3	1.44	12.87			1.16
4	0.30	21.08	971.7	0.64	3.05			0.60
5	0.07	3.41	197.1	0.06	0.33			0.07
6	0.05	2.07	132.7	0.02	0.15			0.00
SUM	1.00	92.53	4239.9	4.45	45.65			3.54

COMPOSITE BRAKE EMISSIONS						
BSCO	=	19.49	g/hp-hr	=	26.13	g/kW-hr
BSCO2	=	892.96	g/hp-hr	=	1197.5	g/kW-hr
BSTHC	=	0.94	g/hp-hr	=	1.26	g/kW-hr
BSNOx	=	9.61	g/hp-hr	=	12.89	g/kW-hr
BS(THC+NOx)	=	10.55	g/hp-hr	=	14.15	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.644	lb/hp-hr	=	0.392	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	15.0%	12.5%	16.5%	20.4%	20.1%			14.434	39.74	212.11	405.66	646.8	235.5	36.3	123.4
2	27.2%	26.9%	35.2%	43.7%	42.9%			14.479	37.83	212.66	398.80	643.0	229.9	36.3	128.6
3	29.1%	29.9%	32.2%	28.2%	28.5%			14.484	37.89	191.43	344.49	607.7	187.3	35.0	116.7
4	22.8%	22.9%	14.3%	6.7%	7.4%			14.412	38.89	172.58	296.18	587.2	152.9	33.3	106.2
5	3.7%	4.6%	1.3%	0.7%	0.8%			14.400	40.53	164.56	277.73	586.0	139.1	32.9	100.0
6	2.2%	3.1%	0.4%	0.3%	0.3%			14.385	41.38	159.81	273.13	595.2	135.6	32.1	95.7

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR. FACTOR	CORR POWER
MODE		[kW]
1	1.0375	6.36

CLASS II - EMISSION STANDARDS	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

Intertek

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	15:10:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0B2	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank without Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	4.9	120.0	3320	17.51	0.81	1.93	26.1	21.9	98.841	0.995	1.097	116.21	1.031
2	3600	75	4.7	120.0	3340	16.42	0.81	1.85	26.1	20.9	98.829	0.995	1.080	108.96	1.030
3	3600	50	3.2	120.0	3400	11.24	0.80	1.42	25.1	18.9	98.815	0.997	1.052	96.54	1.024
4	3600	25	1.5	120.0	3450	5.50	0.74	1.05	24.1	17.5	98.827	0.998	1.033	88.31	1.020
5	3600	10	0.6	120.0	3520	2.80	0.60	0.92	24.1	17.0	98.815	0.999	1.027	85.42	1.019
6	3600	0	0.0	120.0	3640	0.01	0.51	0.85	23.8	16.8	98.807	0.999	1.024	84.09	1.019

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.09	337.82	0.90	39.75	144.19			13.73	248.1	140.29	5869.4	8.17	107.87		
2	5.74	293.66	0.87	35.89	137.91			14.23	248.5	121.82	5668.5	7.37	101.51		
3	4.00	214.50	0.66	23.83	61.63			18.42	248.6	89.41	4345.0	4.92	44.40		
4	1.99	180.88	0.49	11.89	14.15			24.38	248.7	75.80	3218.2	2.47	10.07		
5	1.03	111.32	0.43	3.67	6.55			27.87	248.8	46.93	2830.2	0.77	4.65		
6	0.00	100.50	0.40	1.85	4.15			29.73	248.9	42.44	2644.2	0.39	2.95		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	12.63	528.2	0.74	9.71			0.55
2	0.20	24.36	1133.7	1.47	20.30			1.15
3	0.29	25.93	1260.0	1.43	12.88			1.16
4	0.30	22.74	965.5	0.74	3.02			0.60
5	0.07	3.28	198.1	0.05	0.33			0.07
6	0.05	2.12	132.2	0.02	0.15			0.00
SUM	1.00	91.07	4217.8	4.45	46.38			3.52

COMPOSITE BRAKE EMISSIONS						
BSCO	=	19.27	g/hp-hr	=	25.84	g/kW-hr
BSCO2	=	892.44	g/hp-hr	=	1196.8	g/kW-hr
BSTHC	=	0.94	g/hp-hr	=	1.26	g/kW-hr
BSNOx	=	9.81	g/hp-hr	=	13.16	g/kW-hr
BS(THC+NOx)	=	10.75	g/hp-hr	=	14.42	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.643	lb/hp-hr	=	0.391	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	13.9%	12.5%	16.5%	20.9%	20.5%			14.503	40.01	214.39	407.54	645.5	235.9	37.9	127.2
2	26.8%	26.9%	33.1%	43.8%	42.8%			14.411	38.47	212.94	399.43	639.9	228.4	37.4	129.5
3	28.5%	29.9%	32.1%	27.8%	28.1%			14.462	37.54	192.98	345.35	606.5	186.7	35.7	120.3
4	25.0%	22.9%	16.6%	6.5%	7.4%			14.387	38.68	172.03	295.14	584.8	151.9	33.5	106.3
5	3.6%	4.7%	1.2%	0.7%	0.7%			14.392	39.82	163.83	278.25	585.7	139.0	32.4	97.5
6	2.3%	3.1%	0.4%	0.3%	0.3%			14.406	39.81	159.33	272.64	594.1	135.0	32.2	95.0

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0393	6.37

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

INTERTEK CARNOT EMISSION SERVICES
EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/21/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	16:32:00	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G0B3	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Genset tested using loadbank without Catalyst installed.

	TARGET			MEASURED			Assumed	CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Gen Pwr	Time	Speed	Torque	Efficiency	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[kW]	[sec]	[rpm]	[N-m]	[%]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	4.9	120.0	3310	17.56	0.81	1.91	26.2	19.9	98.774	0.995	1.066	102.83	1.029
2	3600	75	4.7	120.0	3330	16.46	0.81	1.84	26.0	19.3	98.773	0.995	1.057	98.83	1.028
3	3600	50	3.2	120.0	3400	11.24	0.80	1.42	25.2	18.9	98.788	0.997	1.051	96.21	1.025
4	3600	25	1.5	120.0	3450	5.54	0.74	1.05	24.8	18.9	98.829	0.998	1.051	96.00	1.024
5	3600	10	0.6	120.0	3510	2.81	0.60	0.89	24.7	17.6	98.812	0.999	1.035	88.91	1.022
6	3600	0	0.0	120.0	3640	0.01	0.51	0.85	24.1	17.5	98.817	0.999	1.033	88.18	1.020

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	6.09	318.65	0.89	36.55	148.21			13.87	248.2	132.40	5823.9	7.52	107.87		
2	5.74	295.33	0.86	40.25	140.12			14.36	248.6	122.59	5613.7	8.27	101.02		
3	4.00	220.97	0.66	26.71	62.14			18.47	248.7	92.24	4330.8	5.52	44.80		
4	2.00	165.73	0.49	9.02	13.82			24.46	248.8	69.62	3227.9	1.88	10.02		
5	1.03	110.04	0.41	3.47	6.47			28.75	248.8	46.39	2742.2	0.72	4.63		
6	0.00	99.39	0.40	1.77	4.09			29.81	248.9	41.96	2642.8	0.37	2.93		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	11.92	524.2	0.68	9.71			0.55
2	0.20	24.52	1122.7	1.65	20.20			1.15
3	0.29	26.75	1255.9	1.60	12.99			1.16
4	0.30	20.89	968.4	0.56	3.01			0.60
5	0.07	3.25	192.0	0.05	0.32			0.07
6	0.05	2.10	132.1	0.02	0.15			0.00
SUM	1.00	89.42	4195.3	4.56	46.38			3.53

COMPOSITE BRAKE EMISSIONS						
BSCO	=	18.90	g/hp-hr	=	25.34	g/kW-hr
BSCO2	=	886.67	g/hp-hr	=	1189.0	g/kW-hr
BSTHC	=	0.96	g/hp-hr	=	1.29	g/kW-hr
BSNOx	=	9.80	g/hp-hr	=	13.15	g/kW-hr
BS(THC+NOx)	=	10.77	g/hp-hr	=	14.44	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.639	lb/hp-hr	=	0.389	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	13.3%	12.5%	14.8%	20.9%	20.4%			14.414	36.01	214.12	405.35	642.7	232.5	37.6	126.4
2	27.4%	26.8%	36.2%	43.6%	42.9%			14.441	35.40	212.56	396.91	636.7	225.8	37.2	128.1
3	29.9%	29.9%	35.1%	28.0%	28.6%			14.431	37.08	192.68	344.92	605.4	186.5	35.8	118.5
4	23.4%	23.1%	12.3%	6.5%	7.0%			14.502	39.84	172.62	295.96	584.8	152.4	34.5	105.5
5	3.6%	4.6%	1.1%	0.7%	0.7%			14.397	40.27	163.58	276.26	588.5	138.0	32.9	98.9
6	2.3%	3.1%	0.4%	0.3%	0.3%			14.407	40.83	160.24	272.41	593.8	135.5	32.5	95.2

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR. FACTOR	CORR POWER
MODE		[kW]
1	1.0406	6.38

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

APPENDIX C

[redacted]

sn GCANK-1254872

Summary Test Result Sheets
Dynamometer Testing
Without Catalyst Installed

Intertek

INTERTEK CARNOT EMISSION SERVICES

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
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EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/22/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	14:18:38	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5C1	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested without Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	19.7	120.0	3610	19.74	0.00	2.39	27.1	12.8	98.838	0.992	0.981	64.87	1.022
2	3600	75	14.8	120.0	3338	14.72	-0.58	1.69	27.5	12.6	98.826	0.996	0.978	63.72	1.022
3	3600	50	9.9	120.0	3387	9.93	0.66	1.34	26.6	13.0	98.857	0.997	0.983	65.71	1.021
4	3600	25	4.9	120.0	3444	4.96	0.49	1.01	26.3	13.3	98.841	0.999	0.985	66.71	1.020
5	3600	10	2.0	120.0	3592	2.09	5.88	0.88	25.7	13.3	98.802	0.999	0.986	66.98	1.019
6	3600	0	0.0	120.0	3711	0.62	n/a	0.84	25.5	13.4	98.804	0.999	0.986	67.28	1.019

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.46	418.61	1.13	43.57	191.09			11.07	247.7	171.82	7274.9	8.85	126.38		
2	5.14	267.54	0.79	39.72	113.41			15.63	248.5	111.51	5155.5	8.20	75.96		
3	3.52	238.88	0.62	24.62	46.00			19.60	248.6	100.21	4067.7	5.11	31.15		
4	1.79	160.95	0.47	9.04	12.44			25.48	248.7	67.77	3095.3	1.88	8.48		
5	0.79	125.66	0.41	3.82	5.33			28.85	248.8	53.06	2717.3	0.80	3.64		
6	0.24	108.26	0.39	2.20	3.65			30.28	248.8	45.75	2582.0	0.46	2.50		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	15.46	654.7	0.80	11.37			0.67
2	0.20	22.30	1031.1	1.64	15.19			1.03
3	0.29	29.06	1179.6	1.48	9.03			1.02
4	0.30	20.33	928.6	0.57	2.54			0.54
5	0.07	3.71	190.2	0.06	0.26			0.06
6	0.05	2.29	129.1	0.02	0.12			0.00
SUM	1.00	93.16	4113.4	4.56	38.53			3.31

COMPOSITE BRAKE EMISSIONS

BSCO	=	20.97	g/hp-hr	=	28.12	g/kW-hr
BSCO2	=	925.79	g/hp-hr	=	1241.5	g/kW-hr
BSTHC	=	1.03	g/hp-hr	=	1.38	g/kW-hr
BSNOx	=	8.67	g/hp-hr	=	11.63	g/kW-hr
BS(THC+NOx)	=	9.70	g/hp-hr	=	13.01	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.666	lb/hp-hr	=	0.405	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	16.6%	15.9%	17.5%	29.5%	28.2%			14.386	41.15	237.04	462.30	689.3	300.2	27.2	139.7
2	23.9%	25.1%	35.9%	39.4%	39.1%			14.431	40.32	215.34	396.90	631.3	242.1	27.2	130.7
3	31.2%	28.7%	32.5%	23.5%	24.4%			14.421	41.67	195.91	351.32	602.7	203.7	27.2	117.5
4	21.8%	22.6%	12.4%	6.6%	7.2%			14.410	42.55	178.18	306.23	585.6	168.6	27.1	108.1
5	4.0%	4.6%	1.2%	0.7%	0.7%			14.428	42.87	168.04	292.00	590.6	157.5	27.0	99.8
6	2.5%	3.1%	0.5%	0.3%	0.3%			14.410	42.89	164.48	289.78	601.6	155.0	27.1	98.1

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0433	7.84

CLASS II - EMISSION STANDARDS

	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

Intertek

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
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INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/22/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	15:33:31	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5C2	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested without Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	19.7	120.0	3609	19.72	0.00	2.35	28.6	12.1	98.801	0.992	0.974	61.92	1.025
2	3600	75	14.8	120.0	3312	14.86	0.50	1.67	28.0	11.8	98.795	0.996	0.971	60.49	1.023
3	3600	50	9.9	120.0	3361	9.89	0.36	1.31	27.3	12.0	98.781	0.997	0.973	61.27	1.022
4	3600	25	4.9	120.0	3441	4.87	-1.12	1.00	26.8	12.1	98.772	0.999	0.974	61.81	1.021
5	3600	10	2.0	120.0	3598	2.00	1.67	0.87	25.8	12.1	98.758	0.999	0.974	61.89	1.019
6	3600	0	0.0	120.0	3707	0.67	n/a	0.83	25.7	12.5	98.757	0.999	0.977	63.23	1.019

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.45	407.26	1.12	49.60	190.60			11.16	247.7	166.21	7164.7	10.02	124.51		
2	5.15	243.44	0.78	38.02	112.03			15.78	248.6	101.27	5099.6	7.83	74.34		
3	3.48	208.21	0.61	23.57	46.93			19.87	248.7	87.13	4006.3	4.88	31.39		
4	1.76	150.83	0.46	8.80	12.07			25.68	248.9	63.48	3064.4	1.83	8.13		
5	0.76	130.33	0.40	3.79	5.15			29.17	248.9	54.97	2673.9	0.79	3.48		
6	0.26	113.48	0.38	2.46	3.50			30.54	249.0	47.95	2554.3	0.51	2.37		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	14.96	644.8	0.90	11.21			0.67
2	0.20	20.25	1019.9	1.57	14.87			1.03
3	0.29	25.27	1161.8	1.42	9.10			1.01
4	0.30	19.04	919.3	0.55	2.44			0.53
5	0.07	3.85	187.2	0.06	0.24			0.05
6	0.05	2.40	127.7	0.03	0.12			0.00
SUM	1.00	85.77	4060.8	4.52	37.98			3.29

COMPOSITE BRAKE EMISSIONS

BSCO	=	19.43	g/hp-hr	=	26.06	g/kW-hr
BSCO2	=	920.12	g/hp-hr	=	1233.9	g/kW-hr
BSTHC	=	1.02	g/hp-hr	=	1.37	g/kW-hr
BSNOx	=	8.61	g/hp-hr	=	11.54	g/kW-hr
BS(THC+NOx)	=	9.63	g/hp-hr	=	12.91	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.660	lb/hp-hr	=	0.402	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	17.4%	15.9%	20.0%	29.5%	28.5%			14.380	37.66	239.76	459.88	687.7	296.9	27.9	142.5
2	23.6%	25.1%	34.7%	39.1%	38.7%			14.445	37.38	217.13	396.44	630.2	229.7	27.6	131.0
3	29.5%	28.6%	31.4%	24.0%	24.8%			14.478	38.11	198.98	350.02	602.0	193.3	27.5	120.7
4	22.2%	22.6%	12.2%	6.4%	7.0%			14.394	38.99	179.92	306.02	587.2	163.3	27.3	109.7
5	4.5%	4.6%	1.2%	0.6%	0.7%			14.435	39.38	169.00	291.02	589.8	156.8	27.1	102.5
6	2.8%	3.1%	0.6%	0.3%	0.3%			14.407	40.23	165.07	286.47	600.4	148.9	27.1	98.0

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0497	7.89

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/22/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	16:49:32	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5C3	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested without Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	20.3	120.0	3608	20.30	0.00	2.36	28.4	12.7	98.670	0.992	0.979	64.10	1.026
2	3600	75	15.2	120.0	3286	15.23	0.06	1.68	28.0	12.5	98.672	0.996	0.978	63.43	1.025
3	3600	50	10.1	120.0	3341	10.07	-0.83	1.32	27.3	12.6	98.687	0.997	0.979	64.02	1.023
4	3600	25	5.1	120.0	3428	5.12	0.83	1.01	26.5	12.9	98.664	0.999	0.982	65.20	1.022
5	3600	10	2.0	120.0	3575	2.02	-0.64	0.87	26.2	13.0	98.678	0.999	0.982	65.40	1.021
6	3600	0	0.0	120.0	3689	0.66	n/a	0.83	25.8	13.3	98.672	0.999	0.986	67.13	1.021

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.67	395.82	1.12	44.65	188.79			11.13	248.1	161.76	7210.3	9.03	124.13		
2	5.24	254.86	0.78	39.85	113.45			15.70	248.9	105.95	5123.6	8.20	75.77		
3	3.52	224.22	0.61	21.16	45.58			19.77	249.0	93.76	4027.1	4.38	30.66		
4	1.84	156.92	0.47	9.49	12.52			25.39	249.1	65.95	3096.7	1.97	8.49		
5	0.75	121.15	0.40	3.52	4.96			29.31	249.1	51.05	2665.6	0.73	3.38		
6	0.25	118.39	0.38	2.38	3.41			30.64	249.2	49.95	2540.2	0.50	2.33		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	14.56	648.9	0.81	11.17			0.69
2	0.20	21.19	1024.7	1.64	15.15			1.05
3	0.29	27.19	1167.9	1.27	8.89			1.02
4	0.30	19.78	929.0	0.59	2.55			0.55
5	0.07	3.57	186.6	0.05	0.24			0.05
6	0.05	2.50	127.0	0.02	0.12			0.00
SUM	1.00	88.79	4084.1	4.39	38.11			3.36

COMPOSITE BRAKE EMISSIONS

BSCO	=	19.69	g/hp-hr	=	26.40	g/kW-hr
BSCO2	=	905.50	g/hp-hr	=	1214.3	g/kW-hr
BSTHC	=	0.97	g/hp-hr	=	1.31	g/kW-hr
BSNOx	=	8.45	g/hp-hr	=	11.33	g/kW-hr
BS(THC+NOx)	=	9.42	g/hp-hr	=	12.64	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.651	lb/hp-hr	=	0.396	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	16.4%	15.9%	18.5%	29.3%	28.2%			14.413	38.80	237.87	460.14	686.7	294.9	28.0	134.5
2	23.9%	25.1%	37.3%	39.8%	39.5%			14.432	38.60	216.18	397.43	627.7	238.1	27.9	126.5
3	30.6%	28.6%	28.9%	23.3%	23.9%			14.505	39.13	198.87	351.19	600.3	202.1	27.8	119.5
4	22.3%	22.7%	13.5%	6.7%	7.4%			14.389	40.34	180.28	307.92	584.8	164.7	27.6	109.0
5	4.0%	4.6%	1.2%	0.6%	0.7%			14.420	40.68	169.62	289.24	588.2	152.9	27.5	102.4
6	2.8%	3.1%	0.6%	0.3%	0.3%			14.423	41.63	165.37	285.07	597.9	153.8	27.5	98.6

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR. FACTOR	CORR POWER
MODE		[kW]
1	1.0504	8.12

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

APPENDIX D

[redacted]
sn GCANK-1254872

Summary Test Result Sheets
Dynamometer Testing
With Catalyst Installed

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/23/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	8:10:18	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5D1	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested with Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	21.0	120.0	3606	21.01	0.00	2.49	26.7	17.0	98.874	0.992	1.027	85.39	1.025
2	3600	75	15.8	120.0	3285	15.72	-0.27	1.76	27.1	16.3	98.891	0.995	1.018	81.34	1.025
3	3600	50	10.5	120.0	3346	10.45	-0.50	1.39	26.4	16.4	98.901	0.997	1.019	82.09	1.023
4	3600	25	5.3	120.0	3436	5.32	1.26	1.07	26.0	16.4	98.927	0.998	1.020	82.20	1.022
5	3600	10	2.1	120.0	3577	2.05	-2.24	0.90	25.5	16.8	98.935	0.999	1.024	84.30	1.021
6	3600	0	0.0	120.0	3700	0.63	n/a	0.86	25.4	16.8	98.927	0.999	1.025	84.45	1.021

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.93	184.37	1.22	16.21	76.13			10.54	247.3	74.87	7772.2	3.26	52.14		
2	5.41	56.83	0.85	11.94	67.43			14.97	248.1	23.50	5532.2	2.45	46.62		
3	3.66	36.05	0.67	7.21	31.26			18.80	248.2	15.02	4381.1	1.49	21.80		
4	1.91	32.88	0.51	3.57	5.68			24.13	248.3	13.77	3361.5	0.74	3.98		
5	0.77	15.39	0.43	1.41	3.37			28.23	248.3	6.47	2855.3	0.29	2.38		
6	0.24	18.60	0.41	1.06	2.13			29.55	248.4	7.84	2712.7	0.22	1.51		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	6.74	699.5	0.29	4.69			0.71
2	0.20	4.70	1106.4	0.49	9.32			1.08
3	0.29	4.35	1270.5	0.43	6.32			1.06
4	0.30	4.13	1008.5	0.22	1.19			0.57
5	0.07	0.45	199.9	0.02	0.17			0.05
6	0.05	0.39	135.6	0.01	0.08			0.00
SUM	1.00	20.77	4420.4	1.47	21.77			3.49

COMPOSITE BRAKE EMISSIONS

BSCO	=	4.44	g/hp-hr	=	5.96	g/kW-hr
BSCO2	=	945.76	g/hp-hr	=	1268.3	g/kW-hr
BSTHC	=	0.31	g/hp-hr	=	0.42	g/kW-hr
BSNOx	=	4.66	g/hp-hr	=	6.25	g/kW-hr
BS(THC+NOx)	=	4.97	g/hp-hr	=	6.67	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.661	lb/hp-hr	=	0.402	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	32.4%	15.8%	20.0%	21.6%	21.5%			14.389	53.89	233.44	426.71	684.7	379.3	27.2	130.1
2	22.6%	25.0%	33.3%	42.8%	42.2%			14.431	51.20	214.09	342.11	628.5	318.4	27.2	124.5
3	21.0%	28.7%	29.4%	29.0%	29.1%			14.425	51.50	196.61	299.63	604.6	286.4	27.3	116.1
4	19.9%	22.8%	15.1%	5.5%	6.1%			14.384	52.07	177.77	256.51	586.5	253.9	27.1	106.2
5	2.2%	4.5%	1.4%	0.8%	0.8%			14.422	53.36	167.34	236.20	592.8	237.9	27.1	98.8
6	1.9%	3.1%	0.8%	0.3%	0.4%			14.392	53.54	163.27	235.12	602.1	240.3	27.1	96.1

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0413	8.32

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

616 Perrin
San Antonio, TX 78226
tel: 210-928-2230
fax: 210-928-1233

U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/23/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	9:17:41	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5D2	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested with Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	20.8	120.0	3609	20.83	0.00	2.48	27.1	15.5	98.963	0.992	1.009	77.41	1.023
2	3600	75	15.6	120.0	3283	15.56	-0.41	1.74	27.1	14.2	98.959	0.995	0.995	71.30	1.022
3	3600	50	10.4	120.0	3355	10.58	1.59	1.39	26.8	14.8	98.948	0.997	1.001	73.75	1.022
4	3600	25	5.2	120.0	3436	5.22	0.27	1.05	25.8	14.7	98.948	0.998	0.999	73.24	1.019
5	3600	10	2.1	120.0	3565	2.25	7.98	0.90	25.1	14.8	98.946	0.999	1.001	73.83	1.018
6	3600	0	0.0	120.0	3711	0.63	n/a	0.86	25.1	15.7	98.936	0.999	1.011	78.33	1.019

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.87	178.70	1.21	15.77	76.71			10.58	247.1	72.53	7734.8	3.17	51.59		
2	5.35	55.24	0.84	11.24	68.13			15.11	247.9	22.83	5475.0	2.30	46.03		
3	3.72	37.02	0.67	7.55	32.00			18.75	248.1	15.40	4386.6	1.56	21.88		
4	1.88	27.12	0.50	3.04	6.42			24.54	248.2	11.34	3299.8	0.63	4.41		
5	0.84	14.75	0.43	1.25	3.51			28.20	248.3	6.20	2854.8	0.26	2.42		
6	0.25	16.34	0.41	0.98	2.14			29.63	248.4	6.88	2704.4	0.20	1.50		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	6.53	696.1	0.29	4.64			0.71
2	0.20	4.57	1095.0	0.46	9.21			1.07
3	0.29	4.47	1272.1	0.45	6.35			1.08
4	0.30	3.40	989.9	0.19	1.32			0.56
5	0.07	0.43	199.8	0.02	0.17			0.06
6	0.05	0.34	135.2	0.01	0.07			0.00
SUM	1.00	19.74	4388.2	1.41	21.76			3.48

COMPOSITE BRAKE EMISSIONS						
BSCO	=	4.23	g/hp-hr	=	5.68	g/kW-hr
BSCO2	=	940.71	g/hp-hr	=	1261.5	g/kW-hr
BSTHC	=	0.30	g/hp-hr	=	0.41	g/kW-hr
BSNOx	=	4.67	g/hp-hr	=	6.26	g/kW-hr
BS(THC+NOx)	=	4.97	g/hp-hr	=	6.66	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.657	lb/hp-hr	=	0.399	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	33.1%	15.9%	20.2%	21.3%	21.3%			14.401	46.99	235.88	428.41	683.8	392.9	27.8	134.7
2	23.1%	25.0%	32.5%	42.3%	41.7%			14.431	44.80	214.30	341.89	627.2	329.6	27.3	123.3
3	22.6%	29.0%	31.9%	29.2%	29.3%			14.471	46.16	197.35	302.21	604.1	299.7	27.3	115.6
4	17.2%	22.6%	13.3%	6.1%	6.5%			14.407	46.56	177.75	254.58	585.4	258.7	27.1	106.5
5	2.2%	4.6%	1.3%	0.8%	0.8%			14.392	47.31	168.26	237.57	591.9	243.7	26.9	99.7
6	1.7%	3.1%	0.7%	0.3%	0.4%			14.419	49.72	163.28	236.31	601.8	246.9	27.1	96.3

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR. FACTOR	CORR POWER
MODE		[kW]
1	1.0417	8.26

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

INTERTEK CARNOT EMISSION SERVICES

EPA/CARB B-Cycle (ISO 8178 G2) EMISSION TEST RESULTS
INTERTEK CES PROJECT: CPSC-10-01

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U.S. Consumer Product Safety Commision
CPSC-Q-10-0069

ENGINE IDENTIFICATION			FUEL/OIL INFORMATION		TEST CELL INFORMATION		
Engine Manufacturer:	[redacted]		Fuel ID:	UTG	Test Cell/Stand:	1B	
Engine Model Number:	[redacted]		H/C Ratio:	1.84	Test Operator:	TG	0
Engine Serial Number:	GCANK1254782		Engine Cycle:	Otto - 4-stroke	Test Date:	07/23/10	
Engine Displacement [cc/in^3]:	389	23.7	Oil Type:	client provided	Start Test:	10:20:52	
Emission Ctrl System:	0		Engine Mfr Date:		Test No:	T1G5D3	
Rated/Idle Speed:	3600	3600	Engine Family:	0	Engine Start Hr./Duration:	0.00	

Notes: Dynamometer tested with Catalyst installed.

	TARGET			MEASURED				CALCULATED	INLET AIR CONDITIONS			TEST FACTORS			
	Speed	Load	Torque	Time	Speed	Torque	Torque	FUEL FLOW	Temp	Dew Point	Baro	Dry-Wet	NOx Hum.	HumRatio	F Factor
MODE	[rpm]	[%]	[N-m]	[sec]	[rpm]	[N-m]	[% Target]	[kg/hr]	[deg C]	[deg C]	[kPa]	Correction	Correction	grH2O/lbAir	N/A
1	3600	100	20.8	120.0	3605	20.83	0.00	2.47	26.8	13.9	98.936	0.992	0.992	69.85	1.021
2	3600	75	15.6	120.0	3293	15.62	-0.04	1.74	27.3	14.8	98.939	0.995	1.001	74.06	1.023
3	3600	50	10.4	120.0	3356	10.50	0.85	1.38	26.5	14.1	98.944	0.997	0.993	70.50	1.020
4	3600	25	5.2	120.0	3433	5.23	0.46	1.05	26.1	14.9	98.961	0.998	1.002	74.43	1.020
5	3600	10	2.1	120.0	3593	2.13	2.16	0.90	25.4	14.4	98.956	0.999	0.996	71.79	1.018
6	3600	0	0.0	120.0	3727	0.67	n/a	0.86	25.0	14.7	98.964	0.999	1.000	73.50	1.017

	BHP	DILUTE SAMPLE EMISSIONS						DILUTION	DILUTE SAMPLE MASS FLOW						
	from Work	CO	CO2	THC	NOx	CH4	PM	RATIO	PDP Flow	CO	CO2	THC	NOx	CH4	PM
MODE	[kW]	[ppm]	[%]	[ppmC1]	[ppm]	[ppmC1]	[mg]		[scfm]	[g/hr]	[g/hr]	[g/hr C1]	[g/hr]	[g/hr C1]	[g/hr]
1	7.86	168.47	1.21	15.26	77.22			10.59	247.0	68.12	7707.3	3.05	50.87		
2	5.38	54.31	0.85	11.44	72.50			14.94	247.7	22.19	5477.5	2.31	48.72		
3	3.69	36.78	0.67	7.33	32.30			18.91	248.1	15.27	4341.1	1.51	21.88		
4	1.88	23.70	0.50	2.98	6.97			24.51	248.2	9.91	3308.1	0.62	4.79		
5	0.80	16.55	0.43	1.36	3.28			28.32	248.3	6.94	2838.5	0.28	2.25		
6	0.26	17.43	0.41	1.14	2.18			29.56	248.3	7.33	2708.3	0.24	1.50		

	WEIGHT	WEIGHTED SAMPLE MASS FLOW						WEIGHTED
	FACTOR	CO	CO2	THC	NOx	CH4	PM	POWER
MODE		[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[g/hr]	[kW]
1	0.09	6.13	693.7	0.27	4.58			0.71
2	0.20	4.44	1095.5	0.46	9.74			1.08
3	0.29	4.43	1258.9	0.44	6.34			1.07
4	0.30	2.97	992.4	0.18	1.44			0.56
5	0.07	0.49	198.7	0.02	0.16			0.06
6	0.05	0.37	135.4	0.01	0.08			0.00
SUM	1.00	18.82	4374.6	1.39	22.34			3.47

COMPOSITE BRAKE EMISSIONS						
BSCO	=	4.04	g/hp-hr	=	5.42	g/kW-hr
BSCO2	=	938.79	g/hp-hr	=	1258.9	g/kW-hr
BSTHC	=	0.30	g/hp-hr	=	0.40	g/kW-hr
BSNOx	=	4.79	g/hp-hr	=	6.43	g/kW-hr
BS(THC+NOx)	=	5.09	g/hp-hr	=	6.83	g/kW-hr
BSCH4	=		g/hp-hr	=		g/kW-hr
BSNMHC	=		g/hp-hr	=		g/kW-hr
BSPM	=		g/hp-hr	=		g/kW-hr
BSFC	=	0.655	lb/hp-hr	=	0.398	kg/kW-hr

	PERCENT CONTRIBUTION							LAMBDA	RELATIVE	TEMPERATURES					
	CO	CO2	HC	NOx	HC+NOx	CH4	PM	AIR/FUEL	HUMIDITY	HEAD	MF SURF	EXH PRE	EXH POST	CELL	OIL
MODE	%	%	%	%	%	%	%		[%]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]	[deg C]
1	32.6%	15.9%	19.8%	20.5%	20.5%			14.396	42.79	236.47	429.23	683.5	400.2	27.7	134.9
2	23.6%	25.0%	33.3%	43.6%	43.0%			14.454	45.25	215.60	344.85	627.8	335.2	27.8	125.5
3	23.5%	28.8%	31.4%	28.4%	28.6%			14.433	43.85	196.90	299.52	602.5	298.6	27.5	114.6
4	15.8%	22.7%	13.3%	6.4%	6.8%			14.401	46.68	178.14	253.67	587.2	260.2	27.3	104.7
5	2.6%	4.5%	1.4%	0.7%	0.7%			14.384	45.67	167.34	235.63	590.3	243.0	27.1	97.9
6	1.9%	3.1%	0.9%	0.3%	0.4%			14.343	46.72	163.16	236.36	601.2	247.6	27.1	95.6

MANUFACTURER DECLARATIONS				
RATED POWER	8.2	kW @	3600	rpm
PEAK TORQUE	25.1	N-m @	2500	rpm
DECLARED IDLE	N/A	@	N/A	rpm

	CORR.	CORR
	FACTOR	POWER
MODE		[kW]
1	1.0409	8.24

CLASS II - EMISSION STANDARDS			
	EPA Ph2	EPA Ph3	CARB
g/kW-hr	2001-2010	2011+	2008 +
BSCO	610.0	610.0	549.0
BS(HC+NOx)	12.1	8.0	8.0

* Wintertime engines only have to meet CO standard

TAB E

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

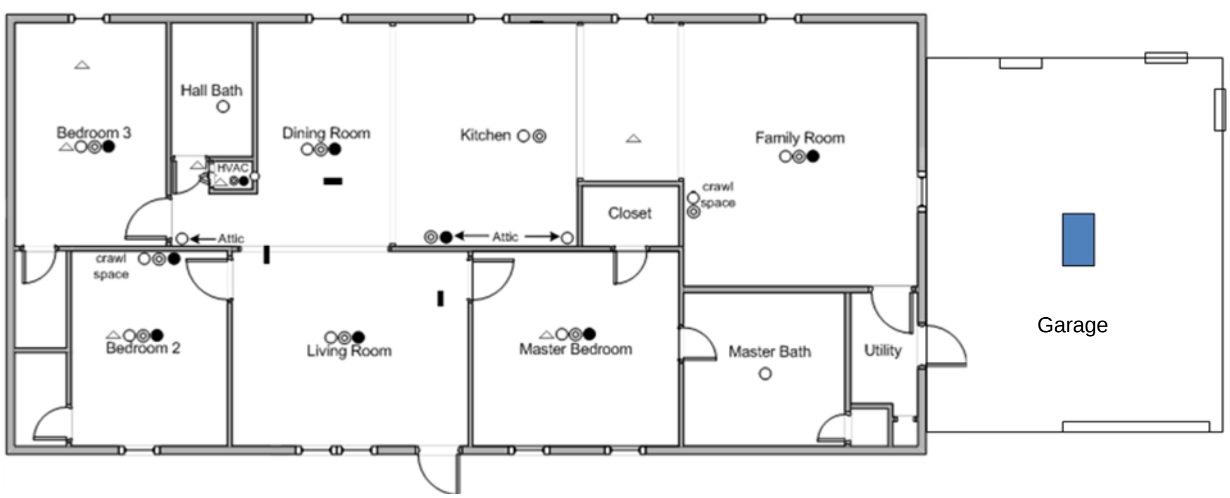
House

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 $^{\circ}$C (140 $^{\circ}$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)**

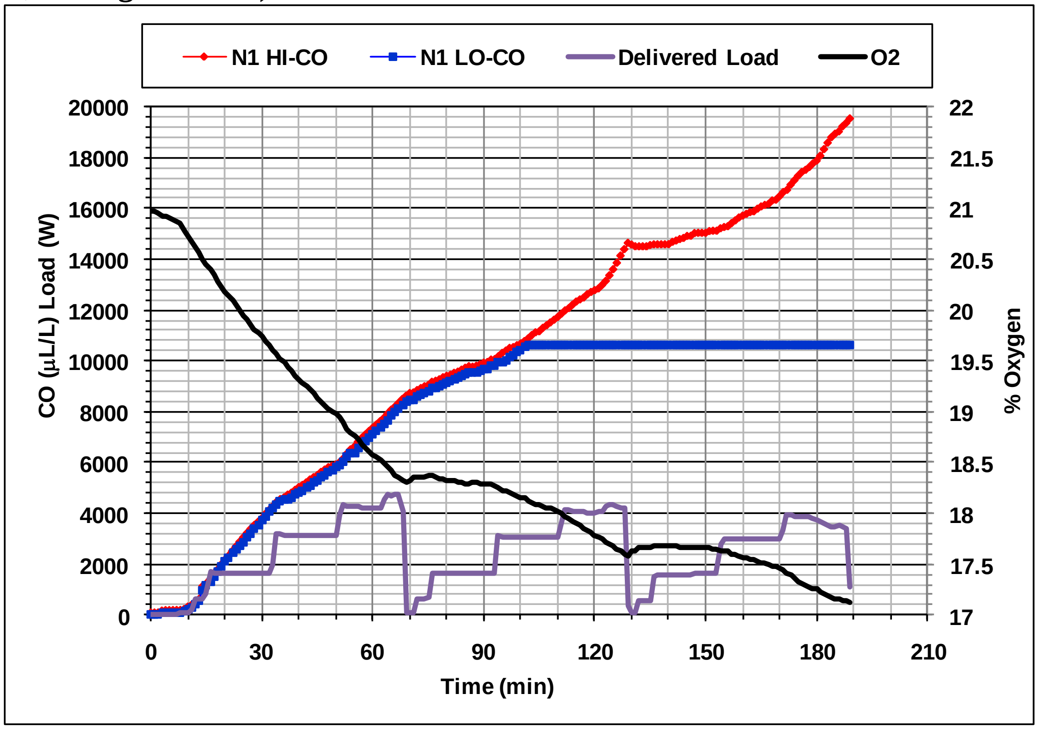


Figure 3a shows the concentration of CO in the garage reached a peak of over 19,500 µL/L (note that µL/L are equivalent to the commonly used unit ppm_v) and the volume fraction of O_2 in the garage dropped by 3.8 % to nearly 17 % when the generator was stopped. It also shows that in the first load cycle, 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)

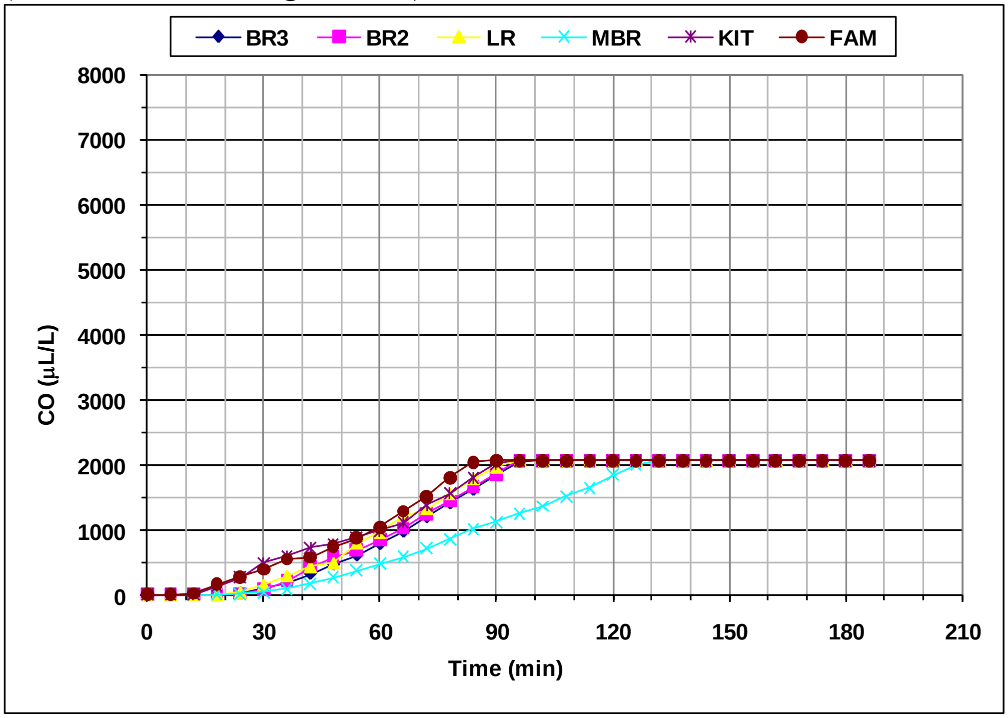
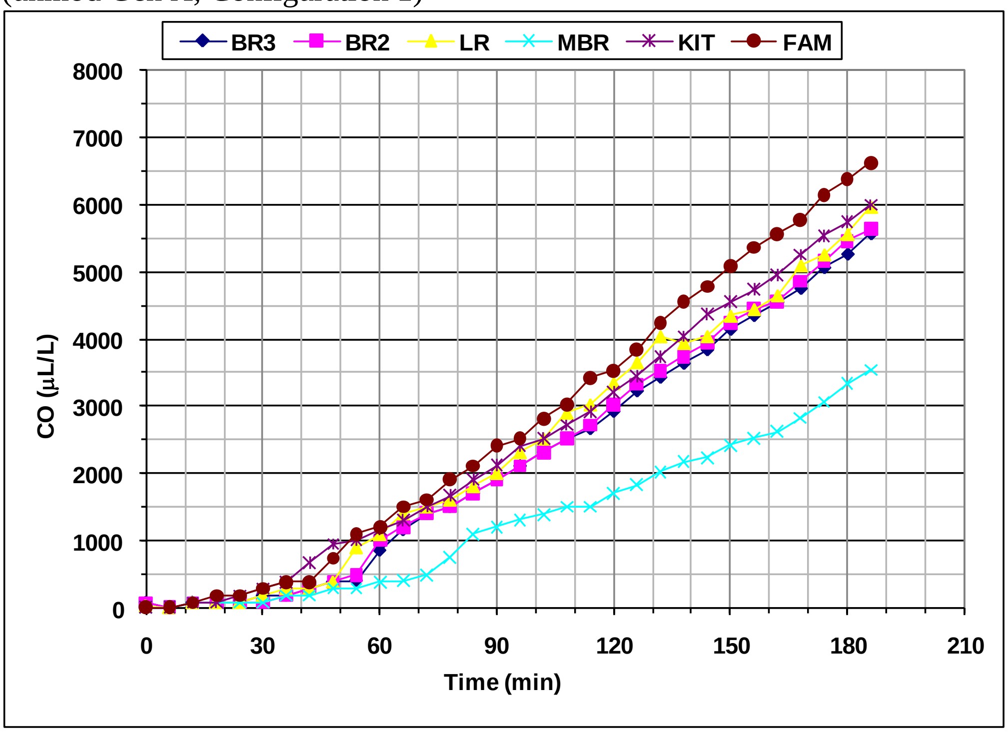


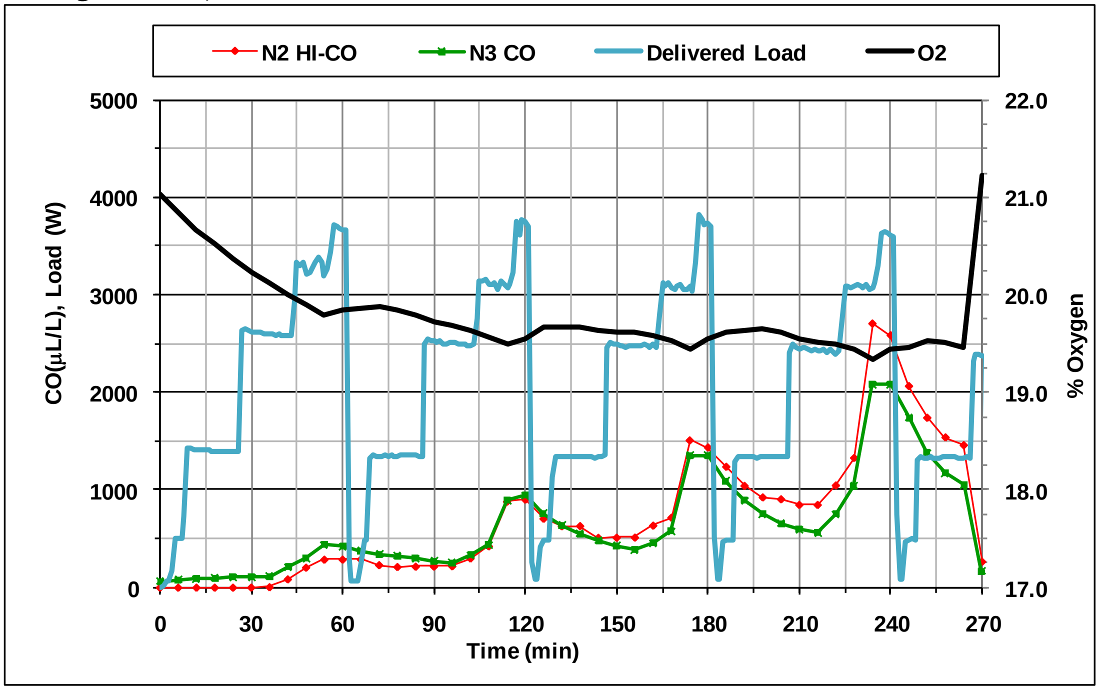
Figure 3c CO (high range) concentrations in the house for Test B (unmod Gen X, Configuration 1)



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)

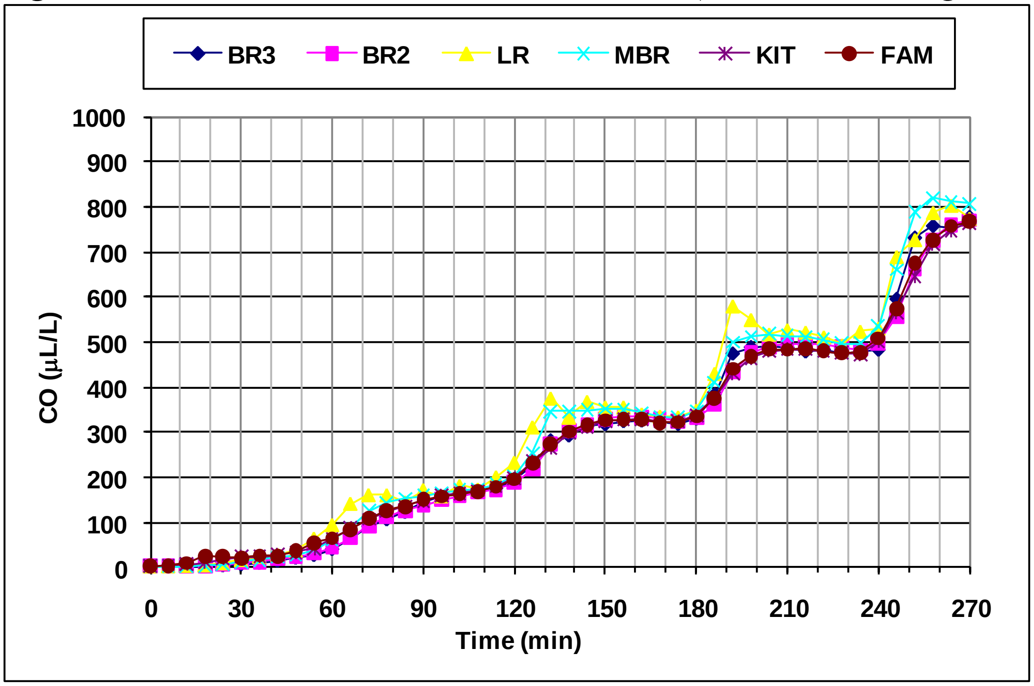


As shown in Figure 4a, the garage CO concentration reached a peak of nearly 3000 μL/L while the garage O_2 concentration dropped by 1.7 % to 19.5 % after completing the fourth cycle of the load profile. Note that the ppm instrument briefly topped out at this time. Also, the initial O_2 concentration 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.

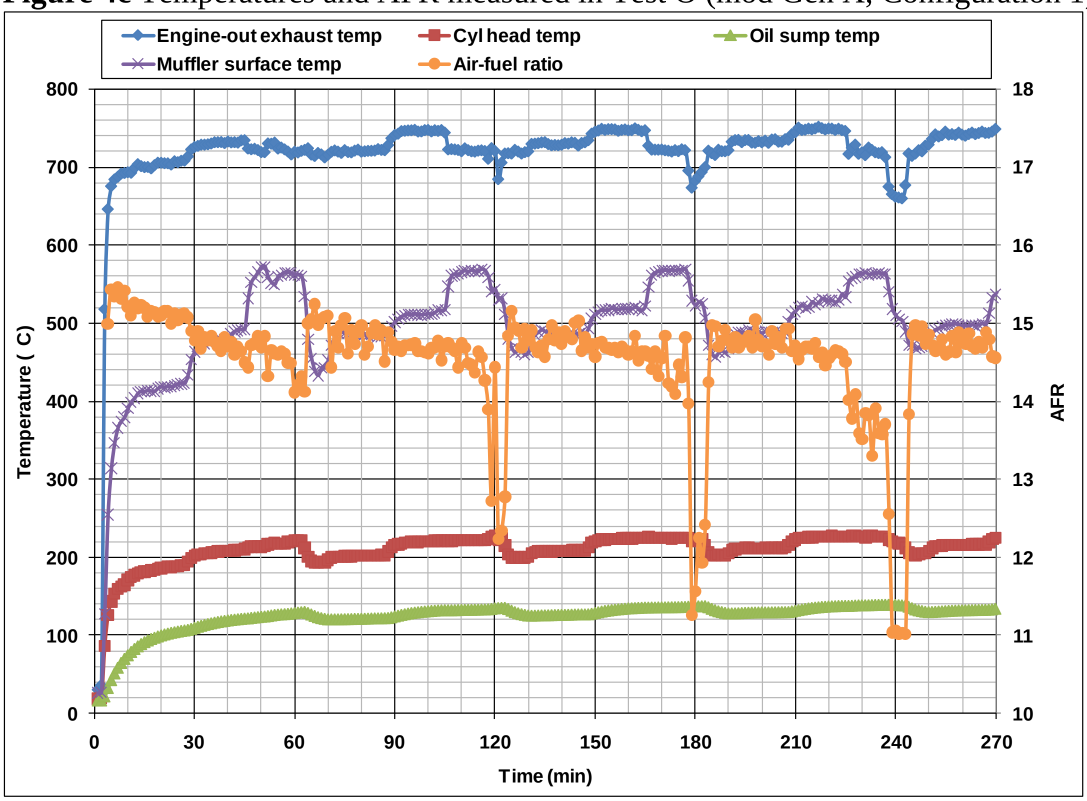
In the first load cycle, as the oxygen dropped, the delivered electrical output was less than the load bank settings for the three highest loads in the load cycle, 3000 W, 4500 W, and 5500 W. While the electrical output stayed near constant for the four cycles, the CO levels increased progressively and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

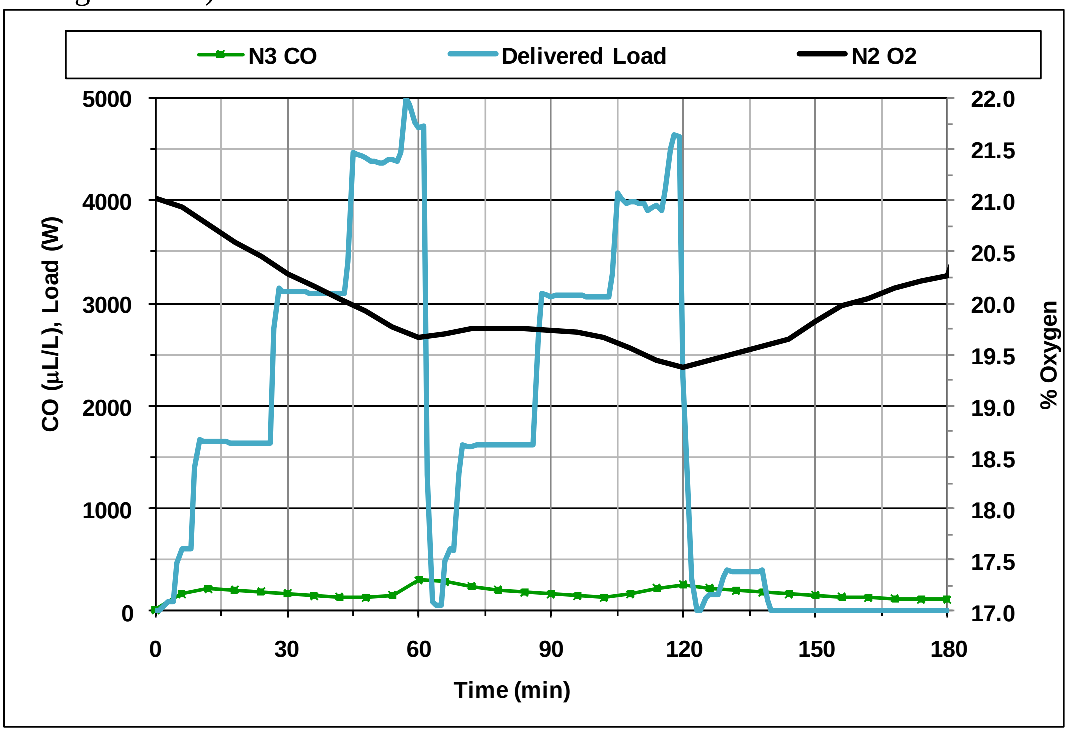
Figure 4c Temperatures and AFR measured in Test O (mod Gen X, Configuration 1)



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.

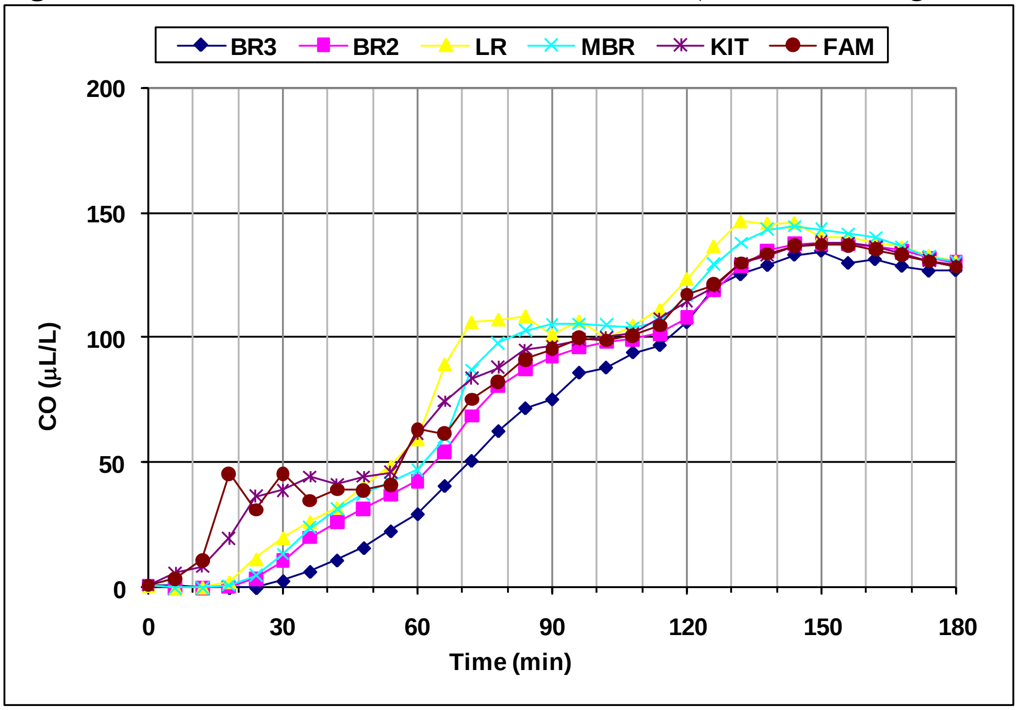
Figures 5a, 5b, and 5c show the results for Test N, which was a two hour test of Gen SO1 with the same test house configuration as used in Test B unmod Gen X and four and Test O of mod GenX (Configuration 1). This test was terminated earlier than planned after a fuse blew on the load bank after 114 min 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)



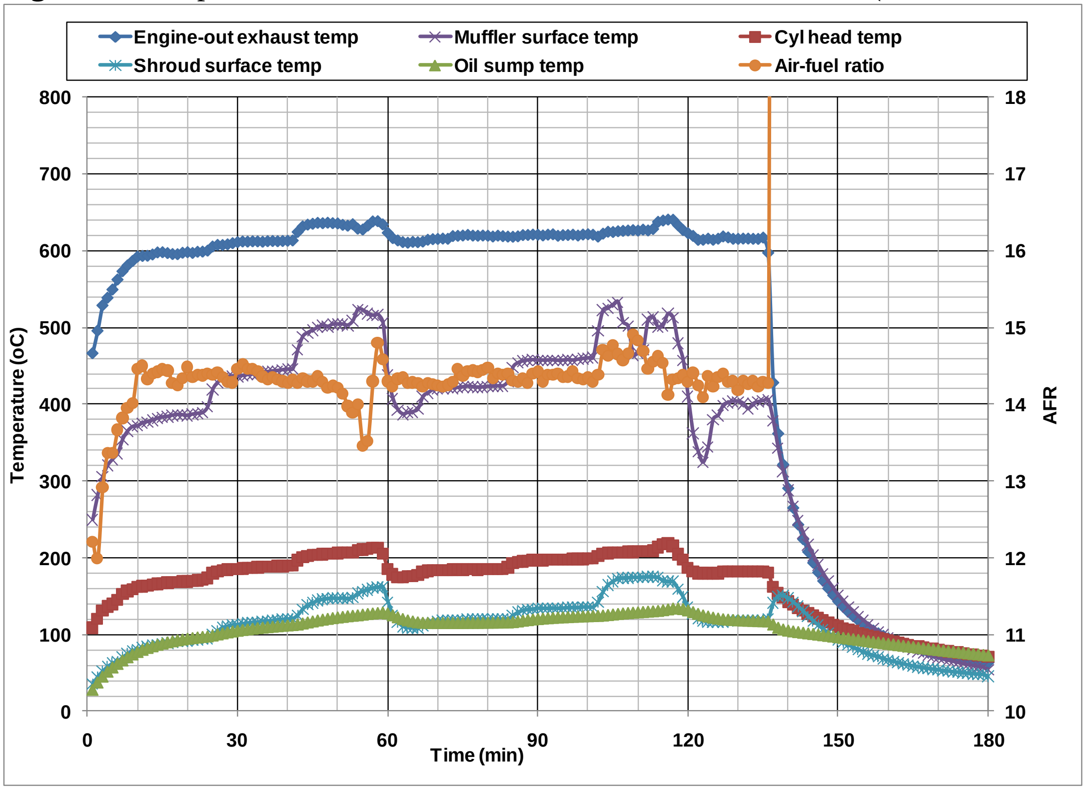
As shown in Figure 5a, there was an initial increase of CO to almost 220 µL/L in the first 12 min after the generator was started. This rise is due to the rich operation upon cold engine start until the oil warms and the ECU transitions to the calibrated AFR fuel control. This initial increase is observed 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.

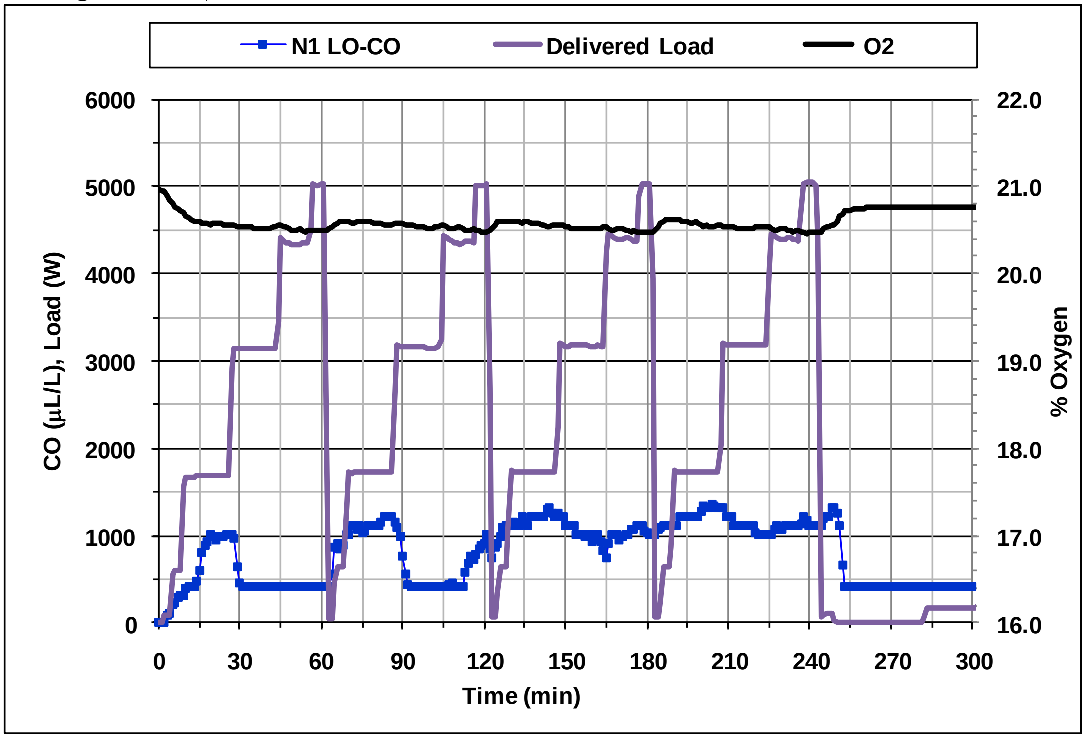
Figure 5c Temperatures and AFR measured on Gen SO1 in Test N (Gen SO1, Configuration 1)



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.

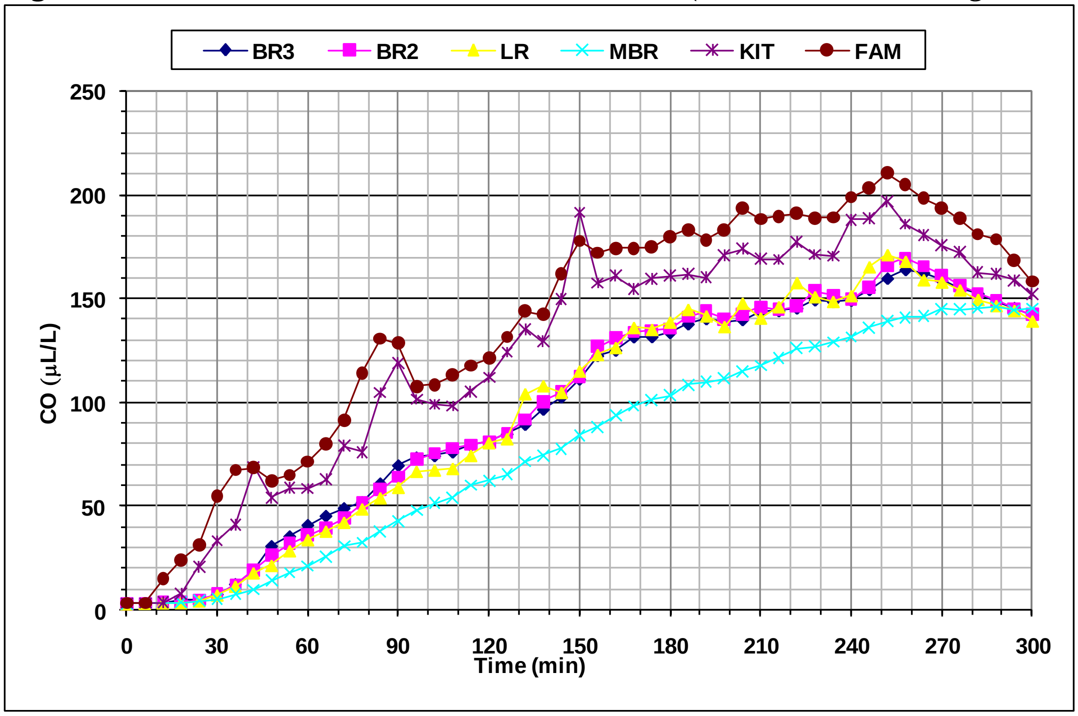
Figure 6a CO and O_2 concentrations in the garage and measured load for Test F (unmod Gen X, Configuration 2)



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.

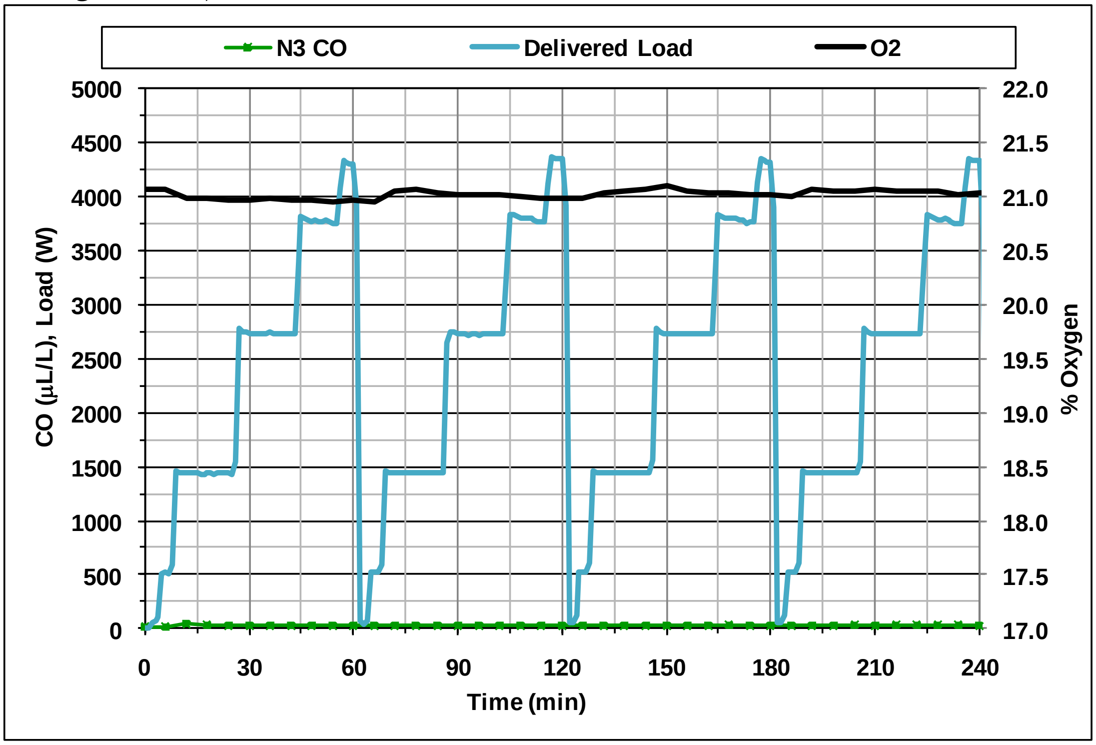
Figure 6b CO concentrations in the house for Test F (unmod Gen X, Configuration 2)



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.

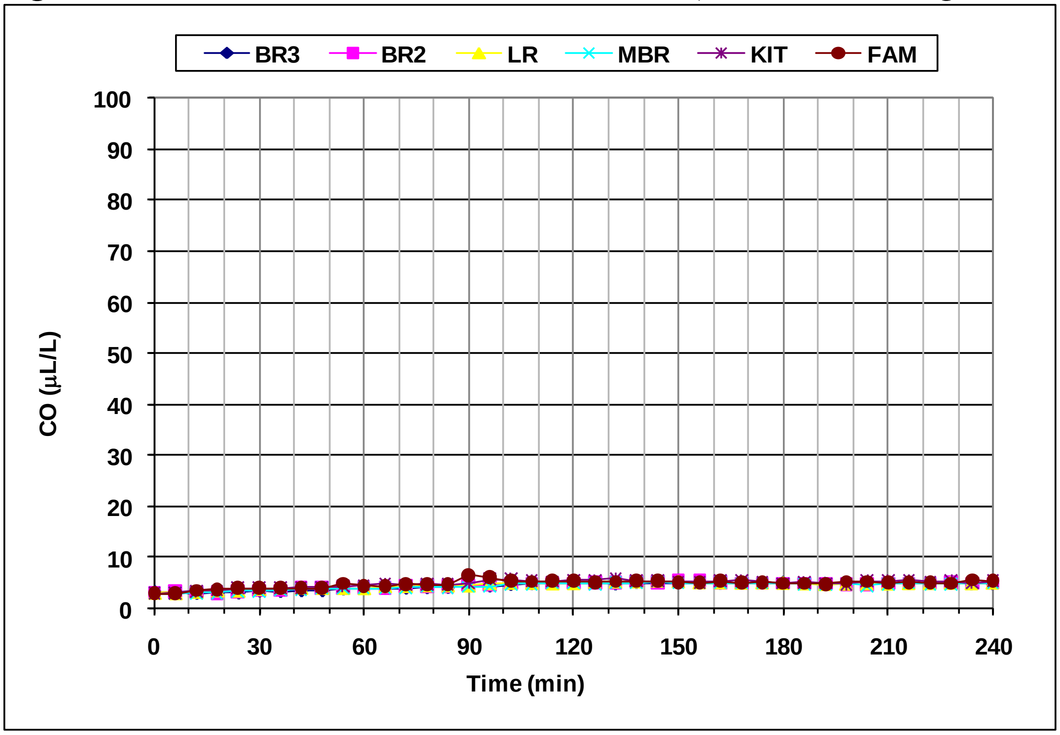
Figure 7a CO and O_2 concentrations in the garage and measured load for Test R (mod Gen X, Configuration 2)



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.

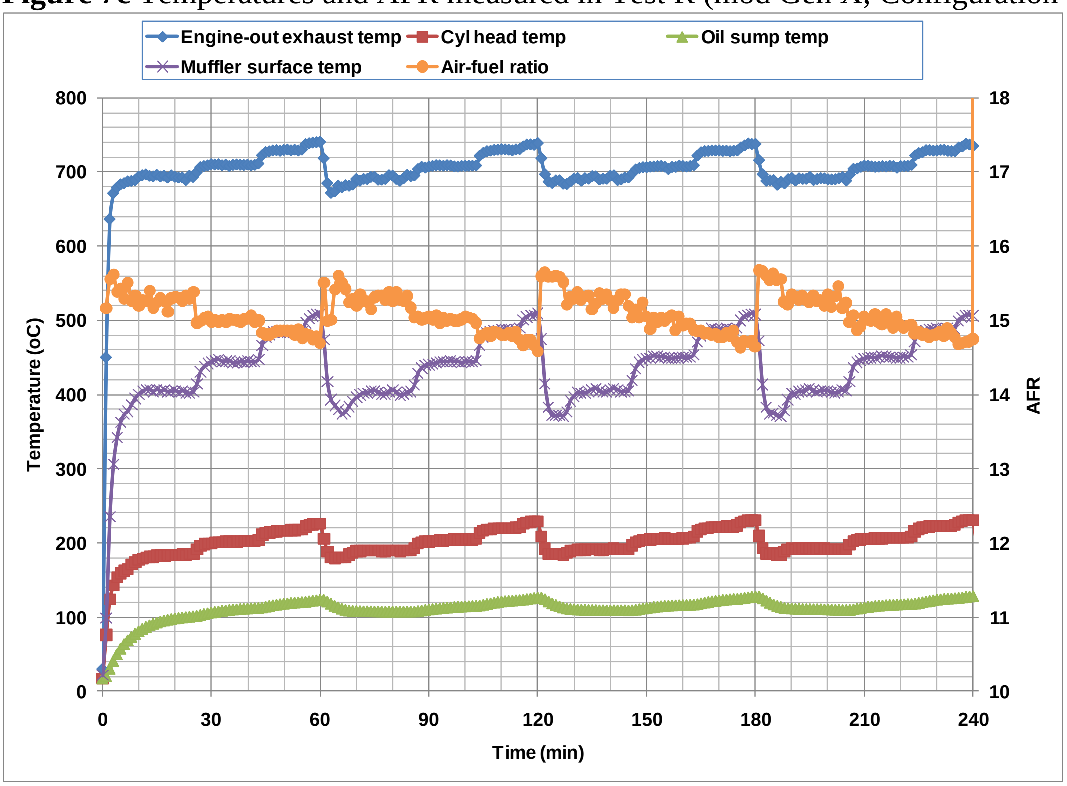
The delivered electrical output was less than the load bank settings for the three highest loads in the load cycle, which occurred with no significant oxygen depletion. After this test, the unit was thoroughly inspected, including the wiring between the generator head and the 240-volt receptacle (in 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 %.

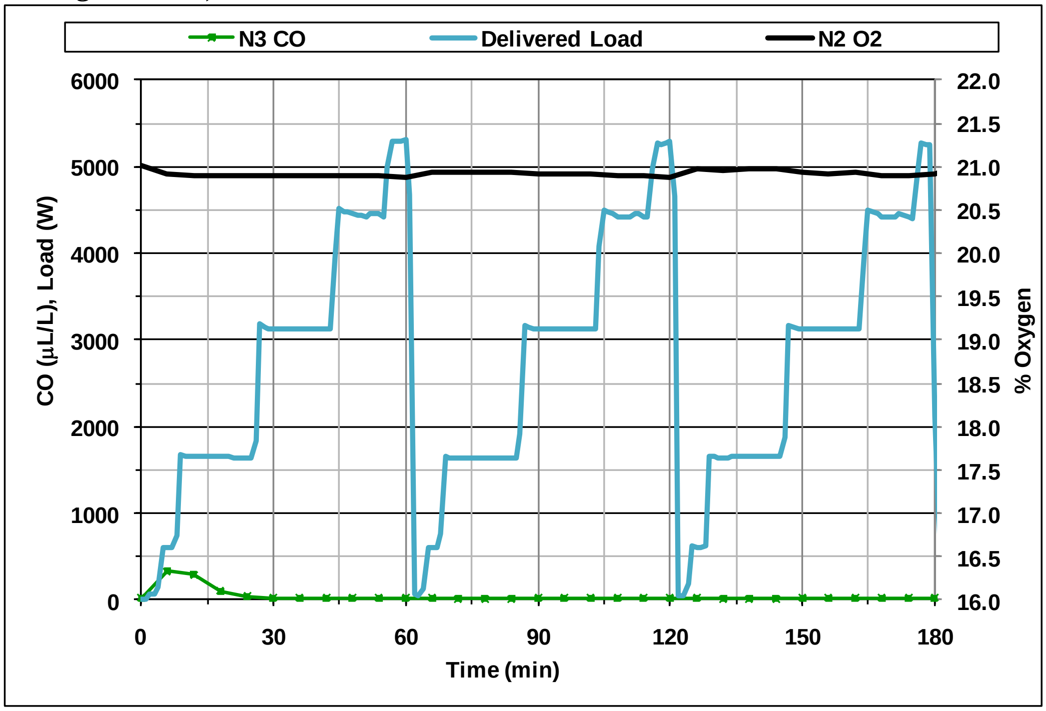
Figure 7c Temperatures and AFR measured in Test R (mod Gen X, Configuration 2)



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.

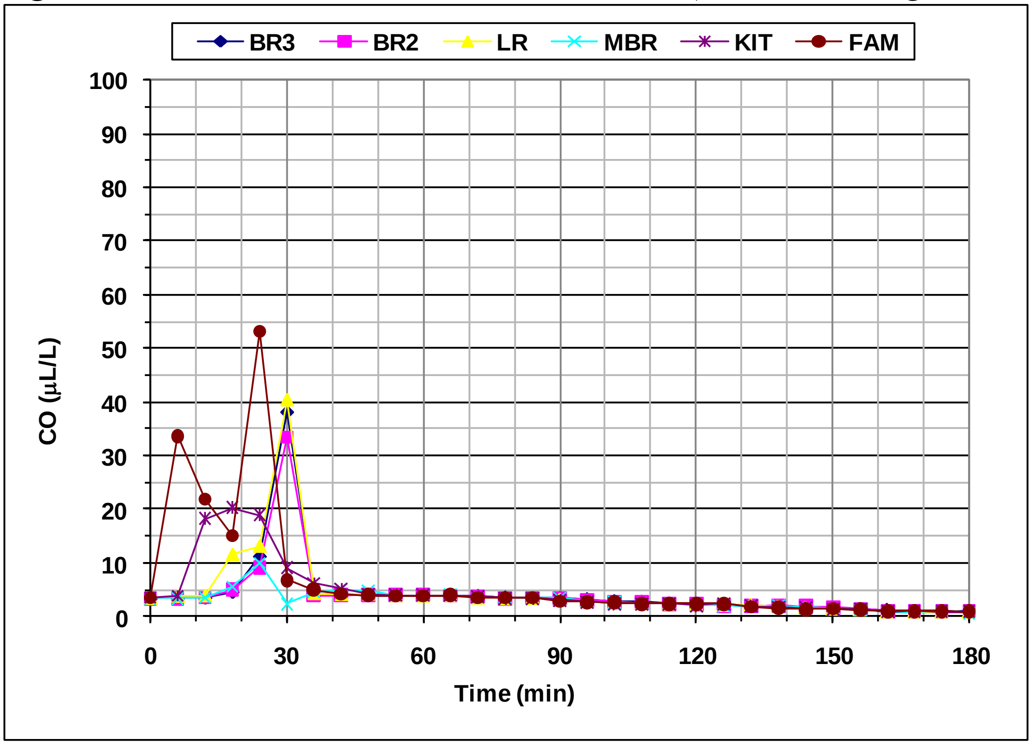
Figures 8a, 8b, and 8c show the results for Test T, which was a three hour test of Gen SO1 with the same test house configuration as used in Test F and Test R of unmod Gen X (Configuration 2). The generator was stopped when a circuit breaker on the 240-volt receptacle tripped. Mechanical venting was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



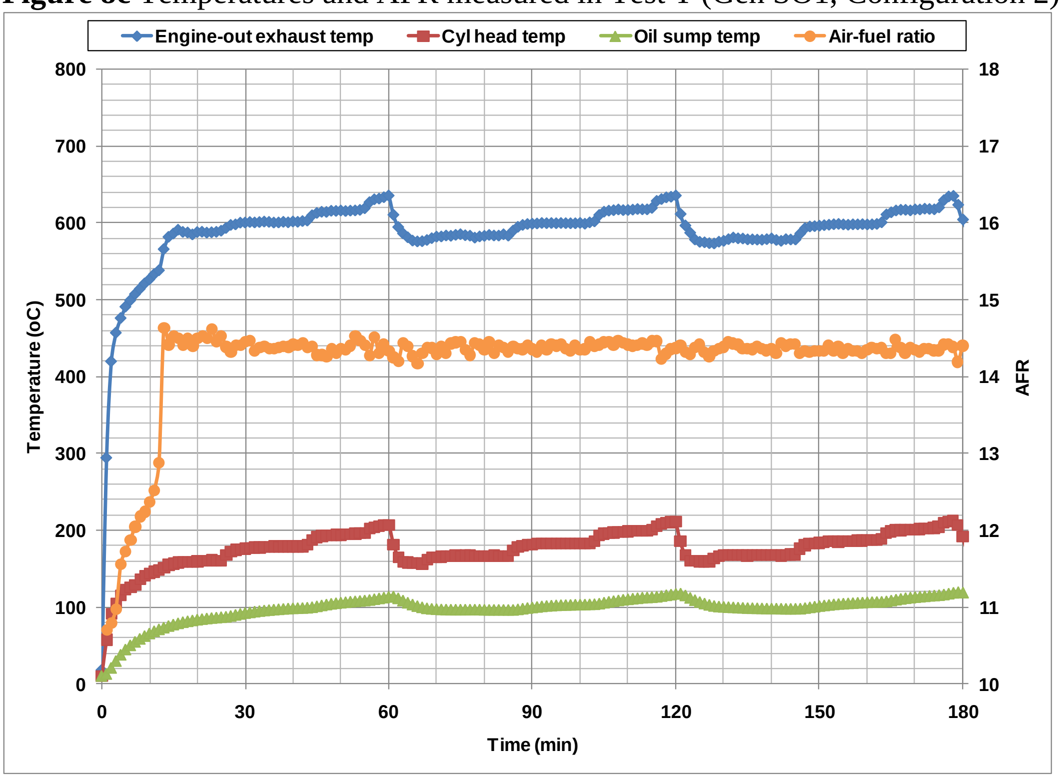
As shown in Figure 8a, there was an initial spike of CO in the garage of over 300 µL/L when the engine was started and as the oil warmed before operation transitioned to the calibrated AFR. The CO concentration then dropped and maintained a nominal level of about 20 µL/L (though the uncertainty of the 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 $^{\circ}$C (158 $^{\circ}$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)

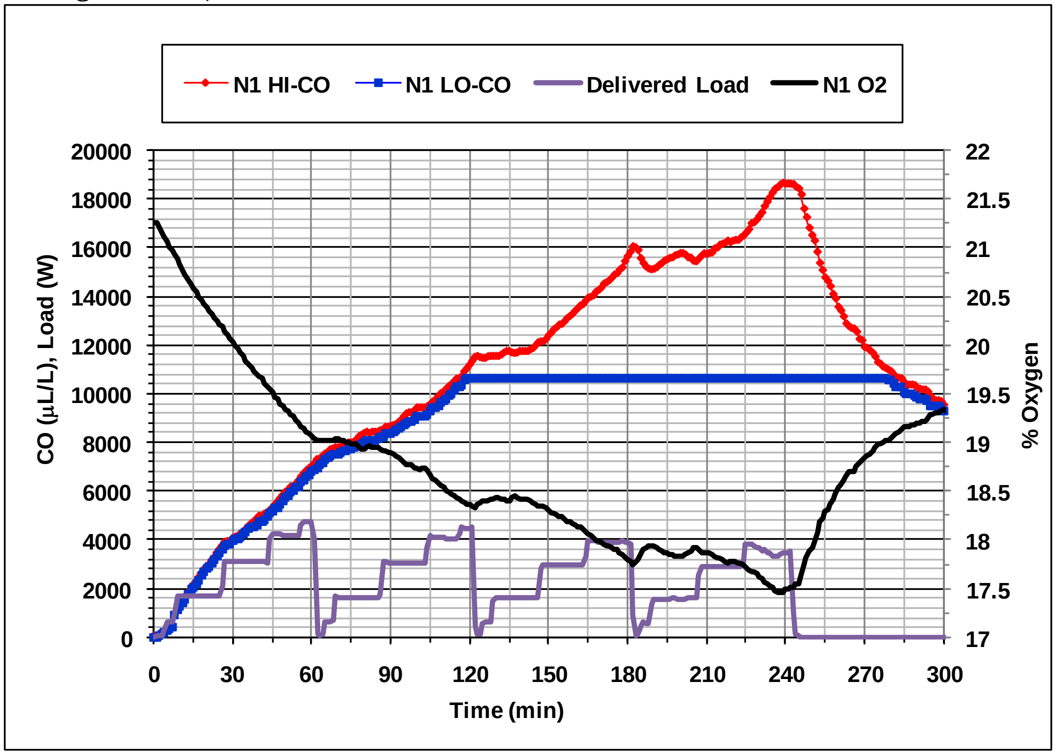


Figure 9a shows that the concentration of CO in the garage reached a peak of about 18,600 µL/L and the concentration of O_2 in the garage dropped by 3.7 % to 17.5 % when the generator was stopped. It also shows that in the first load cycle the delivered electrical output was less than the load bank settings 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)

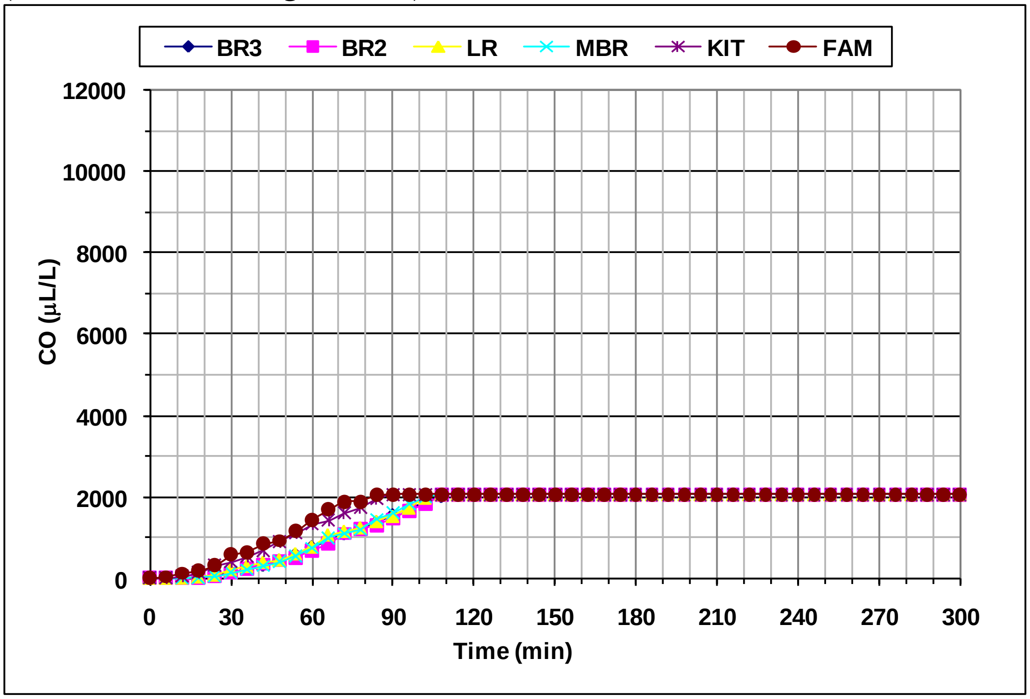
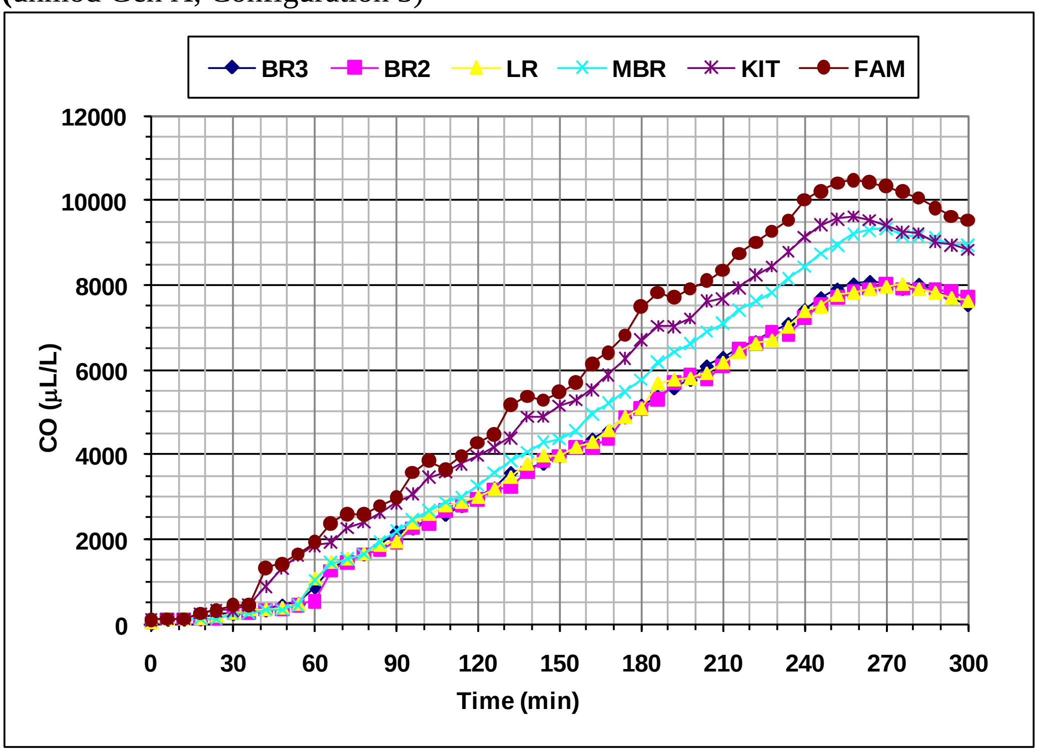


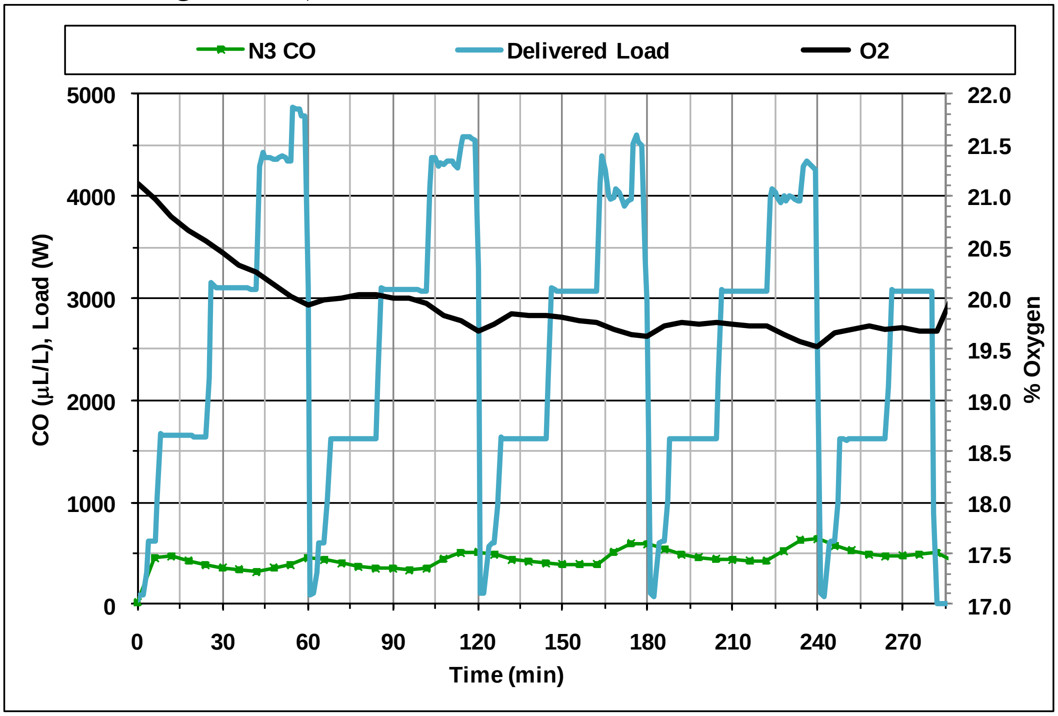
Figure 9c CO (high range) concentrations in the house for Test I **(**unmod Gen X, Configuration 3)



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.

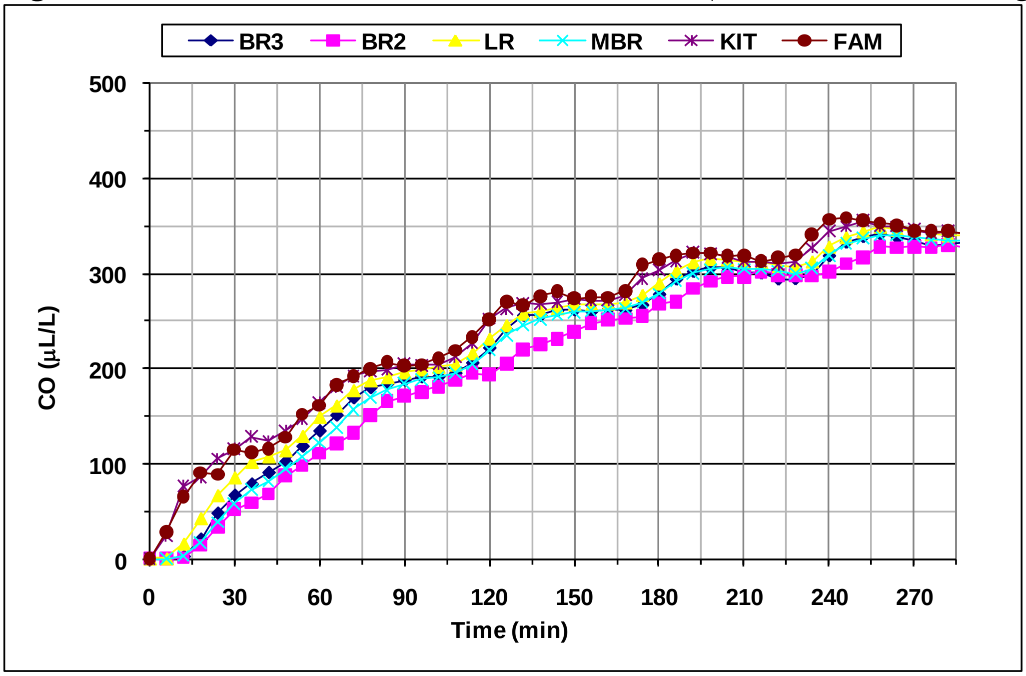
Figure 10a CO and O_2 concentrations in the garage and measured load for Test Z **(**Gen SO1 noncat, Configuration 3)



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.

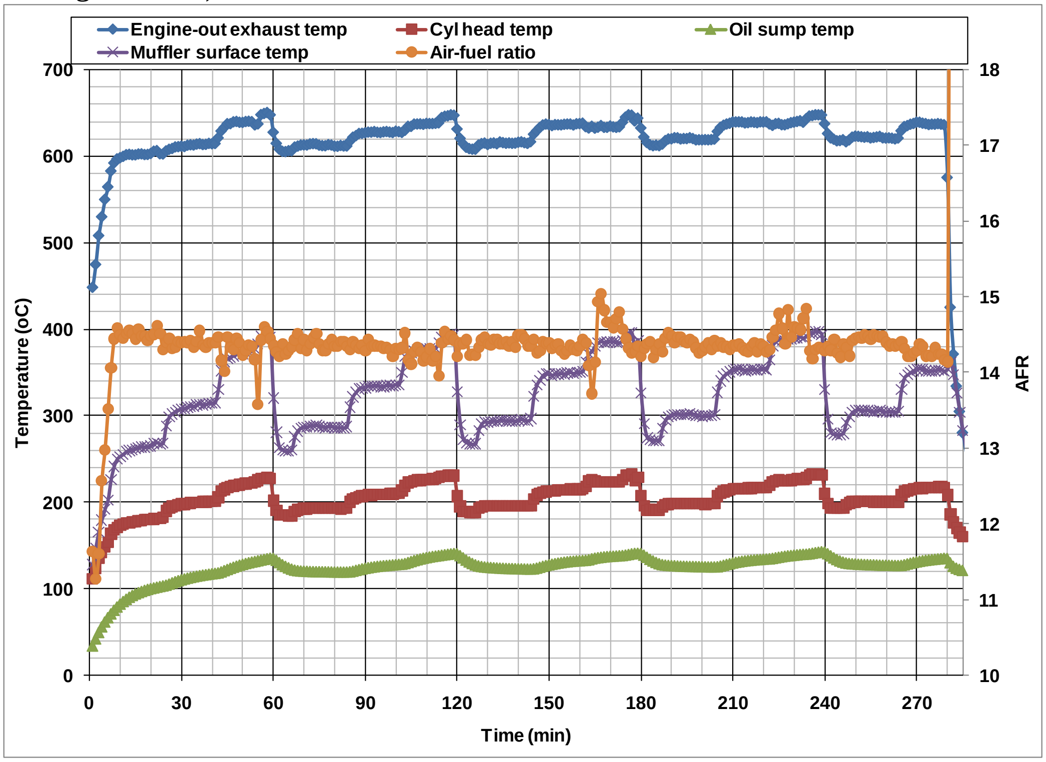
Figure 10a also shows that the delivered electrical output was progressively less than the load bank settings for the two highest loads in the load cycle as the oxygen dropped throughout the test.

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)

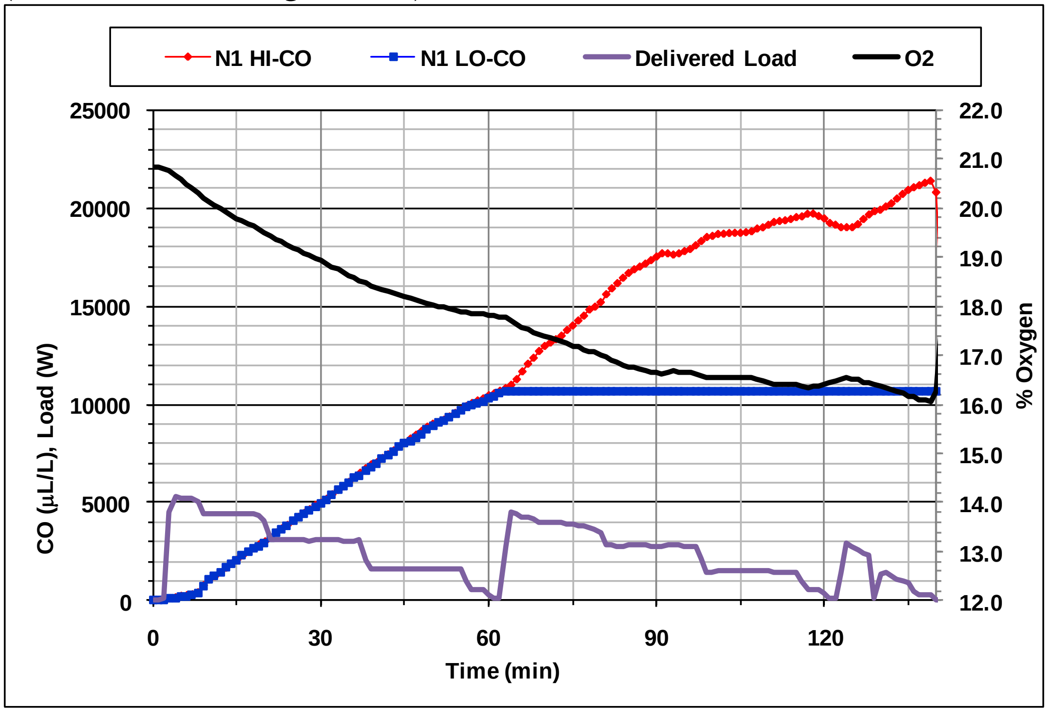


The AFR and temperatures measured on Gen SO1 during Test Z are shown in Figure 10c. With the exception of a few short periods of AFR excursion after the engine warmed up, the engine operated at the calibrated AFR. The spike in AFR at the end of the test corresponds to when the engine was turned off.

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.

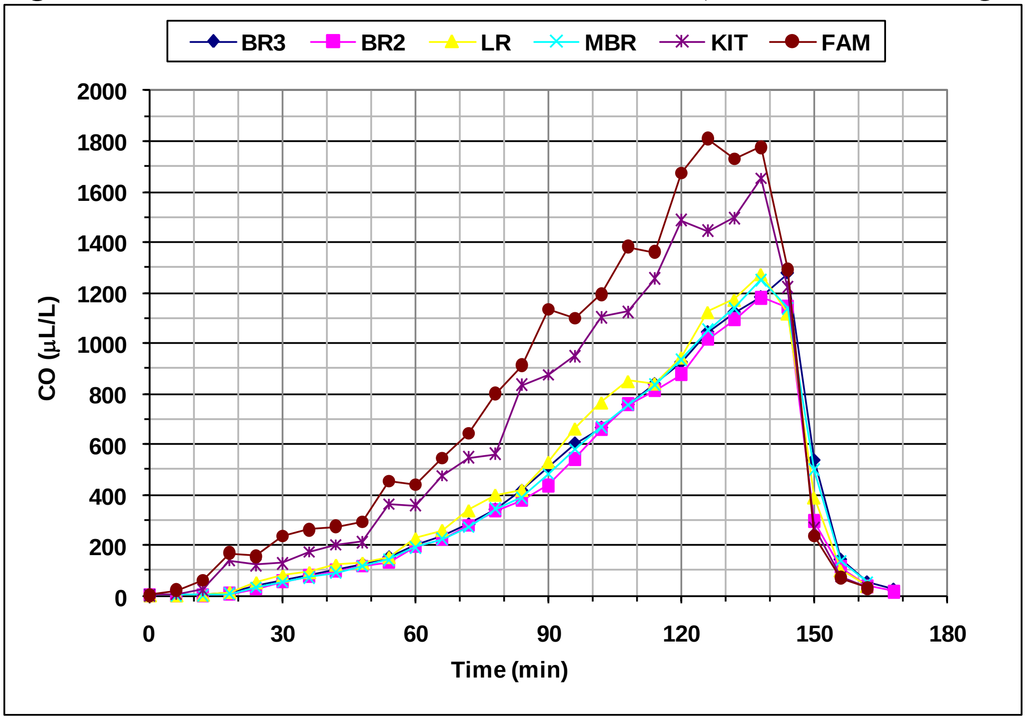
Figures 11a and 11b show the results for the two and a quarter hour test of unmod Gen X, Test J, in Configuration 4 (garage bay door closed, garage access door to house closed, and the house central HVAC fan on). After the generator was stopped, the garage was mechanically vented. For this test, the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

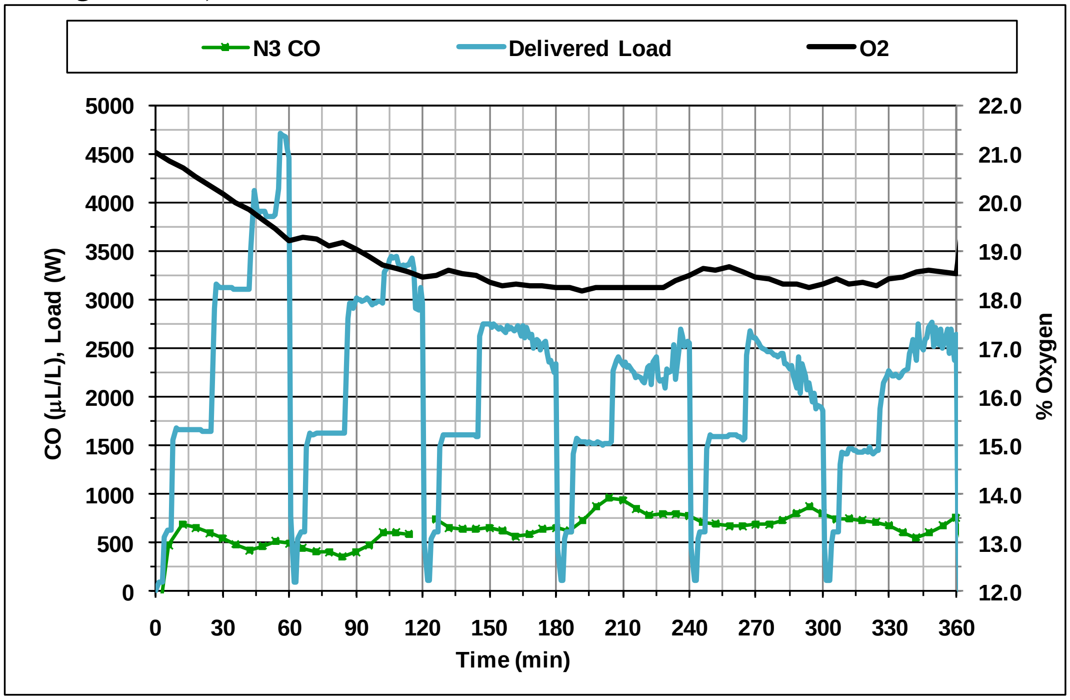
Figure 11b CO concentrations in the house for Test J **(**unmod Gen X, Configuration 4)



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)

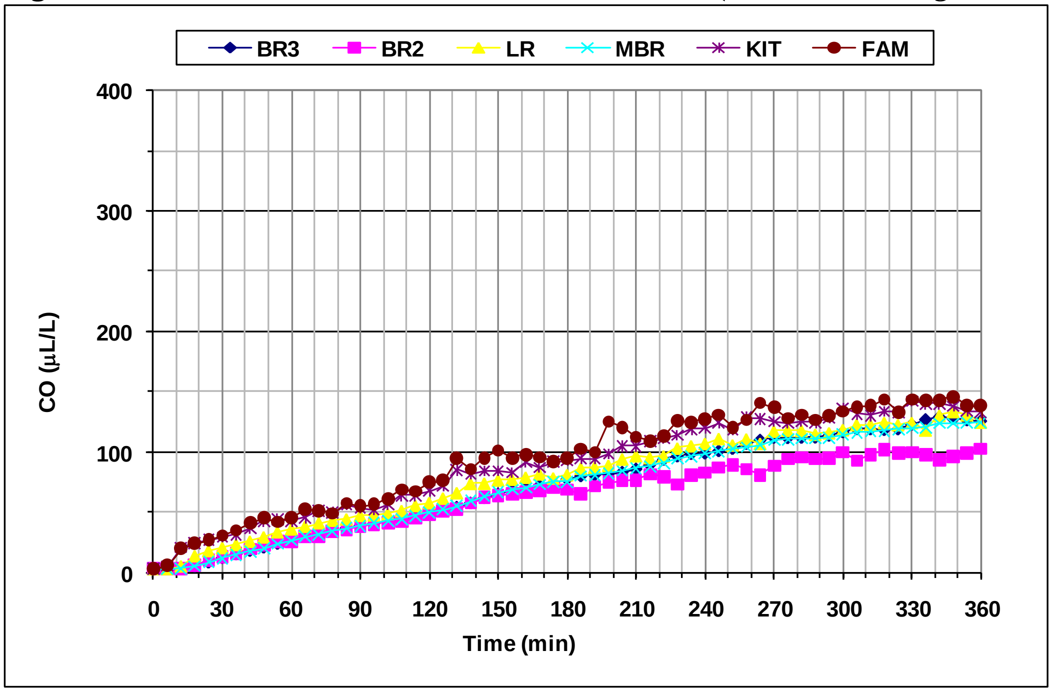


As shown in Figure 12a, the CO concentration in the garage initially rose to 680 µL/L, and then decreased after the engine warmed up. In the fourth load cycle, it reached a peak of about 960 µL/L and the oxygen lowered by 2.8 % to 18.2 %.

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.

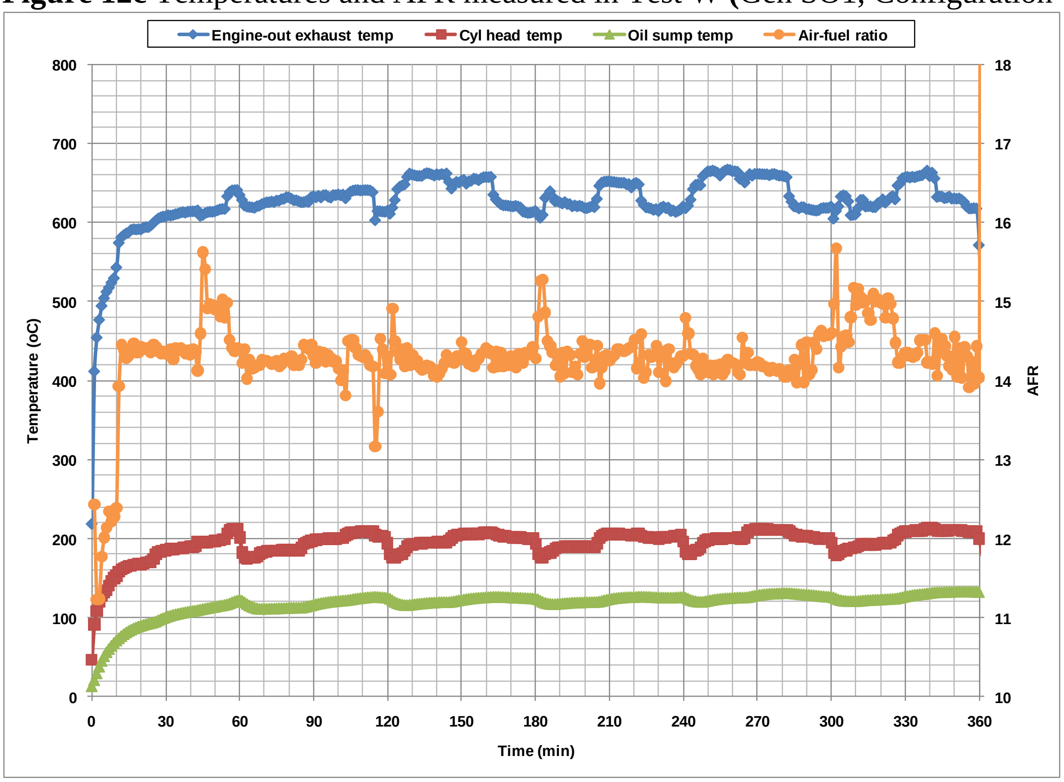
In the first load cycle, the delivered electrical output exceeded the load bank settings except for the two highest loads. In the subsequent load cycles, as the oxygen level dropped, the delivered power was less than the load bank settings for the three highest loads in the cycle.

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)

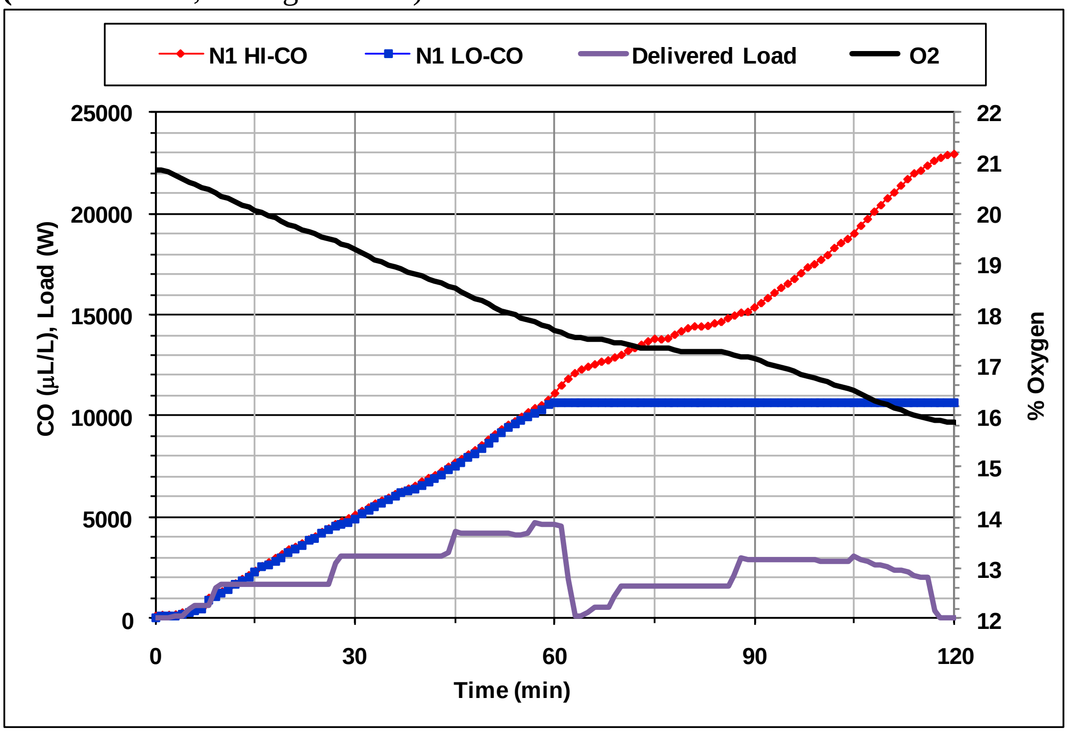


Figure 13a shows the concentration of CO in the garage reached a peak of almost 23,000 µL/L and the concentration of O_2 in the garage dropped by 5.0 % to below 16 % when the generator was stopped. It also shows that in the first load cycle the delivered electrical output was less than the load bank 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)

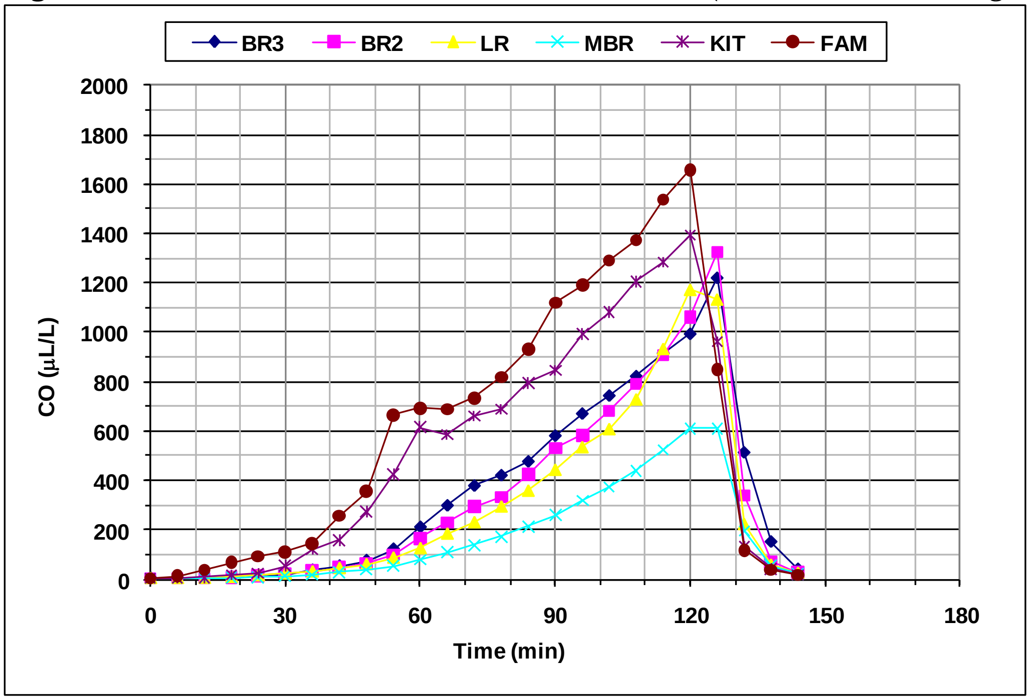
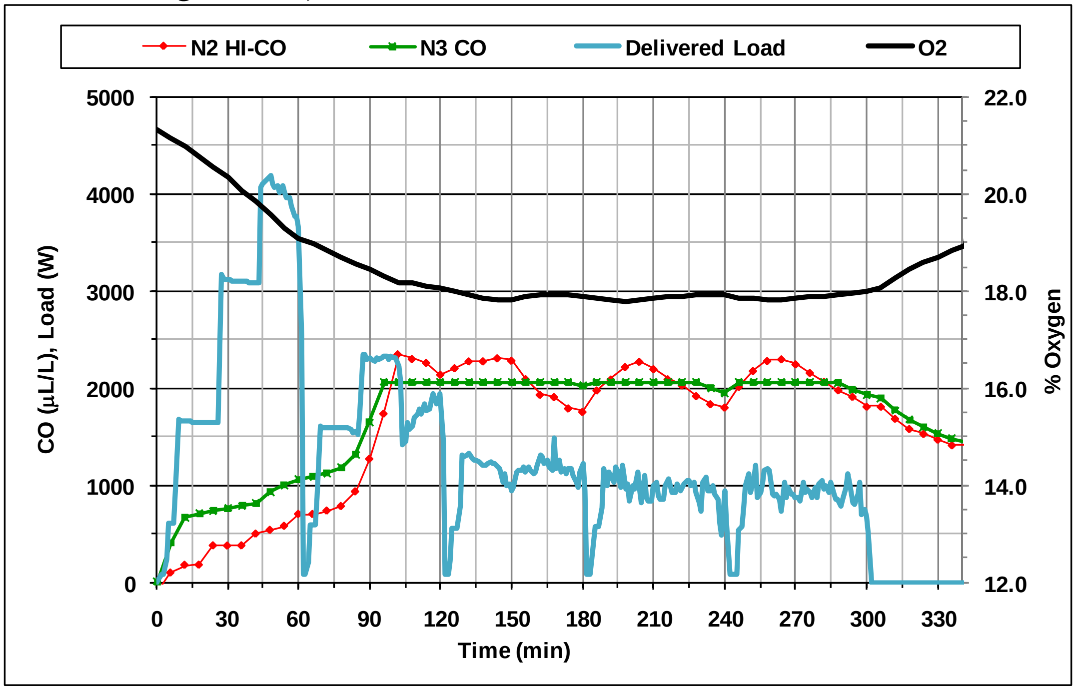


Figure 13b shows the CO reached a peak concentration of almost 1660 µL/L in the family room with peak concentrations in the other rooms ranging from about 600 µL/L to 1400 µL/L. This is a comparable peak CO concentration to the 1670 µL/L measured in the family room at the 2 h point in Test J. When comparing 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.

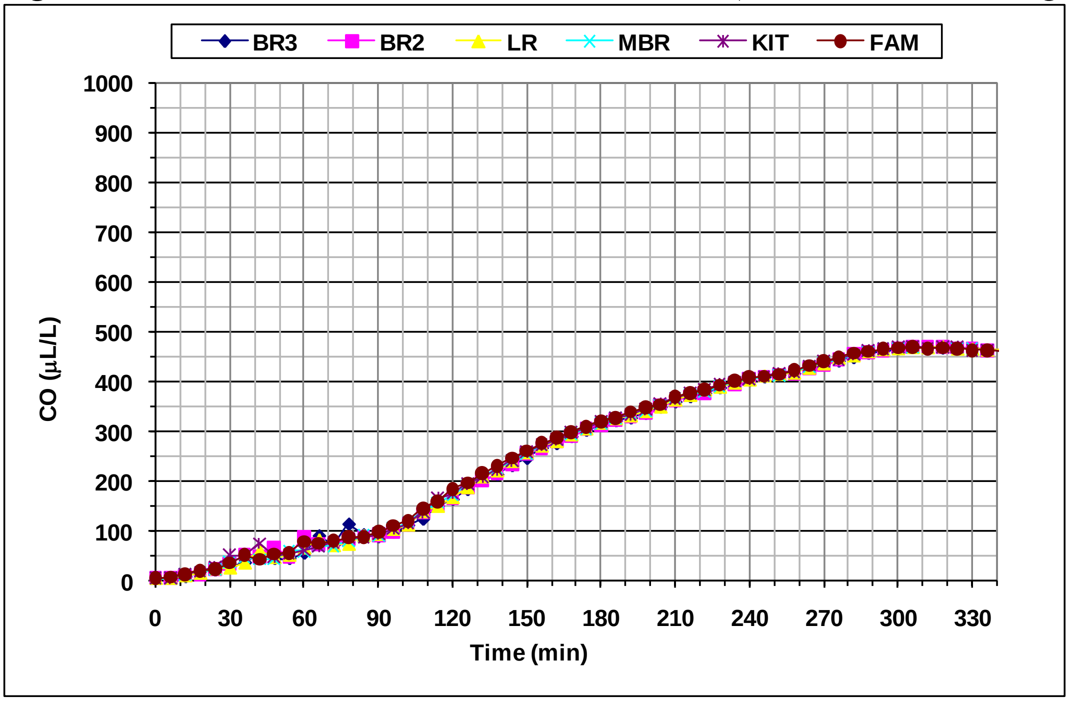
Figure 14a CO and O_2 concentrations in the garage and measured load for Test AH **(**Gen SO1 noncat, Configuration 5)



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.

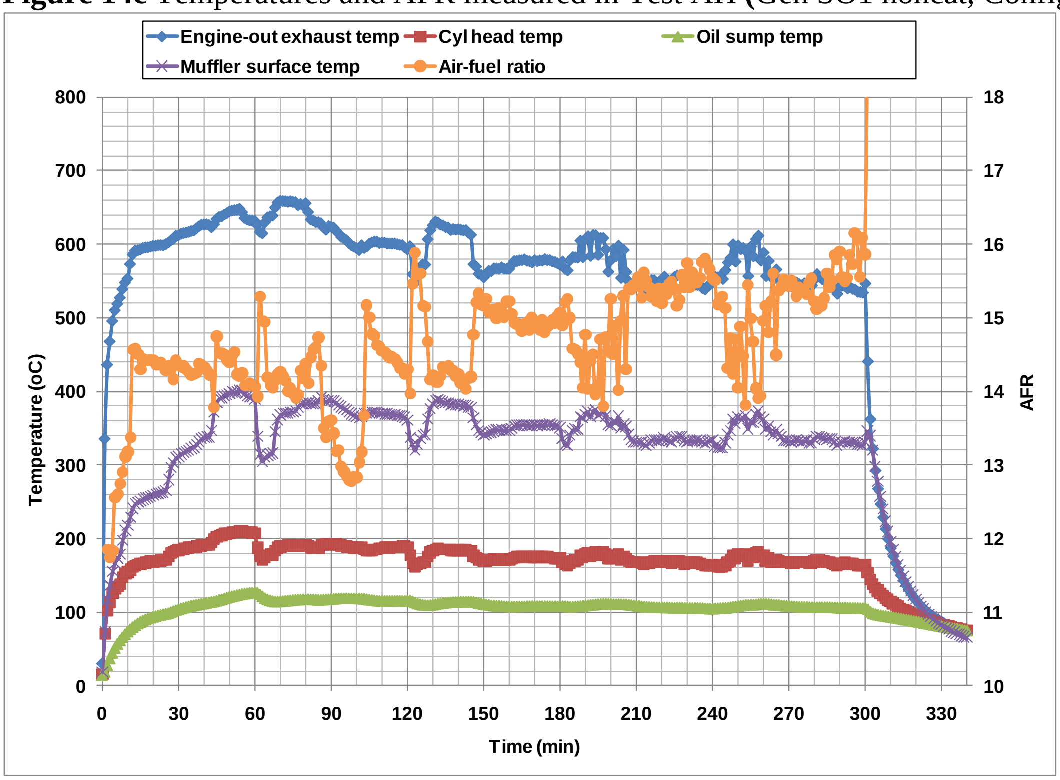
Figure 14a also shows that in the first load cycle the delivered electrical output was less than the load bank settings for the two highest loads in the load cycle. During the subsequent load cycles the delivered power degraded even further as the garage oxygen approached and then dropped below 18 %.

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)

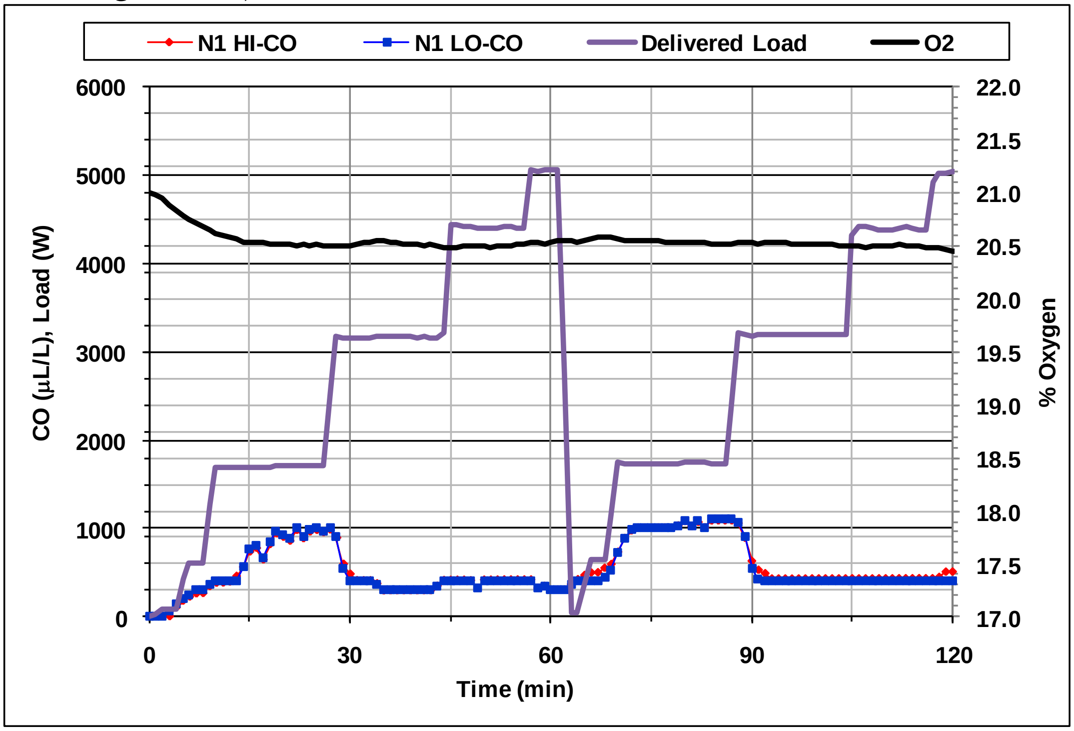


The AFR and temperatures measured on noncat Gen SO1 during Test AH are shown in Figure 14c. After the engine warmed up, it operated at the calibrated AFR for the next 30 min, but then had periods of off-design operation throughout the remainder of the test. The spike in AFR at the end of the test corresponds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

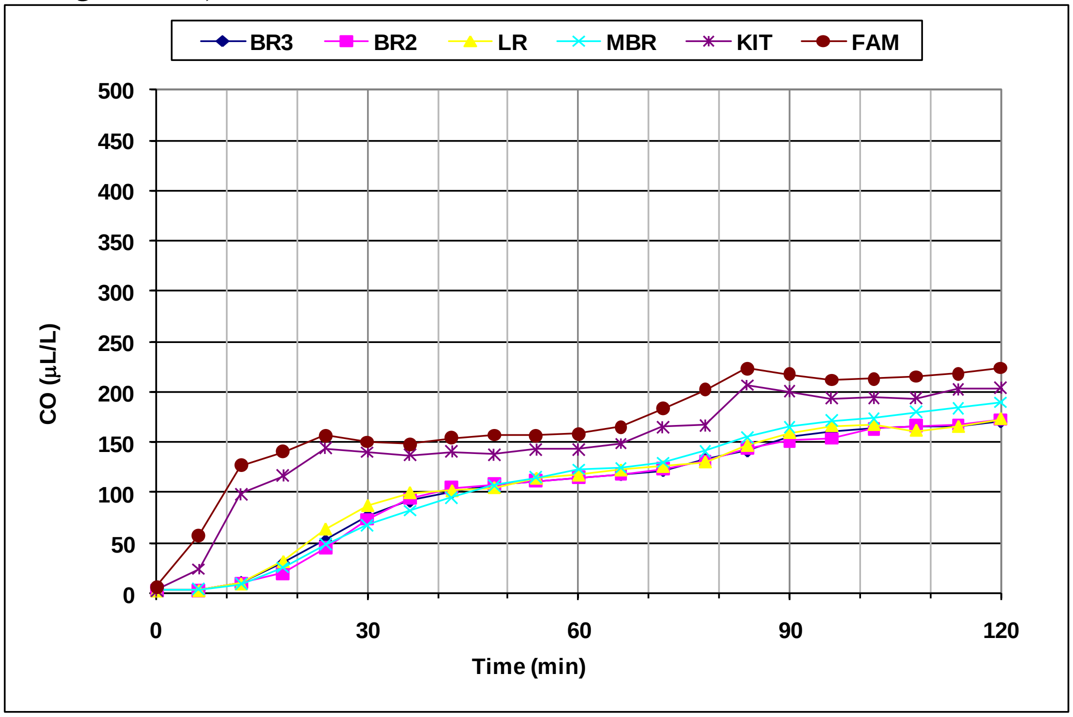
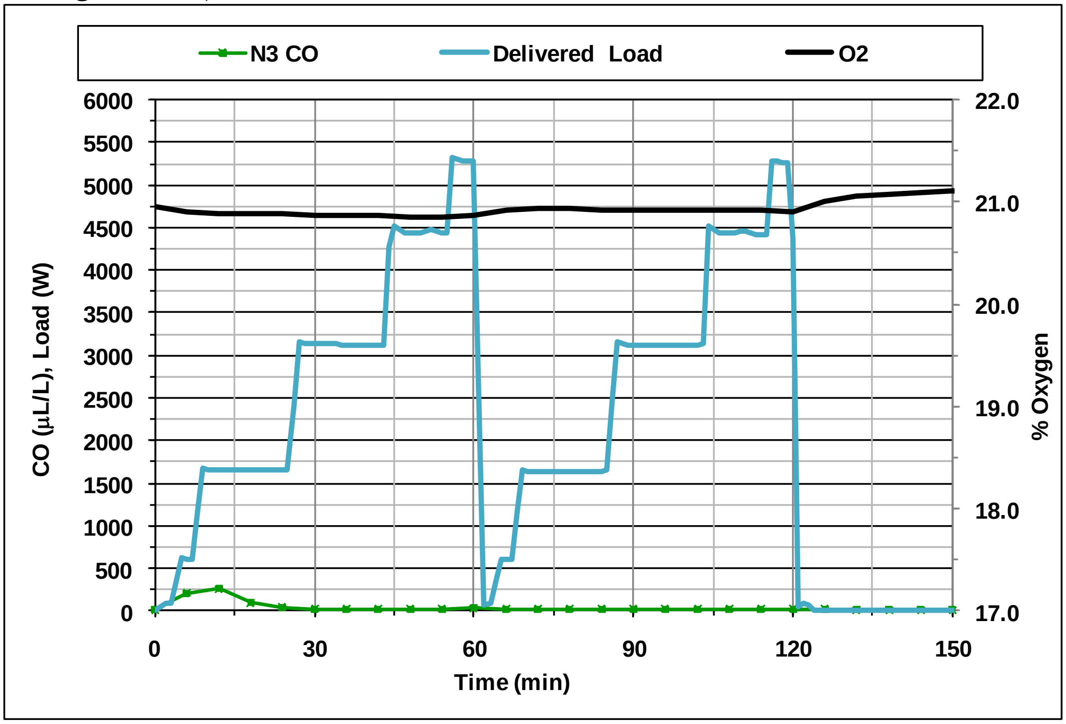


Figure 15b shows the CO reached a peak concentration of about 220 µL/L in the family room with slightly lower peak concentrations in the other rooms of around 190 µL/L to 200 µL/L.

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.

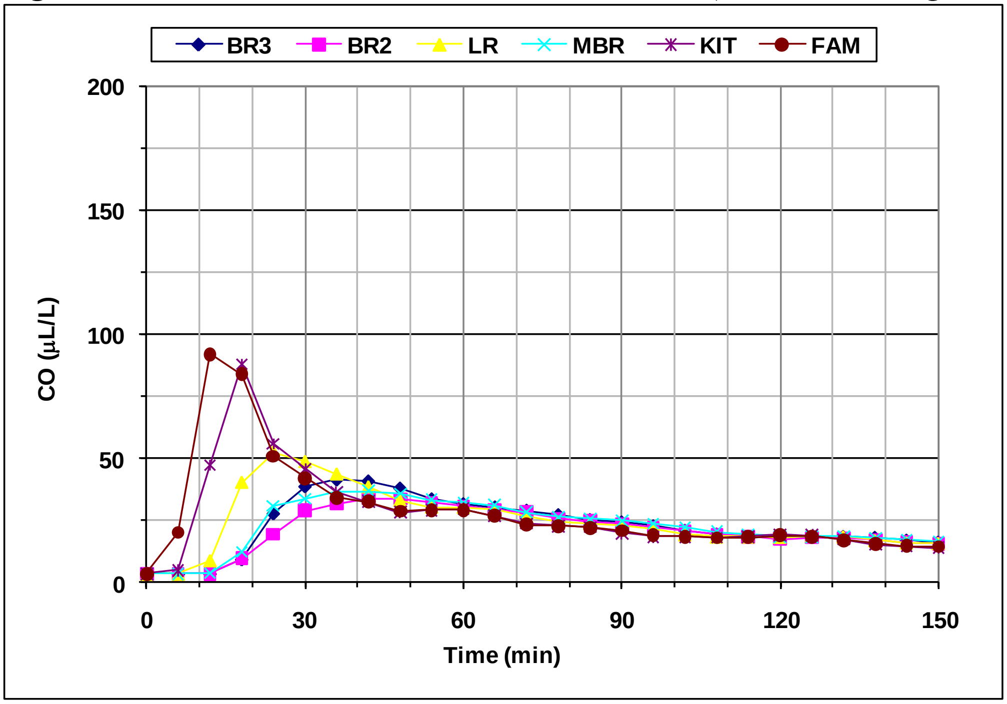
Figure 16a CO and O_2 concentrations in the garage and measured load for Test U **(**Gen SO1, Configuration 6)



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.

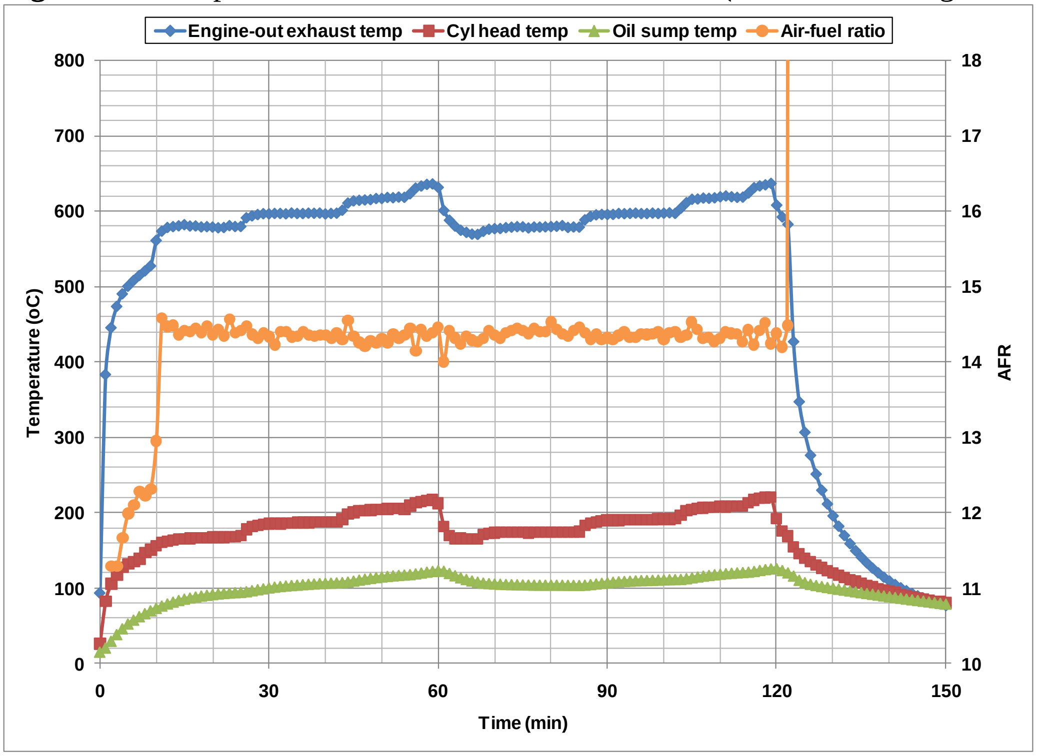
Figure 16b CO concentrations in the house for Test U **(**Gen SO1, Configuration 6)



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.

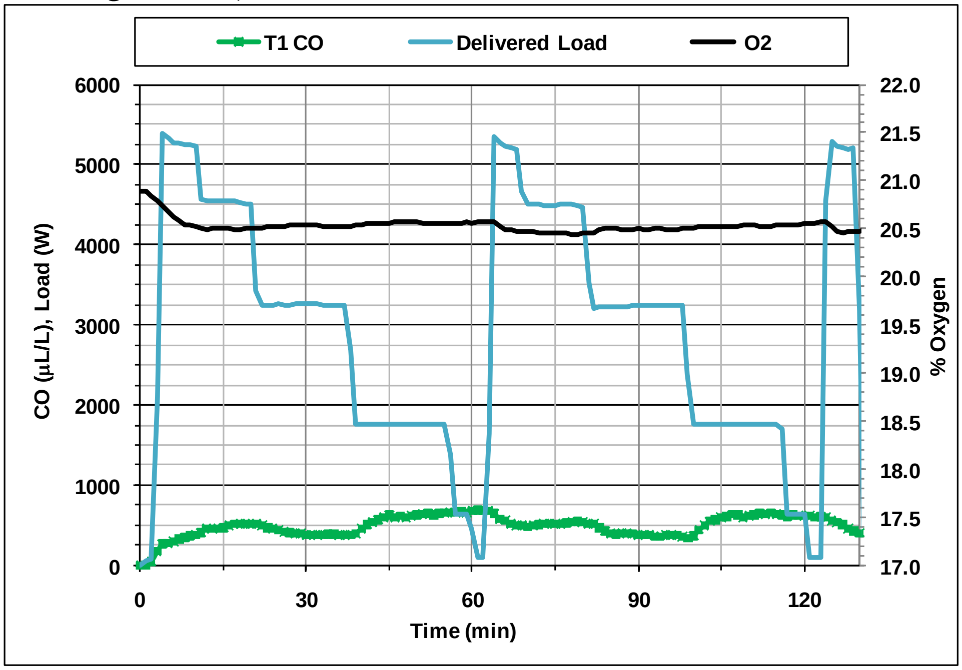
Figure 16c Temperatures and AFR measured in Test U **(**Gen SO1, Configuration 6)



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 °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)

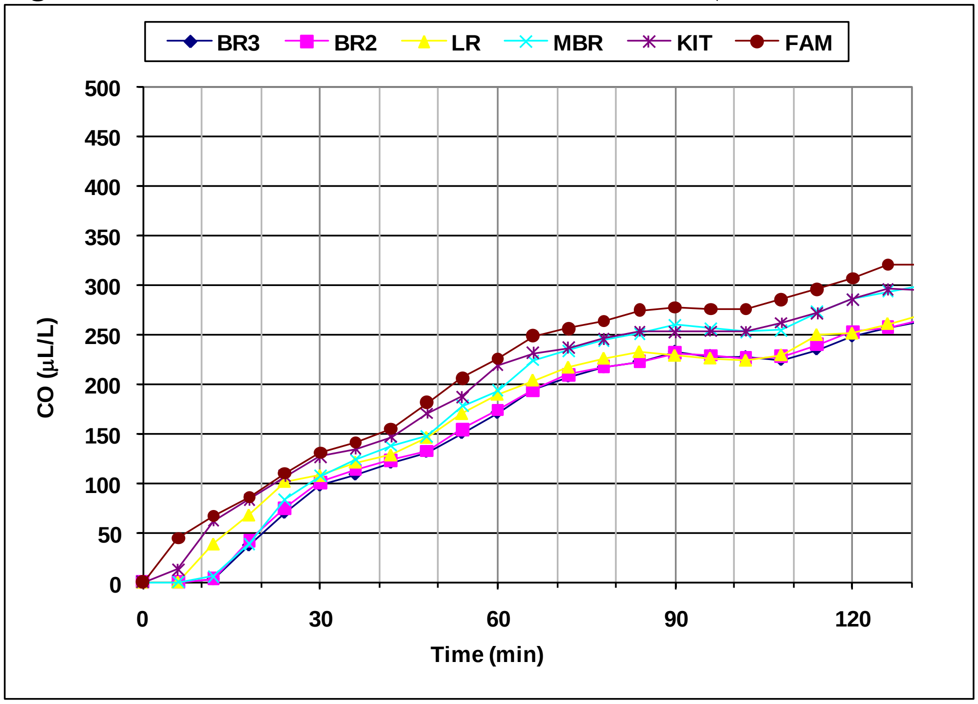
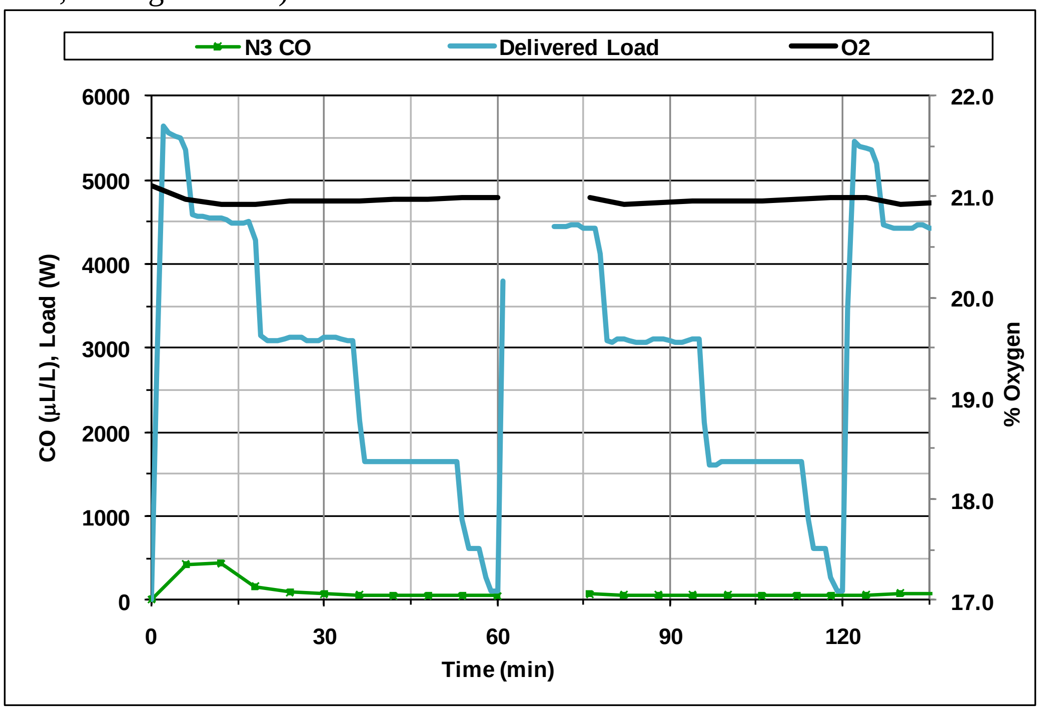


Figure 17b shows the CO reached a peak concentration of 320 μL/L in the family room with peak concentrations in the other rooms just below that value, down to nominally 260 ppm_y when mechanical venting was initiated.

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.

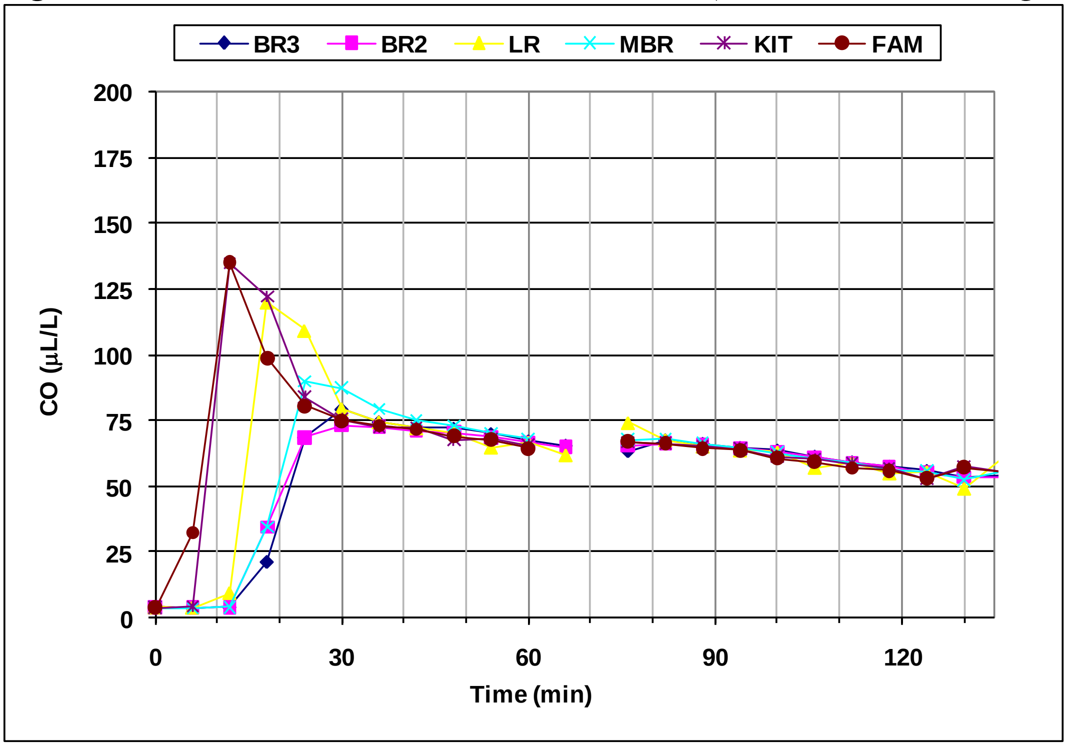
Figure 18a CO and O_2 concentrations in the garage and measured load for Test V (noncat Gen SO1, Configuration 7)



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.

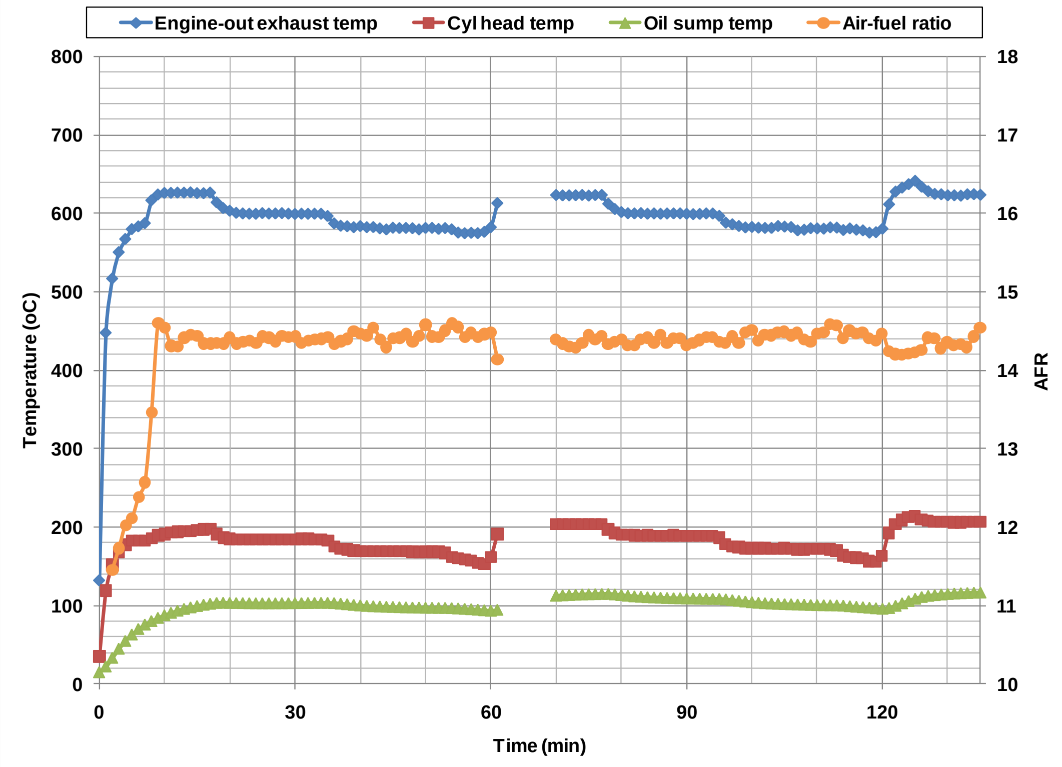
Figure 18b CO concentrations in the house for Test V (noncat Gen SO1, Configuration 7)



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.

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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

TAB F

Algorithm Development for Enclosed Operation Detection and Shutoff of a Prototype Low Carbon Monoxide Emission Portable Gasoline-Powered Generator

Additional Volume to Final Project Report

Contract CPSC-S-06-0079

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I. EXECUTIVE SUMMARY

This report is submitted as an additional volume of the Final Project Report, *Low Carbon Monoxide Prototype Portable Generator* [1], for the University of Alabama's (UA) contract with the U.S. Consumer Product Safety Commission (CPSC). This report describes a task CPSC added to the original contract, CPSC-S-06-0079, directing UA to develop, test, and install an automatic engine shutoff feature on an additional prototype generator, constructed to operate with the same stoichiometric fuel control strategy and catalyst as the durability-tested prototype described in reference [1], for test and evaluation by CPSC. The purpose of this feature is to shut the engine off before the generator creates an unacceptable carbon monoxide (CO) exposure environment in the possible event that, when the prototype generator is operated in an oxygen depleted environment, its ability to meet its target CO emission rate is compromised. CPSC specifically requested that the algorithm be programmed into the prototype generator's engine control unit (ECU), and that it have the ability to be enabled and disabled for testing purposes. CPSC also specifically directed that the algorithm rely only on data already existing in the ECU and not use any additional sensors so as to serve as a supplementary means of further reducing the risk of CO poisoning associated with the prototype generator without adding any additional component cost.

To develop the algorithm, the new prototype, equipped with the ECU, was initially tested at UA in a highly confined space. Data from the ECU was collected and analyzed. The purpose of the initial testing was to identify trends within the collected data that could be utilized for detecting confined space operation. These analyses resulted in the development of an initial algorithm that is summarized within the body of this report and detailed in the Appendix[1]. The algorithm was tested through post-processing the ECU data collected and then implemented in the ECU software by the manufacturer. While the resulting detection method was completely heuristic in nature and made no provision for shutoff at particular O2 or CO concentrations, the initial results from testing the algorithm at UA were promising. The prototype, with the initial algorithm programmed into the ECU, was then tested in a test facility [3] at the National Institute for Standards and Technology (NIST), where the developed algorithm was refined through variation of programmable parameters. However, three specific issues sporadically surfaced from additional testing at NIST:

1. With sudden and significant load changes, as well as under constant load (though less frequently), the algorithm would sometimes cause the engine to shut off when operated unconfined in the outdoors.
2. Rarely would the algorithm cause the engine to shut off in an enclosed environment with extremely light loads.
3. Rarely, but even with high load, the algorithm would not shut the engine off when operating in an enclosed environment.

[1] This algorithm was the subject of a Master's of Science thesis, developed, written, and defended by Jennifer B. Smelser, who was a graduate research assistant working on this project. Her thesis, entitled "Oxygen Depletion Shutdown Algorithm for Portable Gasoline Generators," was accepted by the University of Alabama in 2009 [2].

Even with these limitations, the initial algorithm resulted in a proof of concept in demonstrating its capability to shut off the engine when a shutoff decision was rendered. Work on the initial algorithm also provided valuable information for another possible advanced approach to a shutoff algorithm. This approach, based on employing data from the ECU to estimate the O2 concentration in the intake air, shows the most promise to date.

II. PROTOTYPE GENERATOR SET DESCRIPTION

For the performance of the effort on enclosed operation detection and shutoff, an additional generator set was introduced, and this generator set was labeled SO1 (shutoff 1). At the time of acquisition of SO1, the same model generator set used for the baseline and durability tested prototypes, which are described in reference [1], was no longer available. However, a similar model was selected that employs the same engine as the other generator sets but comes with a different alternator and has an advertised continuous output power rating of 7 kW. As stated previously, SO1 is similar to the durability-tested prototype, in that it is has the same catalyst in the muffler and is controlled to a stoichiometric air-fuel ratio (AFR). However, it employs a newer model ECU made by the same manufacturer of the previously utilized ECU because the manufacturer no longer supported the latter.

The newer model ECU offers several improved features over the previous model. One improvement is that the newer ECU uses an external MAP sensor placed directly at the intake manifold minimizing the tube loss and acoustic delays associated with the MAP sensor located inside the housing of the previous controller. This close placement also reduces the likelihood of gas condensing in the tube or being trapped in the transducer cavity and distorting the MAP signal. Since both ECU models are MAP-based and use the speed-density method to determine the amount of fuel to inject, the more accurate MAP measurements with the newer ECU appears to result in more accurate fueling parameter calculations. A photo of the ECU mounted on the durability-tested prototype can be found in Figure II.1, and a photo of the newer model ECU mounted on SO1 can be found in Figure II.2.

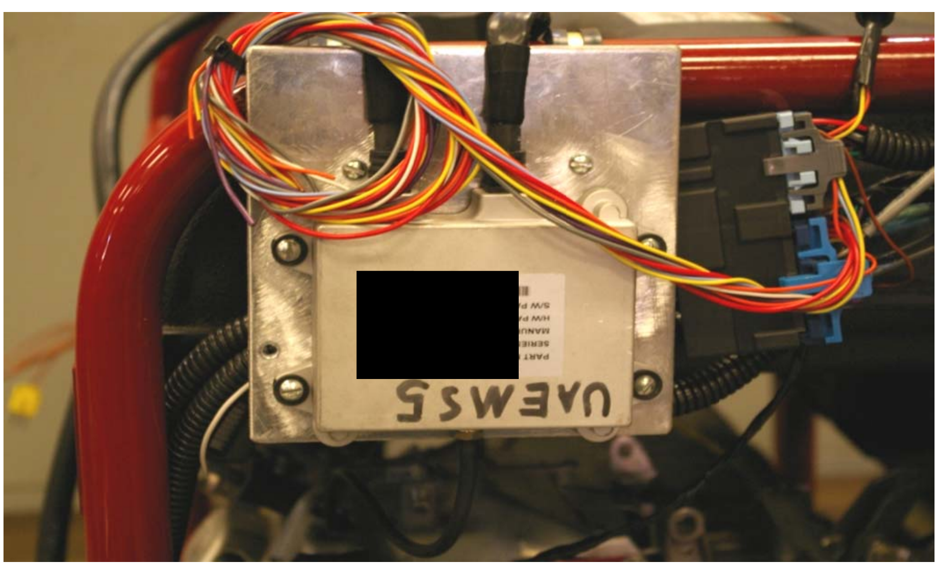

Figure II.1: ECU mounted on the durability-tested prototype.

Figure II.2: ECU mounted on SO1.

In addition to the external MAP sensor, the newer model ECU also includes a block learn memory (BLM) feature. This feature compensates for long-term variations in engine operating conditions, thus removing some of the control force requirements from the closed-loop controller. Large control forces in the short term may indicate trends that will last for the long term, and thus a fixed compensation is inserted into the calculation for the duration of which the injector is opened for injecting fuel, referred to as the base pulse width, such that the closed-loop controller need only compensate for changes about that fixed value, which varies based on the BLM function. In effect, the BLM feature produces a trim factor which is applied to the base pulse width for the fuel injector. This trim can adjust for errors or changes over time in the volumetric efficiency table that has been calibrated into the ECU. Another notable difference with this newer ECU is that the manufacturer programmed it such that closed loop control is not activated until the oil temperature nominally exceeds 60^{o}C, a feature intended to improve engine durability. Another feature of the newer ECU, not available in the previous model, is the ability to define the lines in the calibration look-up tables to cover the nominal range of MAP values expected during engine operation in the generator application with far more resolution, as opposed to the hard-coded tables of the previous ECU. Additionally, the newer controller utilizes a heated oxygen sensor, which is more durable and precise than the unheated sensor employed by the previous model.

Aside from these differences, SO1 was modified into the prototype configuration using the same sensors and components as the durability tested prototype, which are described along with the EMS operating principles, in reference [1].

III. Initial Testing

Since no additional sensors were to be employed to detect operation within a confined environment, we were constrained to make a decision for shutoff based upon data, referred to as real-time data, existing within the ECU. Real-time data is data that is stored in memory on the ECU and that changes dynamically as the control system operates. For example, a temperature signal may be measured every

50 ms and stored in a specific memory location. Thus, this value in memory is updated every 50 ms to track that temperature.

The obvious approach to the problem was to place the generator set in open and closed environments, store a real-time history of the ECU data as well as O2 and CO content in the intake air, and then analyze the data to determine if a combination of signals and trends could be used to detect operation in a confined space. The ECU manufacturer provided software for a laboratory laptop computer that interfaced with the ECU to log and view real-time data. By logging the data, we were able to analyze the data after the experiment, which is referred to as post-processing. To illustrate the post-processing concept, the experiment could be run and shut down. We could then cycle the logged data through a number of different algorithms and determine if they accurately detected the generator operating in a confined space.

In order to assess the response of the controller variables to operation in an O2 depleted or CO rich environment, a small test enclosure (8' x 4' x 9'6") was fabricated outside the Engines Laboratory at UA. The enclosure is shown in Figure III.1 with the doors closed and opened. During testing, the generator's engine variables and exhaust emissions were monitored from inside the laboratory, away from any poisonous exhaust fumes. The sampling line for the ambient air was located at the midpoint of the enclosure. In other words, the sample line terminated halfway between the floor and ceiling, halfway between the left and right walls, and halfway between the front and back walls. The sample line fed back to a standard five gas emissions bench with Rosemount Analytical Analyzers integrated by Richmond Instruments, which is described in reference [1].

Figure III.1: Outdoor test house.

The focus of initial testing was to analyze the real-time ECU data to determine how the variables responded differently when the engine was operated in a closed environment compared to an open environment. Open environment tests were conducted with the generator in the test enclosure, but with the doors fully open. These conditions were for testing only, and do not imply that such operation is safe or recommended.

The initial test scenarios performed on the generator were with open-door and closed-door settings under warm start conditions. A warm start condition, meaning the generator had to run for at least ten minutes before beginning to collect the test data, was used to ensure that the engine was running in closed-loop control (CLC). Upon a cold start, by manufacturer design, the ECU uses no feedback and simply commands a fuel pulse width that is rich. The rich mixture results in cooler combustion and reduces the risk of overheating the piston. Once the engine temperature reaches a predetermined threshold, which the manufacturer set at 60 °C, the ECU will enable CLC and begin to actively control the fuel pulse width to the necessary value to obtain a stoichiometric AFR. With CLC enabled, BLM learning takes place and the engine control variables respond to the ambient conditions such that the controller runs the engine at a 14.6 to 1 AFR. Note that the test data presented was collected after warm up. Later work showed that the CO content in the exhaust spikes from the rich mixture but is quickly decreased once closed-loop control is enabled.

During each open-door test, after warmup, real-time ECU and emissions data was collected with a specific load applied to the generator. In order to vary the load applied to the generator, a Simplex 10 kW (variable), single-phase, 60 Hz load bank with 250 watt switches was employed. Table III.1 shows the load settings applied to the generator, which are nominally the same loads applied to the durability-tested prototype during emission testing and in the durability protocol. Separate open door tests were conducted for modes 1, 4, and 6. Modes 2, 3, and 5 were not tested because the full span of loads was expected to provide adequate data for establishing a response pattern. After each open-door test was completed, the engine was shut down for a substantial period of time allowing any residual exhaust gas to be cleared from the enclosure and the enclosure air temperature to return to ambient conditions. This process was used for each test performed. The closed-door scenarios were performed in the same manner except that after the engine was warm, the doors were closed before the load was applied to the generator. Once the test was complete, the door was adjusted to the open position to allow the test house to return to an ambient state before proceeding to the next load setting.

Table III.1: Load bank setpoints.

Mode	Load (W)
1	5500
2	4750
3	3500
4	1500
5	500
6	0

Figures III.2 through III.10 show several of the ECU's measured sensor signals and O2 content vs. time, fueling parameters and O2 content vs. time, and emissions output vs. time for the three load conditions under open-door scenarios. The measured sensor signals and fueling parameters are oil temperature

(VCLTS), intake air temperature (IAT), manifold absolute pressure (MAP), fuel pulse width (FPW2), and block learn memory correction factor (FBLMCOR). This latter term is the trim factor previously discussed, and will also be referred to as a pulse width correction factor (carries more meaning in some contexts). The emissions output displays percent oxygen (O2), and carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxide (NOx) in parts per million (ppm). Listed in the order tested, each graph displays the test condition and load point. While many more variables from the ECU are available, those that are shown in the following figures were those that were originally selected as key indicators of operation in an enclosed environment. This selection was made after much analysis of all of the available data.

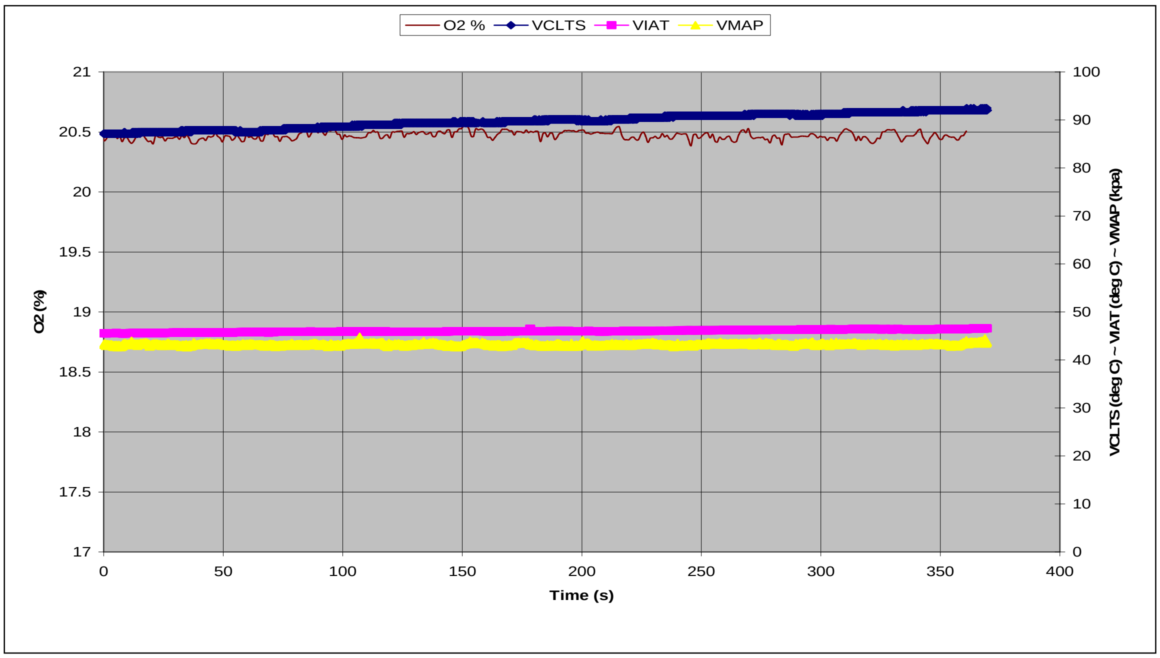

Figure III.2: Measured sensor signals and O_2 vs. time, open-door, 0 W.

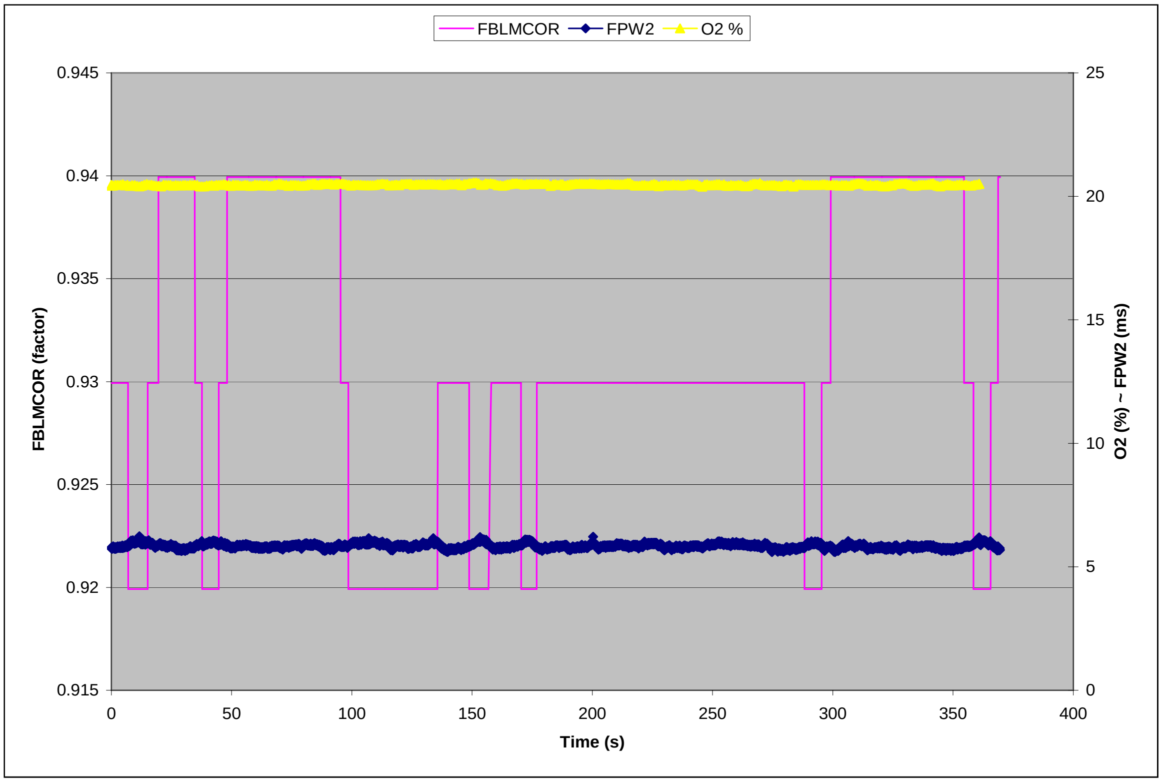

Figure III.3: Fueling parameters and O_2 vs. time, open-door, 0 W.

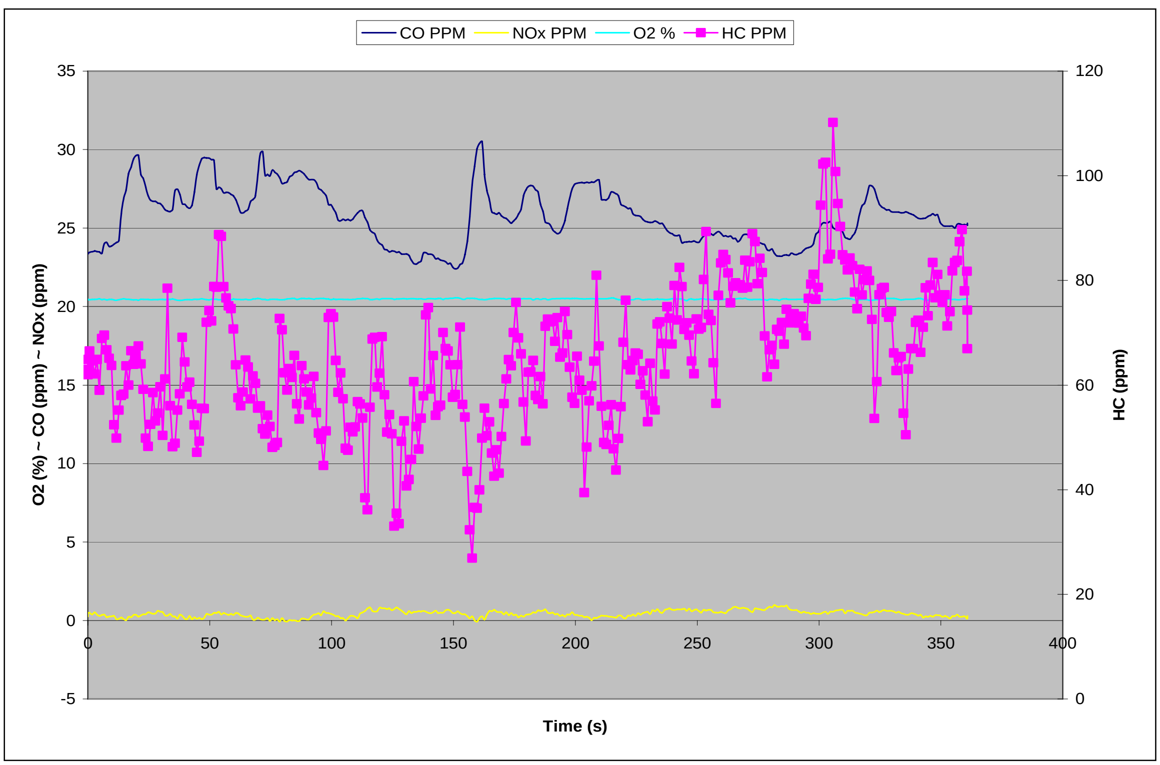

Figure III.4: Emissions data, open-door, 0 W.

In Figure III.2, it can be seen that the O2 content is relatively constant, as is the intake air temperature. Figure III.3 shows the block learn memory adjusting for ambient conditions, but the fuel pulse width remains quite stable. Figure III.4 illustrates minor variation in CO content, but yet a relatively constant average value.

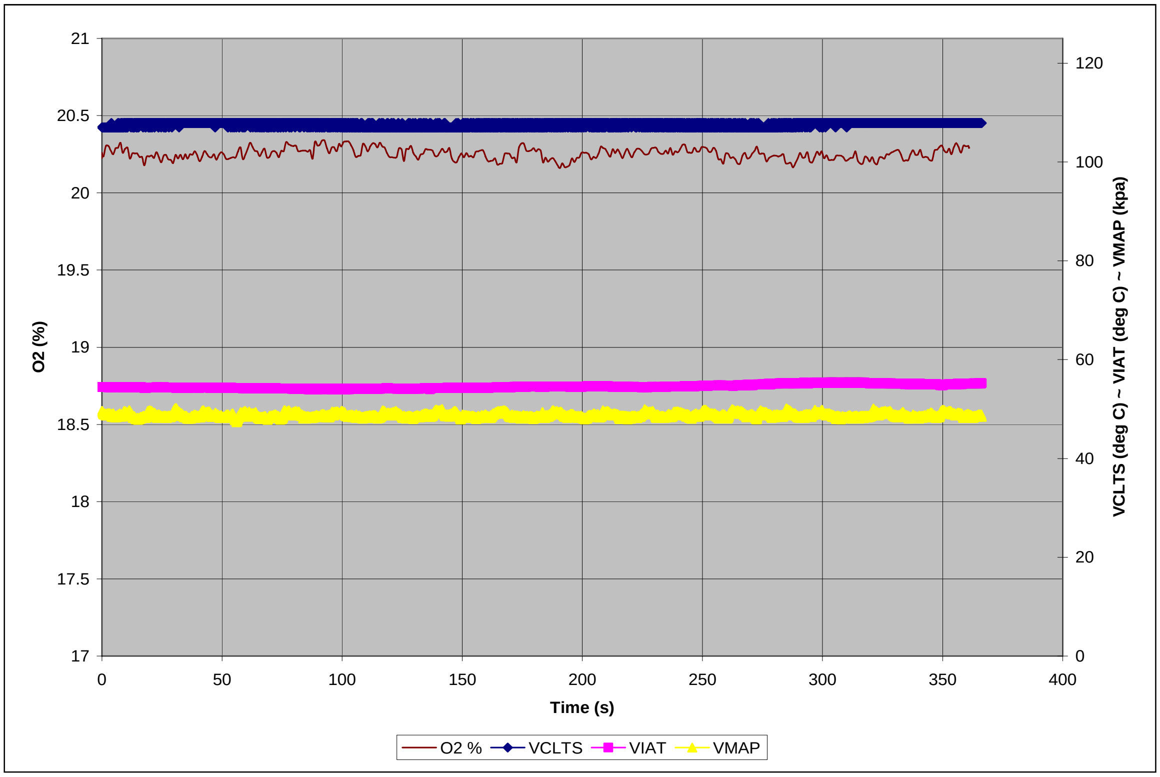

Figure III.5: Measured sensor signals and O_2 vs. time, open-door, 1500 W.

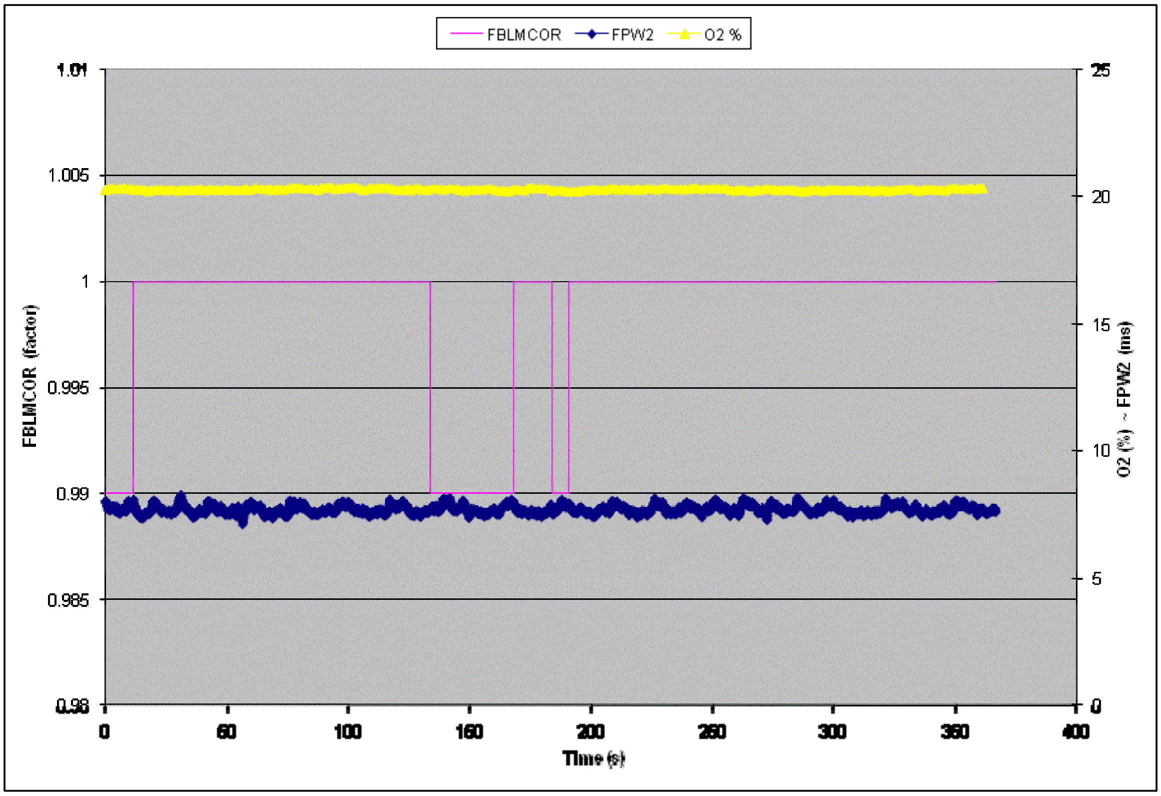

Figure III.6: Fueling parameters and O_2 vs. time, open-door, 1500 W.

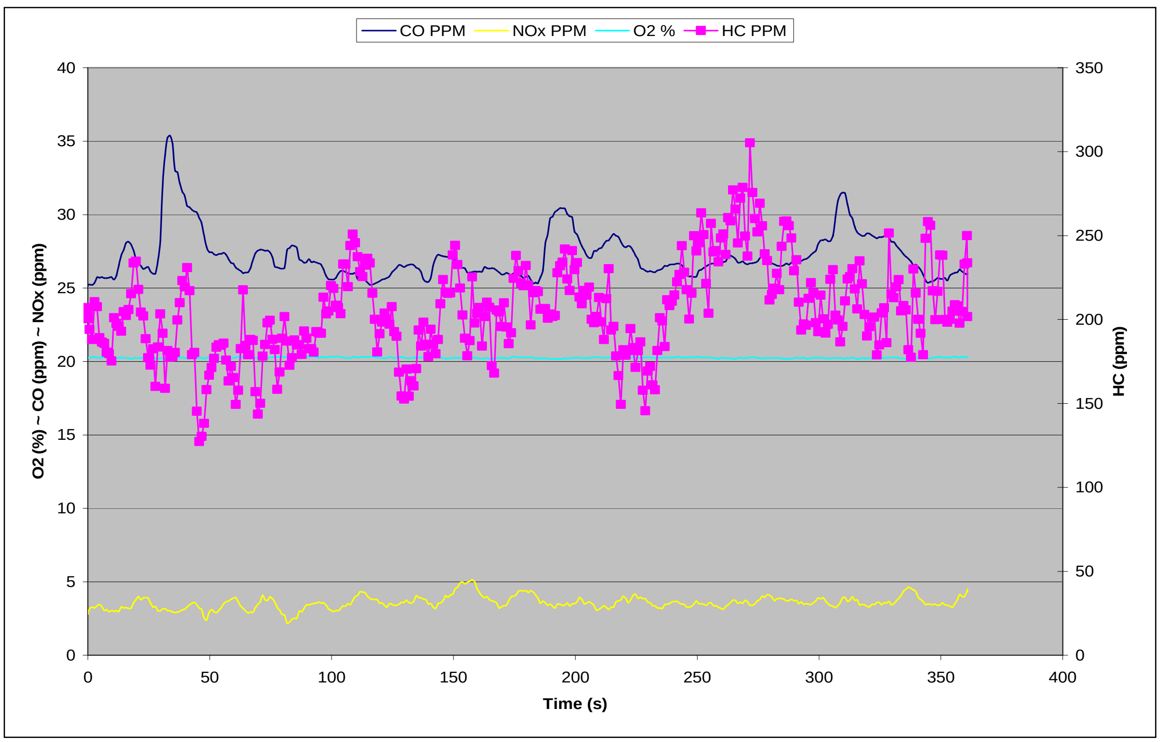

Figure III.7: Emissions data, open-door, 1500 W.

Figures III.5 through III.7 demonstrate the same general trends as Figures III.2 through III.4: a relatively constant O2 content and intake air temperature as well as block learn memory adjustments for ambient conditions. Furthermore, the fuel pulse width remains quite stable. Figure III.7 illustrates minor variation in CO content, but yet a relatively constant average value, as in Figure III.4.

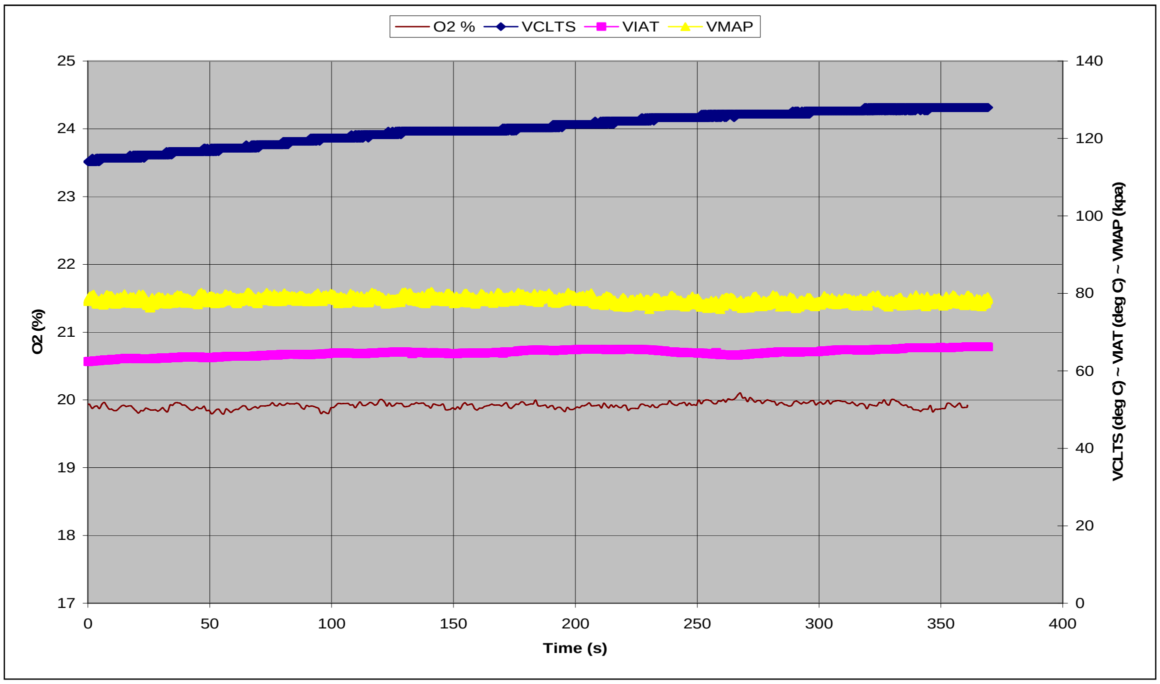

Figure III.8: Measured sensor signals and O_2 vs. time, open-door, 5500 W.

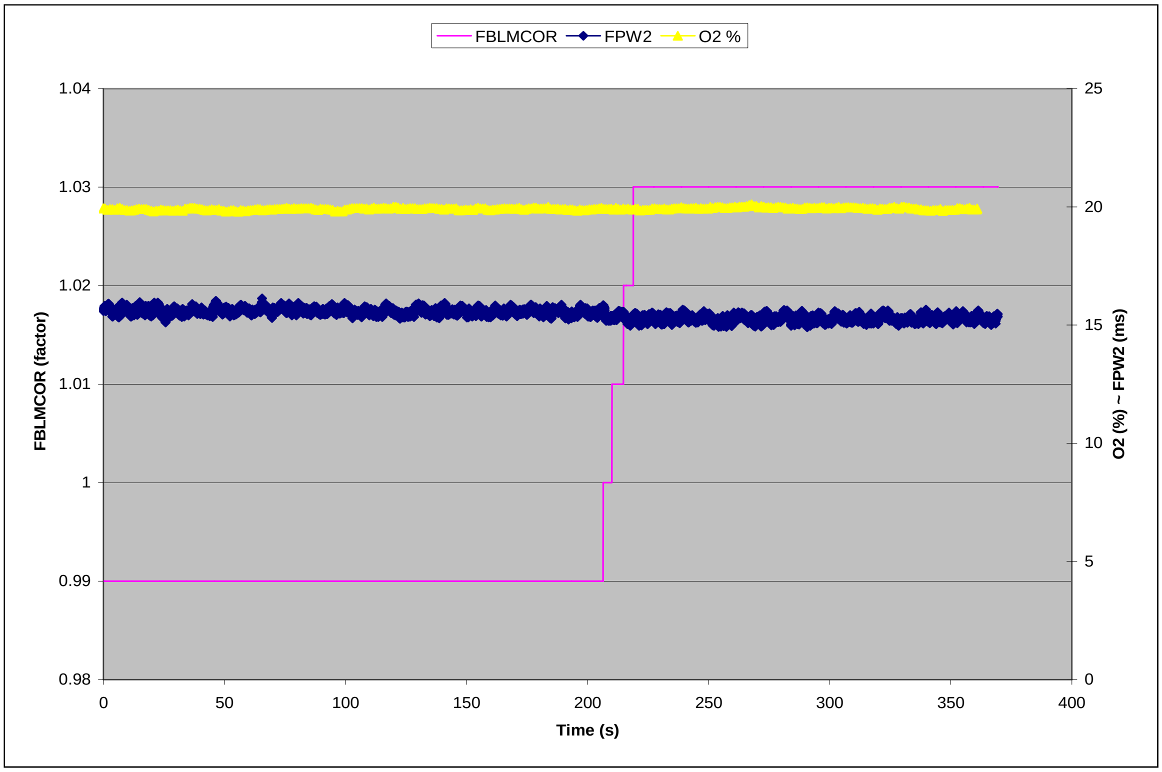

Figure III.9: Fueling parameters and O_2 vs. time, open-door, 5500 W.

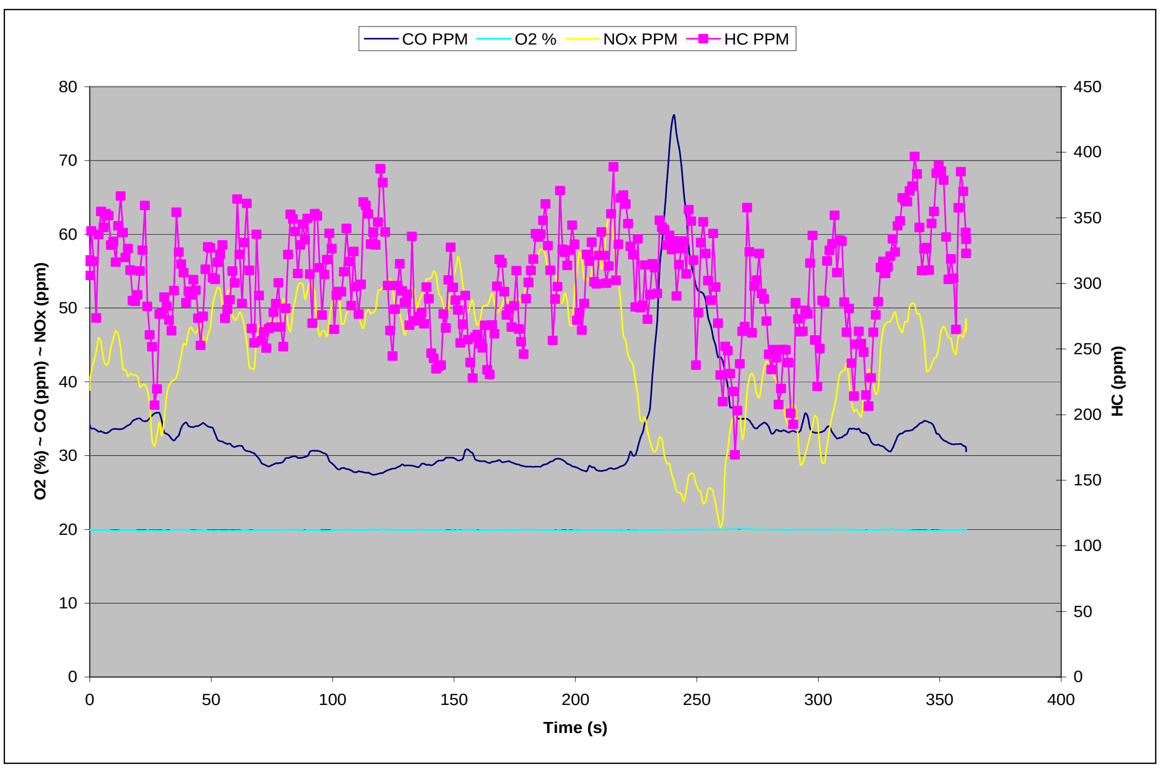

Figure III.10: Emissions data, open-door, 5500 W.

Figure III.8 through III.10, representing maximum load under open-door conditions, are similar in result to the previous data presented for the 0 and 1500 W cases. However, in Figure III.10, a brief spike in CO and corresponding drop in NOx, which was due to a nominally fifteen-second AFR fluctuation down to the 14.1 to 14.3 range, are seen at around 240 seconds. An additional point of interest is that minor O2 depletion appears to be occurring even under open-door conditions since the confined space is so small. This is most obvious in comparing the oxygen levels in Figures III.2, III.5, and III.8 which shows the steady-state oxygen level decreases with increasing load on the alternator. Note that the plots initiate after the engine is warm and CLC is in operation. Although a steady-state O2 level is reached, it is was reached before the oil temperature reached 60 °C.

The expectations for closed-door conditions were that the engine would tend toward running rich due to the engine exhaust displacing fresh air at the intake and thus reducing the intake oxygen. As a result, control action would compensate to maintain the stoichiometric AFR by decreasing the fuel pulse width. This would result in a power reduction that tends toward a drop in engine speed. However, control action of the governor forces the throttle open to regulate the speed, which in turn causes the MAP to increase allowing a greater air flow rate to provide adequate oxygen to the engine. This results in an increasing fuel pulse width control action. The long-term cumulative effect of the control action is that the fuel pulse width would gradually increase to compensate for what appear as a load increase based on MAP, but the BLM correction factor will decrease to compensate for the decreasing oxygen content in the intake air. Furthermore, as the engine runs under closed-door conditions, the exhaust output significantly increases the intake air temperature.

The closed-door test results show that at 0 W, the O2 content of the test house dropped to 18.2% in 6 minutes. At 1500 W the O2 content of the test house dropped to 18.1% in 4 minutes, and at 5500 W the O2 content dropped just below 17.5% in 3 minutes. Figures III.11 through III.19 show the measured sensor signals and O2 content vs. time, fueling parameters and O2 content vs. time, and emissions output vs. time for these three load points. The test condition and load point are specified for each graph, and they are listed in the order they were tested.

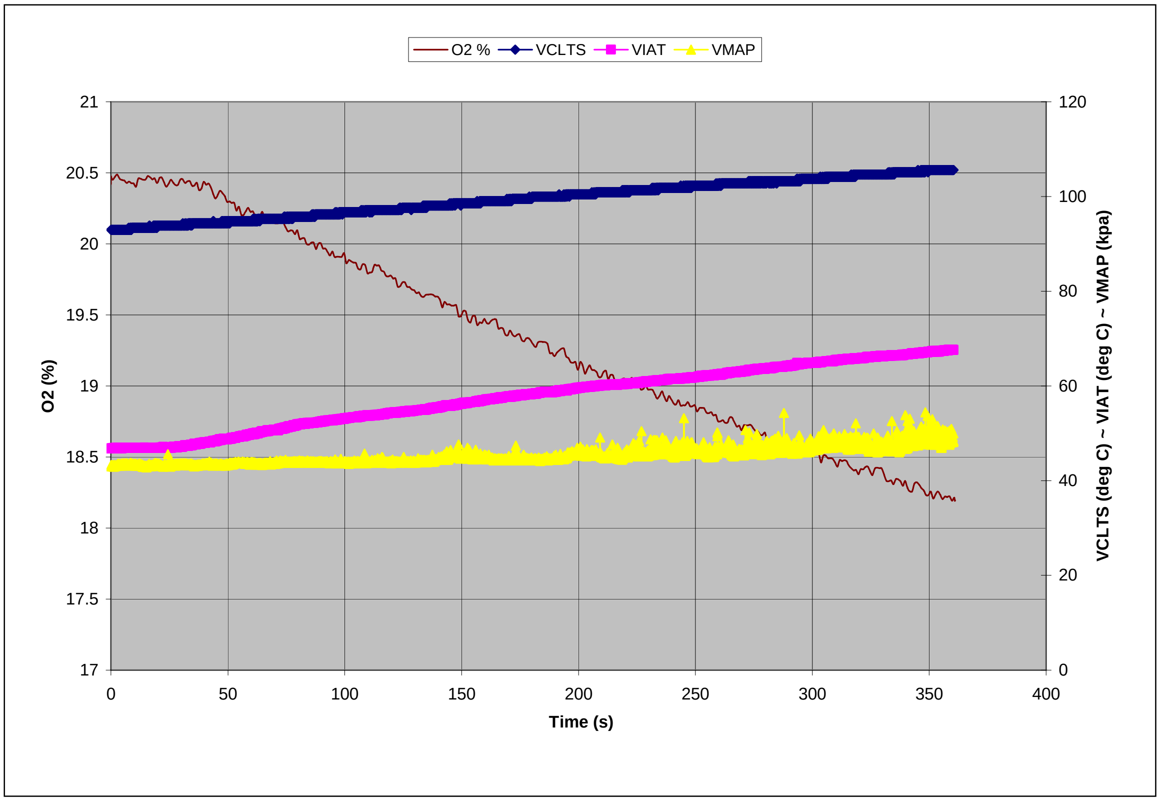

Figure III.11: Measured sensor signals and O_2 vs. time, closed-door, 0 W.

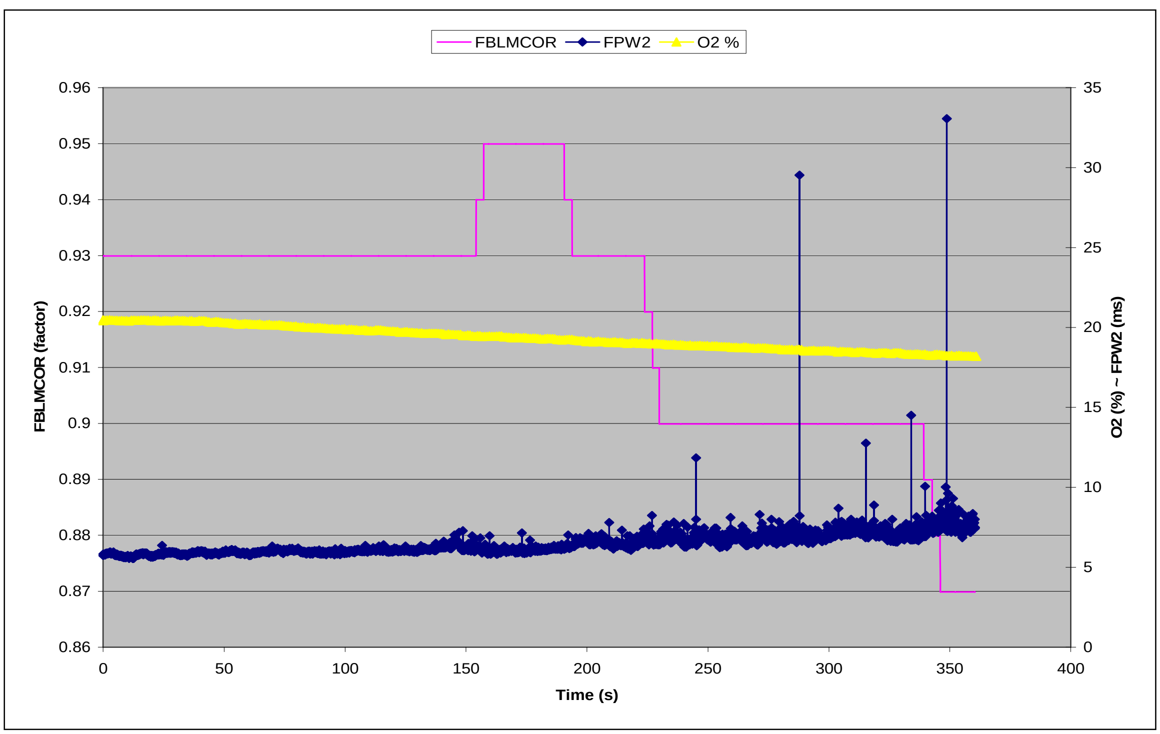

Figure III.12: Fueling parameters and O_2 vs. time, closed-door, 0 W.

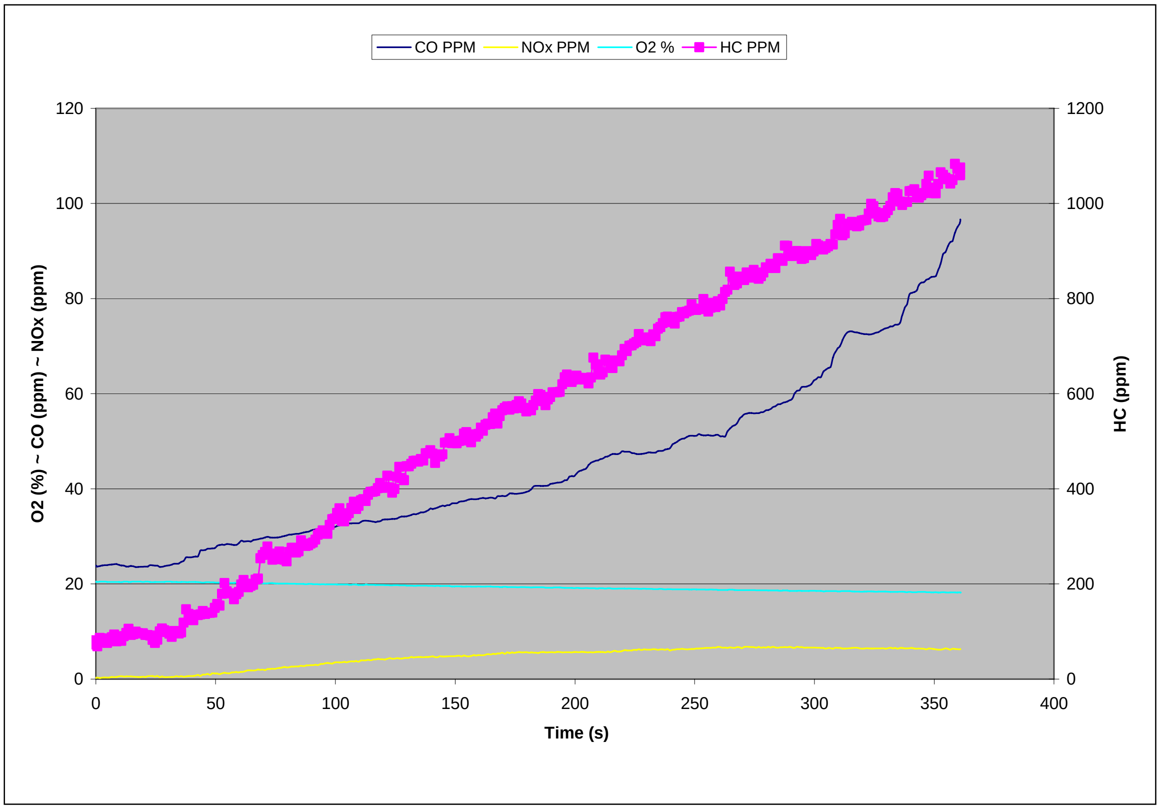

Figure III.13: Emissions data, closed-door, 0 W.

Figures III.11 through III.13, even with no external load applied, demonstrate what appears to be a linear decreases in O2 content, a linear increase in intake air temperature, and an exponential increase in CO content. Notice also, that the MAP signal is gradually increasing. Typically, MAP is related to engine load, which is itself related to electrical load on the generator. Hence, the O2 depleted (or CO rich) environment results in data similar to that of a load increase. One interesting feature in Figure III.12 is the presence of large magnitude spikes on the FPW2 (fuel pulse width) signal. Though a definitive explanation is not available, it is surmised that minimal engine load creates a situation in which the engine response is highly susceptible to minor variations in fuel pulse width. Hence, controller gains adjusted for heavy load conditions may result in more signal swing without such load applied.

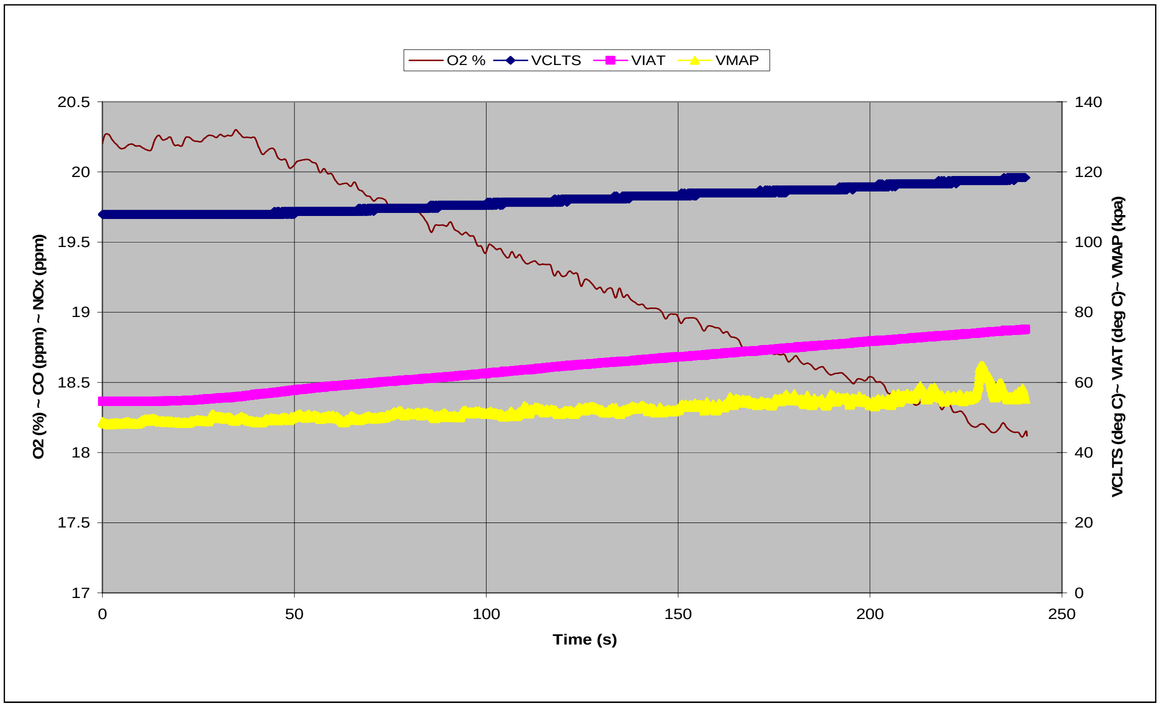

Figure III.14: Measured sensor signals and O_2 vs. time, closed-door, 1500 W.

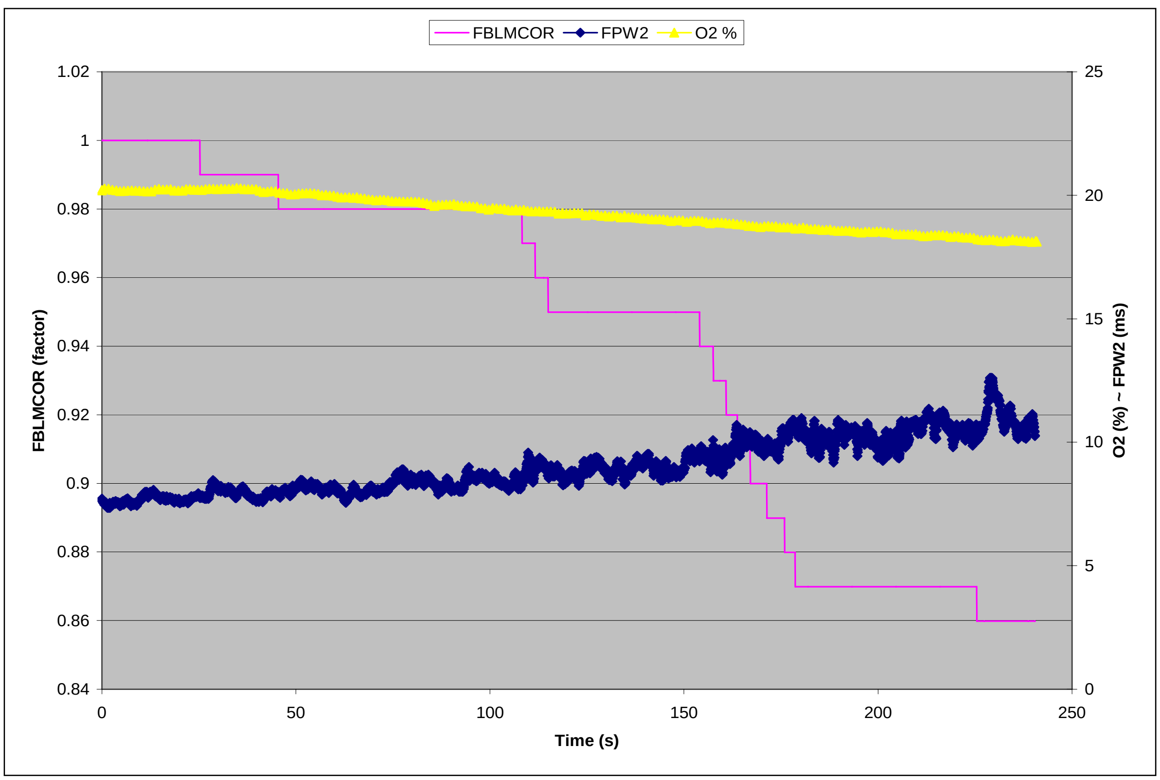

Figure III.15: Fueling parameters and O_2 vs. time, closed-door, 1500 W.

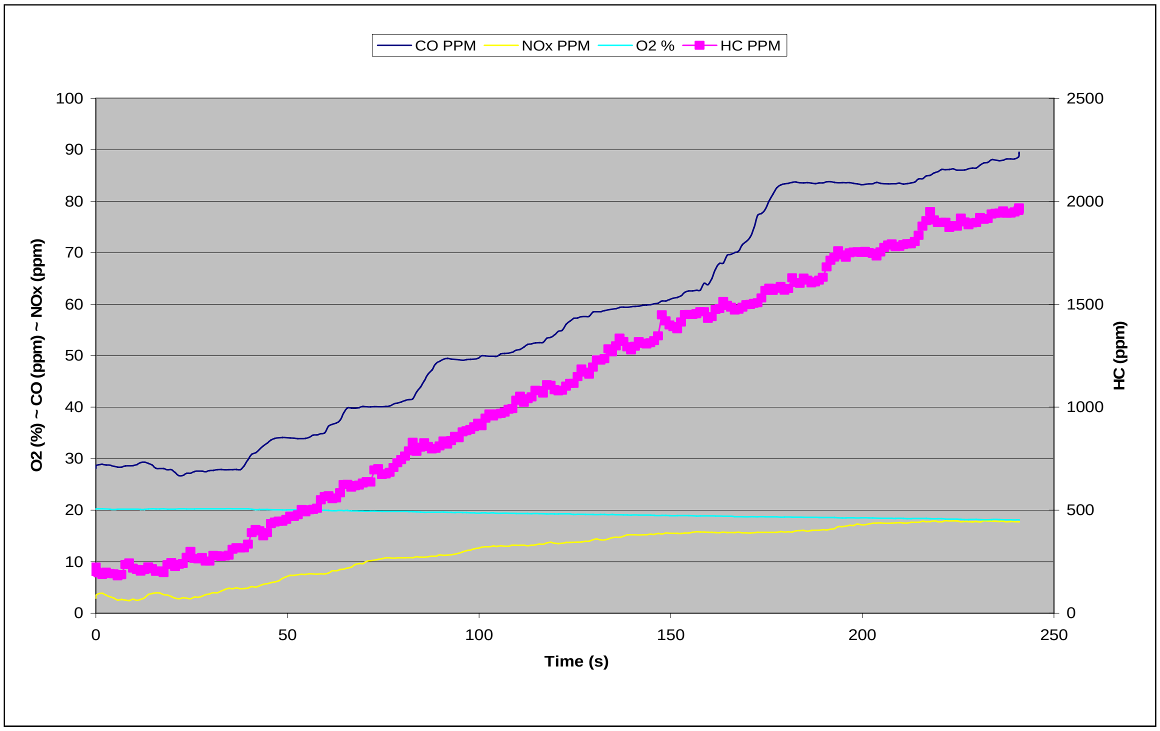

Figure III.16: Emissions data, closed-door, 1500 W.

Figures III.14 through III.16, with a 1500 W load, demonstrate O2, CO, and intake air temperature trends similar to the case with no load. However, the rate of change in these variables is increased by the additional load. Again, the MAP increases steadily as well.

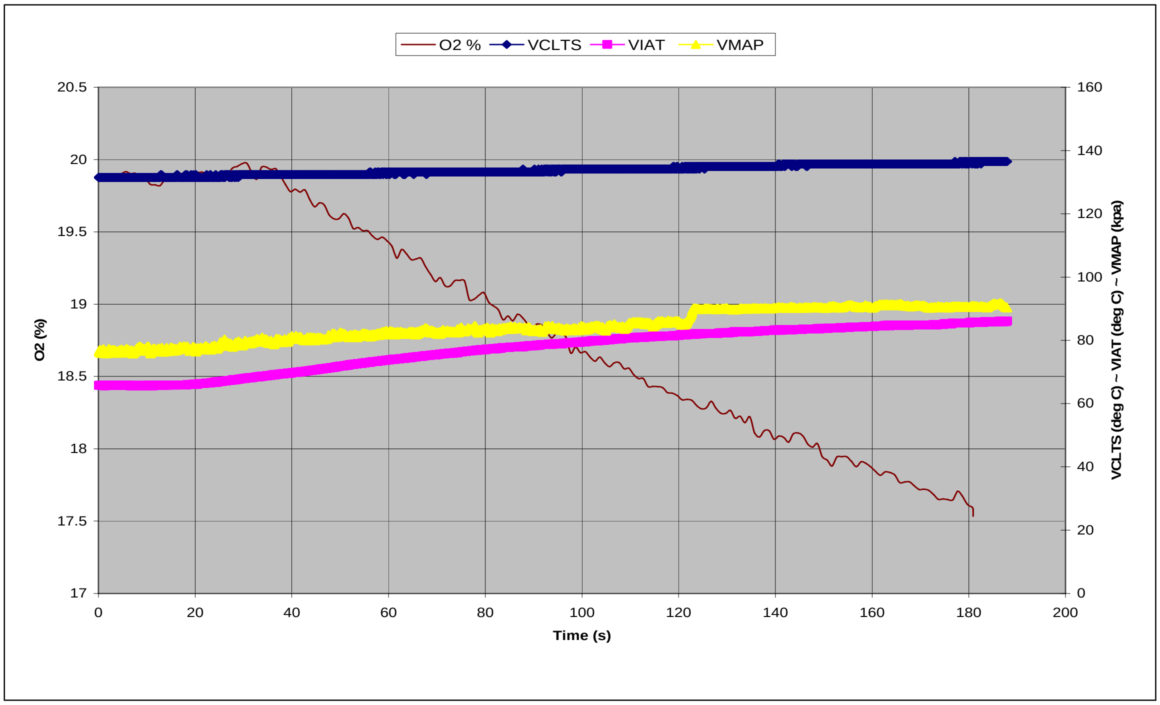

Figure III.17: Measured sensor signals and O_2 vs. time, closed-door, 5500 W.

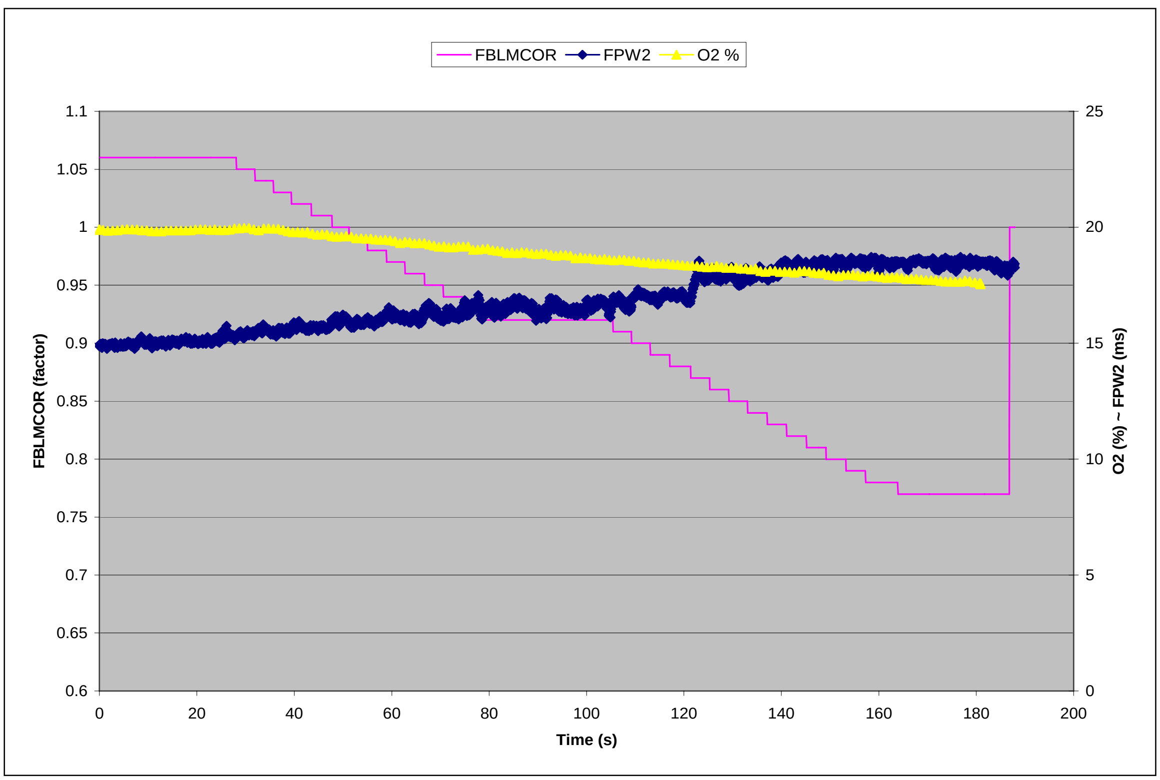

Figure III.18: Fueling parameters and O_2 vs. time, closed-door, 5500 W.

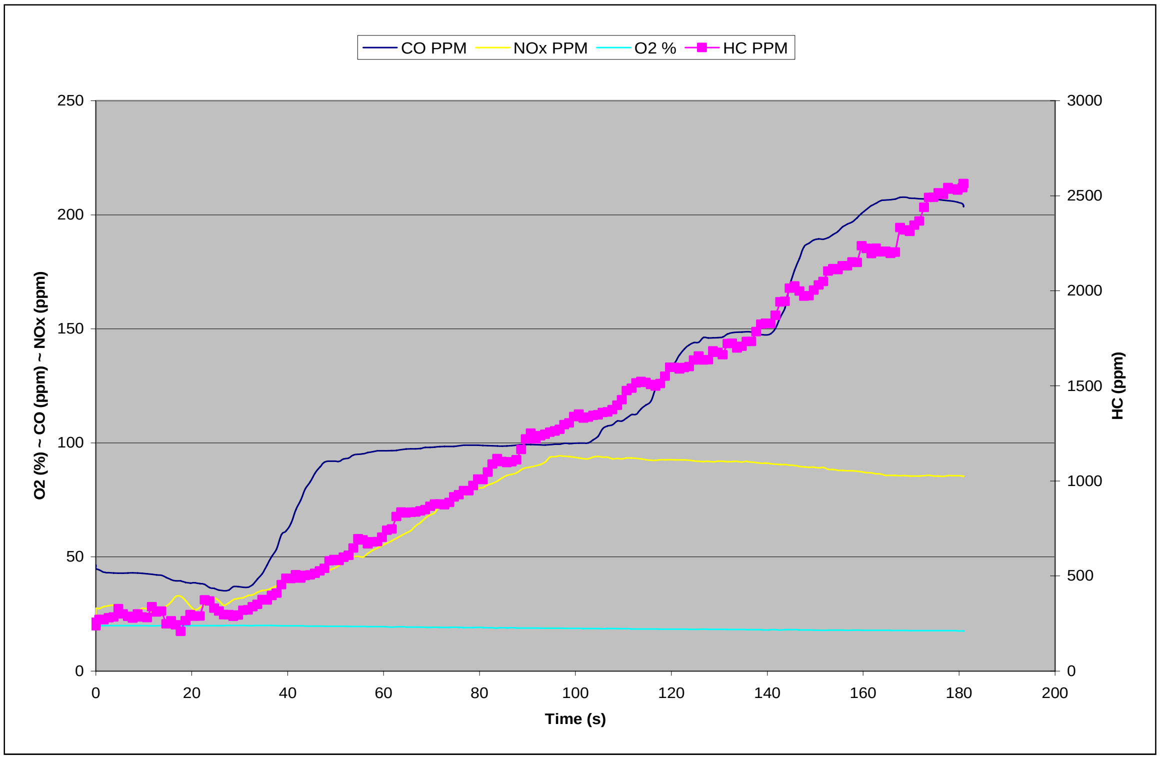

Figure III.19: Emissions data, closed-door, 5500 W.

With maximum load, 5500 W, Figures III.17 through III.19, illustrate the same general trends, but with rates of change increased over the 0 and 1500 W cases. It is important to note, as will be discussed in the following section, that fuel pulse width is steadily increasing while the block learn memory correction factor decreases.

IV. Enclosed Operation Detection Strategy

Initial Algorithm

Analysis of the data presented in section III indicated that when the engine is running with a fixed load in a confined space, the fuel pulse width (FPW2) increases, and the pulse width correction factor (FBLMCOR) decreases. In addition, the intake air temperature (IAT) increases since the engine intake air is actually composed of not just fresh air but hot exhaust gas as well. Under operation with a fixed load in the open enclosure, the fuel pulse width and pulse width correction factor do not both change in this manner, nor do any variations in this signal last for as long a period of time as when operating in a fully enclosed environment. Thus, the fuel pulse width and pulse width correction trends were selected as key identifiers of operation with a fixed load in a confined space. In addition, the enclosed environment will trap exhaust gas, which is generally at a temperature greater than the ambient air. Thus, intake air temperature (IAT) is expected to be increasing in an enclosed environment. Note that none of these tests were conducted for longer than six minutes. Due to the small dimension of the enclosure, the impact on test data was visible in a short time.

The initial detection algorithm is based on pseudo-derivatives of moving averages of the intake air temperature, injector base pulse width, and injector pulse width correction factor (IAT, FPW2, and FBLMCOR). As each new sample of these signals is received, the difference between it and a previous value (many samples earlier) is computed. When all three pseudo-derivatives have been at unacceptable levels for a significant number of samples within a window of a fixed number of samples, the algorithm triggers an engine shutdown (trips) by having the ECU send a signal that disables fuel injection. In essence, when the IAT and FPW2 have been steadily increasing, and FBLMCOR has been steadily decreasing, for some period of time, the algorithm concludes that the engine is operating in an enclosed environment and disables fuel injection to the engine, thereby shutting it off.

In order to verify the algorithm, the data collected at UA was post-processed through the algorithm. Much of this data is analyzed in the Appendix, along with a description of the software employed. One specific case is supplied here: the 5500 W load case with the enclosure doors fully closed. Figure IV.1 presents the IAT (labeled Intake Air Temp), FBPW2 (labeled Base Pulse Width or FPW), and FBLMCOR (labeled Pulse Width Correction or FPWC) signals for this test case. Note that the actual data and data passed through the moving average filter are both shown for each signal. Figure IV.2 displays the pseudo-derivatives of these signals, and Figure IV.3 illustrates the running count of the number of consecutive data windows that each pseudo-derivative exceeded the allowable range. These counts are referred to as fail hits. Lastly, Figure IV.4 shows the trip signals from each of the three indicators and the overall trip signal (labeled Shutoff Signal) that indicates all three independent trip signals are active and meeting the criteria to trigger an engine shutoff at nominally 35 seconds after generator start up for this test case.

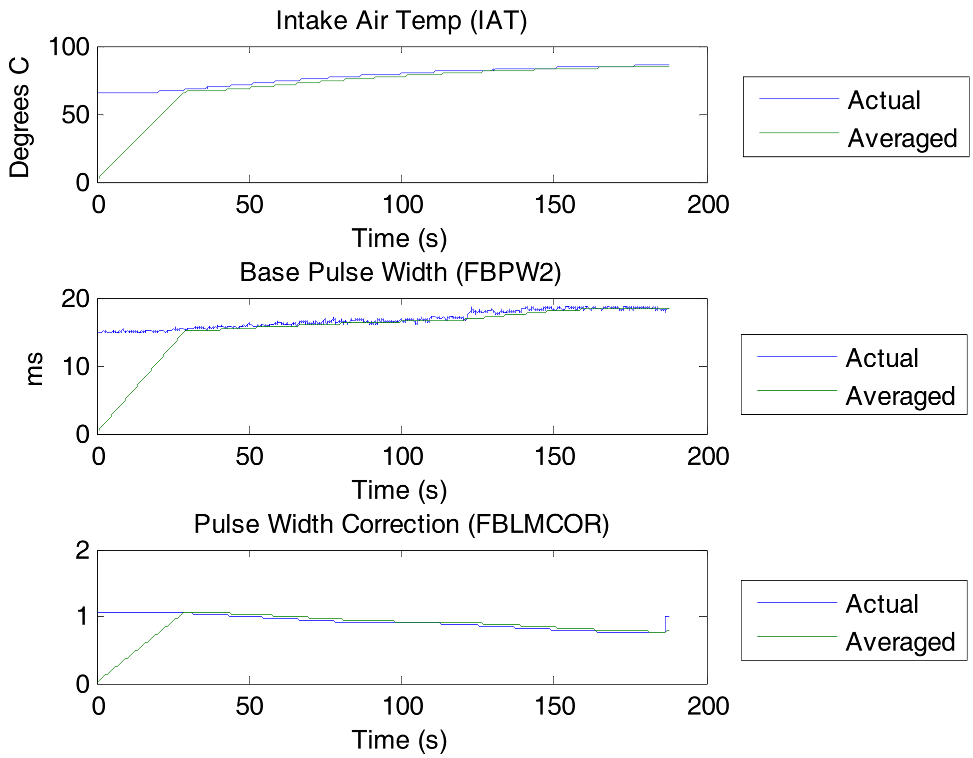

Figure IV.1: Key signals for enclosed operation detection (5500 W, closed-door).

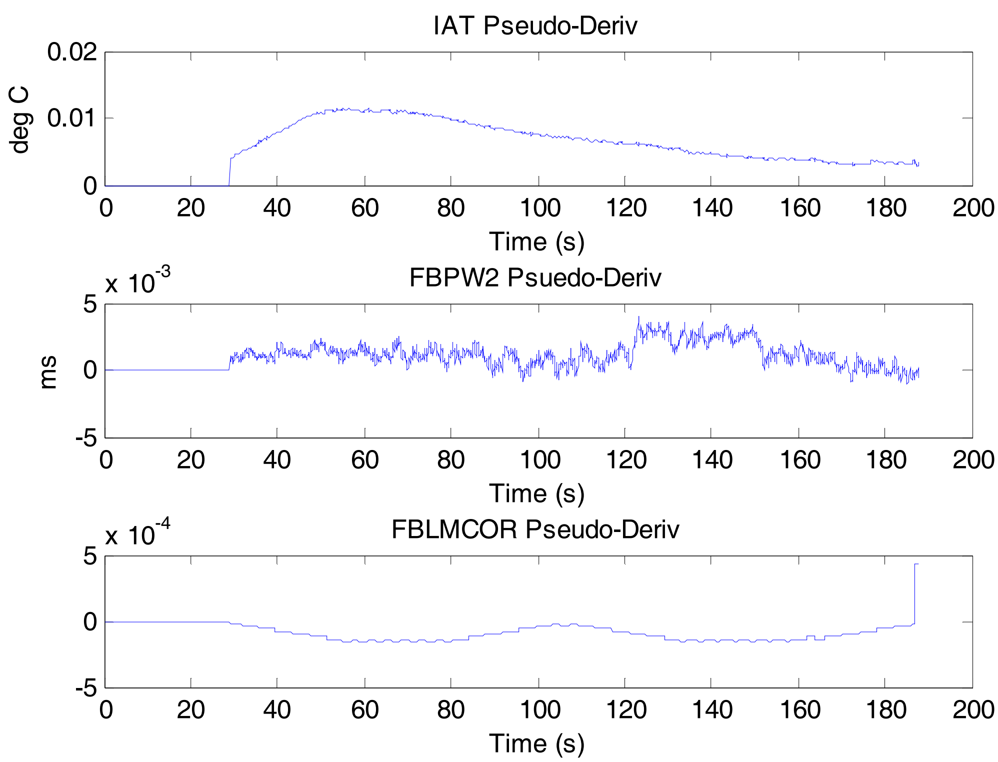

Figure IV.2: Pseudo-derivatives for the 5500 W, closed-door case.

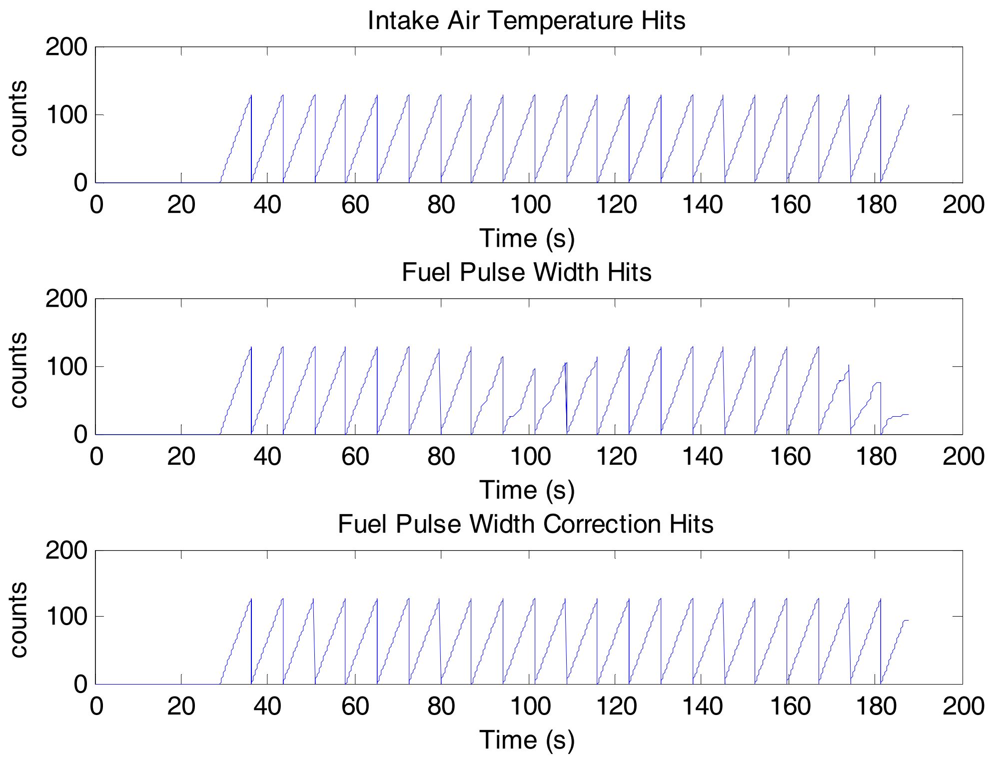

Figure IV.3: Fail hits for the 5500 W, closed-door case.

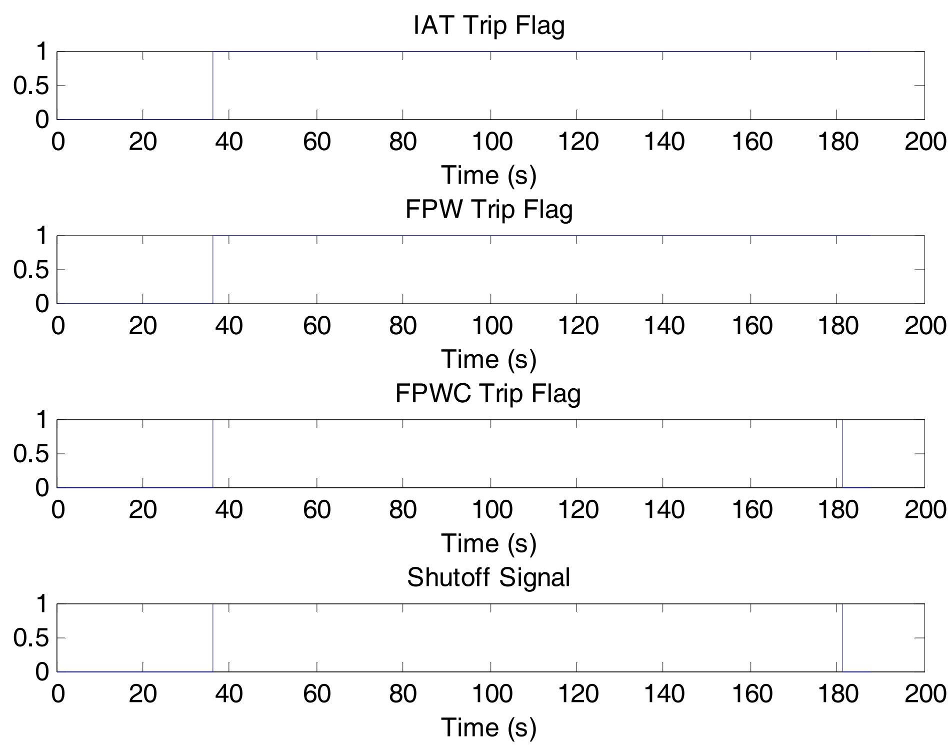

Figure IV.4: Trip signals for the 5500 W, closed-door case.

The algorithm was validated, in a post-processing sense, for all test cases performed at UA. The results were 100% accurate for a specific set of parameters and thresholds. Upon validation, the algorithm was programmed into the existing ECU software by the manufacturer, and the physical implementation was validated through subsequent testing on the UA campus with 100% accurate performance after only a second iteration in software development. Attention was then focused on testing the algorithm performance in the test facility at NIST. This test facility, designed for conducting residential indoor air quality (IAQ) studies, is a double-wide manufactured house with an attached one-car garage.

Testing of SO1 at NIST with Initial Algorithm Enabled

SO1 was shipped to NIST and setup in the garage attached to the test house. A number of test scenarios were executed, and the results of these tests lead to variations in the default parameters and thresholds employed by the algorithm. The test scenarios from UA were evaluated and still operated properly. Adjustments were required to accommodate the fact that a garage is a much larger volume than the small enclosure used at UA. Full details on all of the test scenarios and results, as well as parametric and threshold definitions, are provided in the Appendix.

While the Appendix contains a tremendous amount of data from many test cases, one illustrative example is presented here. The test scenario has the garage door fully closed, and the generator is loaded to 5500 W. Figure IV.5 presents the key signals for the test case, and Figure IV.6 shows the three fail hit counters and the overall system shutdown signal.

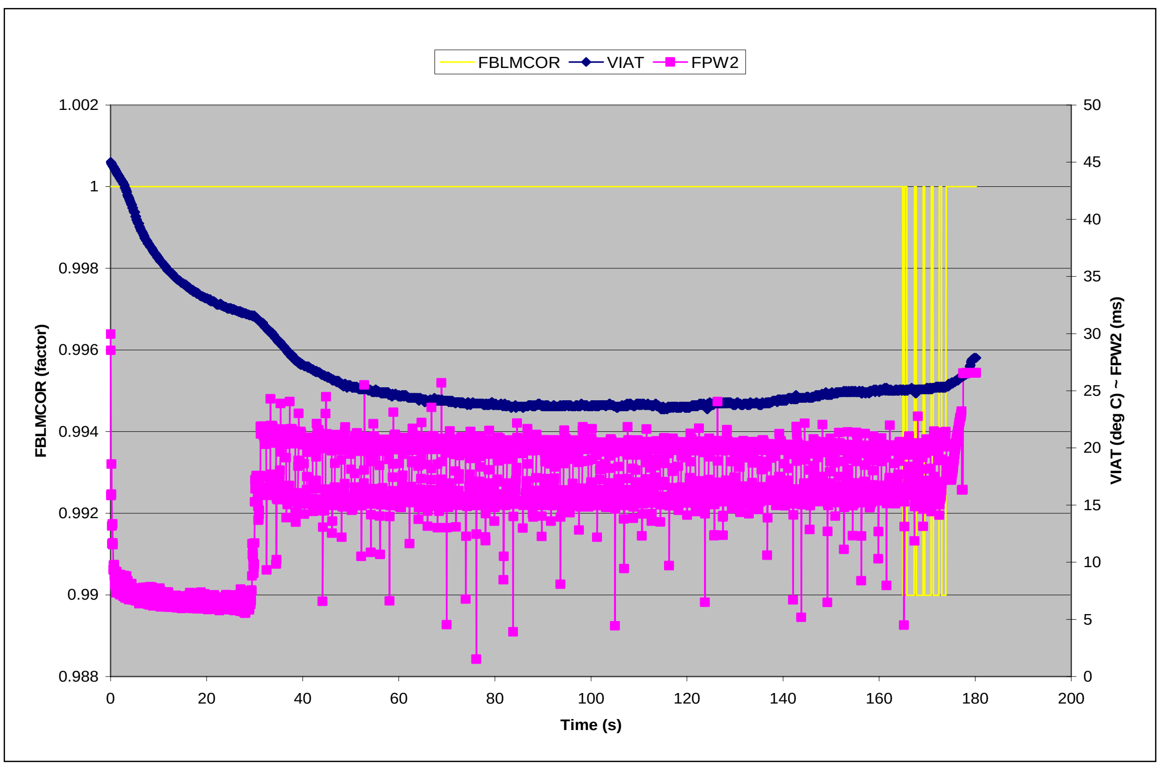

Figure IV.5: Key signals for the closed-door, 5500 W case.

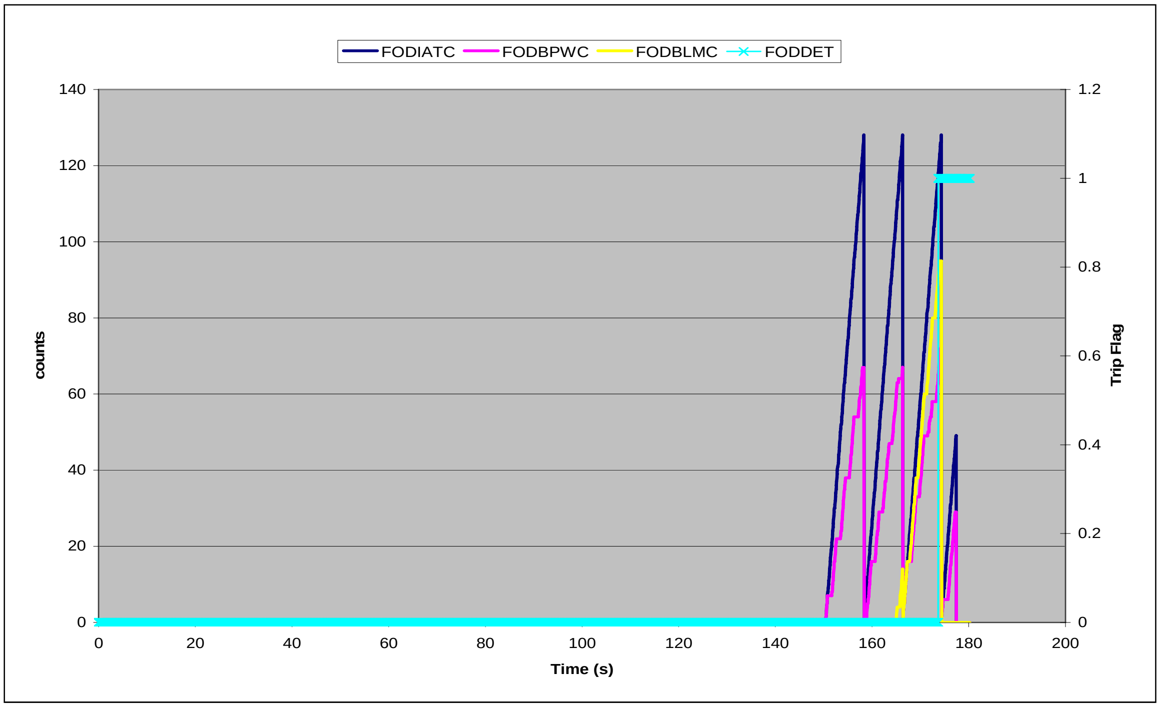

Figure IV.6: Algorithm fail counters and trip flag for the closed-door, 5500 W case.

Note from Figure IV.6, that the algorithm properly disabled the generator approximately 175 seconds after starting operation in the enclosed environment, when the FODDET signal, which is the shutoff signal, for the trip flag went from 0 to 1.

Initial Algorithm Performance

The initial algorithm provides a proof of concept demonstration that an ECU with a programmed shutoff algorithm is capable of shutting off a portable gasoline-powered generator when the conditions meeting the programmed criteria for shutoff are met. However, the developed algorithm, implemented within existing hardware, was found to have the following shortcomings that sporadically surfaced through subsequent testing at NIST:

1. With sudden and significant load changes, as well as under constant load, the algorithm will sometimes cause the engine to shutoff when operated unconfined outdoors.
2. Rarely would the algorithm cause the engine to shutoff in an enclosed environment with extremely light loads.
3. Rarely, but even with high load, the algorithm will not shut the engine off when operating in an enclosed environment.

A number of attempts were made to improve algorithm performance, and those are presented or discussed in the Appendix. However, no adjustments to the algorithm were found that could address these issues. As a result, a different analysis of the real-time data was performed to determine if any of the parameters could be used to estimate the oxygen concentration in the intake air and thus be used as the basis for an advanced shutoff algorithm.

Method for Estimating Oxygen Concentration in the Intake Air

Numerical estimation of O2 concentration in the intake air is derived from the EMS operating principles presented in reference [1]. As explained there, the ECU uses the ideal gas law, as indicated in (IV.1), to calculate the manifold density (ρ_{man}) from manifold absolute pressure (P), the intake charge air temperature (CAT), and R, the gas constant for air.

$$\rho_{man} = \frac{P}{RT} \qquad \text{(IV.1)}$$

When the intake gas is composed of less air and more CO, the effective gas constant for the intake gas will be different from that of air. Thus, if the gas constant can be estimated from internal controller signals, then the oxygen concentration can be estimated. However, directly estimating the intake gas constant is unlikely to yield the precision necessary to distinguish between values that are only slightly different from the gas constant for air, which is 0.286 kJ/kg-K. For frame of reference, the gas constant for pure CO is 0.297 kJ/kg-K. Therefore, some simplification was applied by looking at the ratio of the base pulse width, which the controller computes using the gas constant for air, to the actual or final pulse width, which is based on the controller feedback. This ratio of base pulse width to final pulse width is a measure of how much the controller has to compensate for lack of oxygen in the intake gas stream and is defined as an approximate ratio of gas constants in (IV.2).

$$\frac{\mathrm{R_{actual}}}{\mathrm{R_{air}}} \cong \frac{\mathrm{t_{PW_{base}}}}{\mathrm{t_{PW_{final}}}} \qquad \text{(IV.2)}$$

Applying (IV.2) to a number of different data sets, relationship (IV.3) was heuristically developed to estimate the percentage of oxygen in the intake air.

$$\%O2 = \frac{\mathrm{t_{PW_{base}}}}{\mathrm{t_{PW_{final}}}\mathrm{T}} 175 + 18 \qquad \text{(IV.3)}$$

In (IV.3), *T* is the intake charge air temperature (CAT) in absolute temperature units. The CAT is calculated using a weighted average of the intake air temperature, measured by a sensor located in the air filter housing, and the oil temperature, measured by a sensor located in the crankcase.

Validation of Method for Estimating Oxygen Concentration in the Intake Air

After the limitations of the initial algorithm described above were identified, a series of tests were conducted on SO1 at NIST with the initial algorithm switched to the disabled mode. These tests were conducted as part of a larger series of tests performed to assess the efficacy of the prototype design, with and without the catalyst, in reducing the CO poisoning hazard by measuring the CO and O2 concentrations in the garage as well as all rooms in the house [4]. In these tests, SO1 was operating in the garage and, since the algorithm was disabled, it would run until the test operator manually shut the engine off. Four of the seven tests were conducted with the garage bay door fully closed, causing oxygen depletion to occur in the garage. While these tests were not conducted to support the development of an advanced strategy for a shutoff algorithm, UA was able to post-process the real-time ECU data acquired during these tests to validate the relationship presented in (IV.3). The seven tests conducted on SO1 at NIST with the initial algorithm disabled are listed in Table IV.1; the reader is referred to reference [4] for more detail on these tests. Six of the seven tests (all but test V) were conducted with the hourly cyclic load profile presented in Table IV.2 applied using a resistive load bank. Test V was conducted with the load profile applied in the reverse order (starting with 5500 watts applied for the first 5.5 minutes, then 4500 watts applied for the next 12 minutes, etc.)

Table IV.1: Tests on SO1 with algorithm disabled, used by UA to validate O2 estimation.

Test ID	Catalyst Installed in Muffler	Position of Garage Bay Door	Position of Entry Door between Garage and House	Maximum O2 Drop Measured in Garage During Test
N	Yes	Closed	Open 2"	1.6%
T	Yes	Open 24"	Closed	ambient
Z	No	Closed	Open 2"	1.6%
W	Yes	Closed	Closed	2.8%
AH	No	Closed	Closed	3.5%
U	Yes	Open 24"	Open 2"	ambient
V	No	Open 24"	Open 2"	ambient

Table IV.2: 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

The results from Tests N and T, shown below in Figures IV.7 and IV.8, are discussed in detail since they are representative of similar tests in which oxygen depletion was and was not, respectively, occurring. The results from the other five tests are also presented below, in Figures IV.9 through IV.13, with discussion of any additional notable issues. In each of these figures, the estimated O2 concentration based on real-time ECU data is compared to the O2 concentration measured by NIST in the garage. The actual O2 concentration was sampled once every 6 minutes, and the raw real-time data was sampled roughly every 58 ms. Due to the enormous quantity of ECU data, 9 data points were skipped between points plotted as raw data. This results in a sampling period of approximately 0.6 seconds. A third trace on each of these plots is that of a low-pass filtered version of the raw estimate. Time zero is when the generator was started.

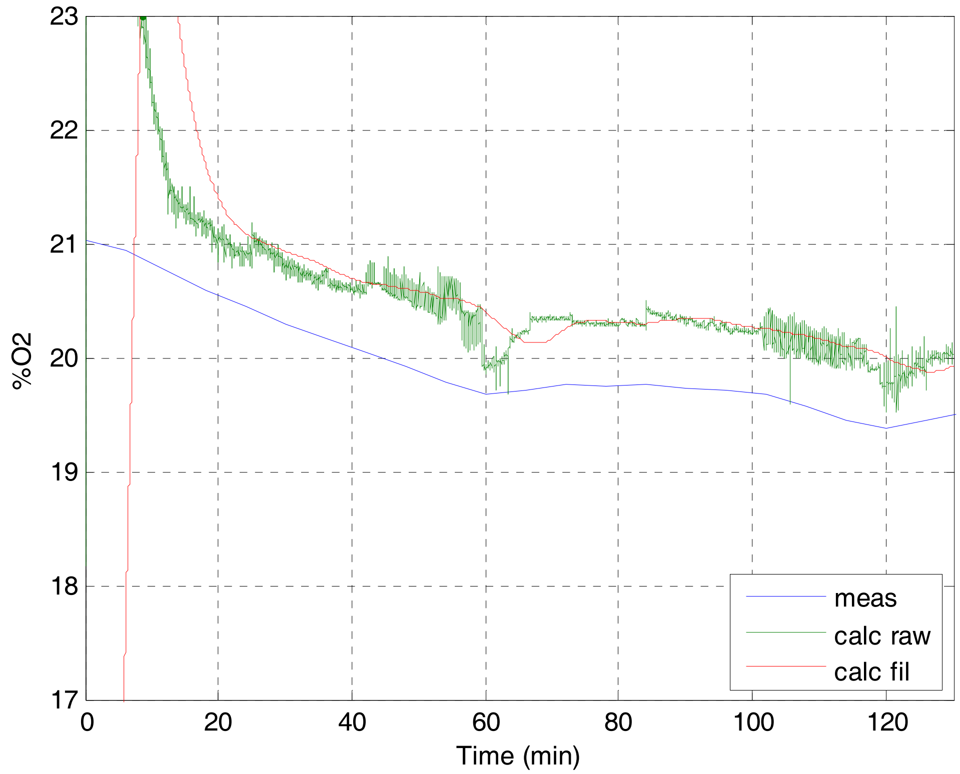

Figure IV.7: Measured and estimated O2 concentration for test N.

For test N, in which the garage oxygen level dropped by 1.6% over the course of the two-hour test, the estimated O2 trace based on the raw data starts tracking the measured trace, with a small offset, after about fifteen minutes of generator operation, and 7 minutes after operation in CLC (evidenced by AFR data as provided in ref [4]). This is explained by the fact that the CAT is based in part on oil temperature, and it takes this long for the oil temperature to increase at a linear, as opposed to exponential, rate (evidenced by the oil temperature data as provided in ref [4]) after the generator is started. The discontinuities in the raw trace occur when the load changes. This is also explained by the oil temperature, which is directly affected by load; increasing load causes the oil temperature to rise and conversely, decreasing load causes the oil temperature to decrease, with some associated time lag. The filtered raw data "softens" these discontinuities but they still exist to some degree. The filtered trace largely tracks the measured data after about 25 minutes of generator operation.

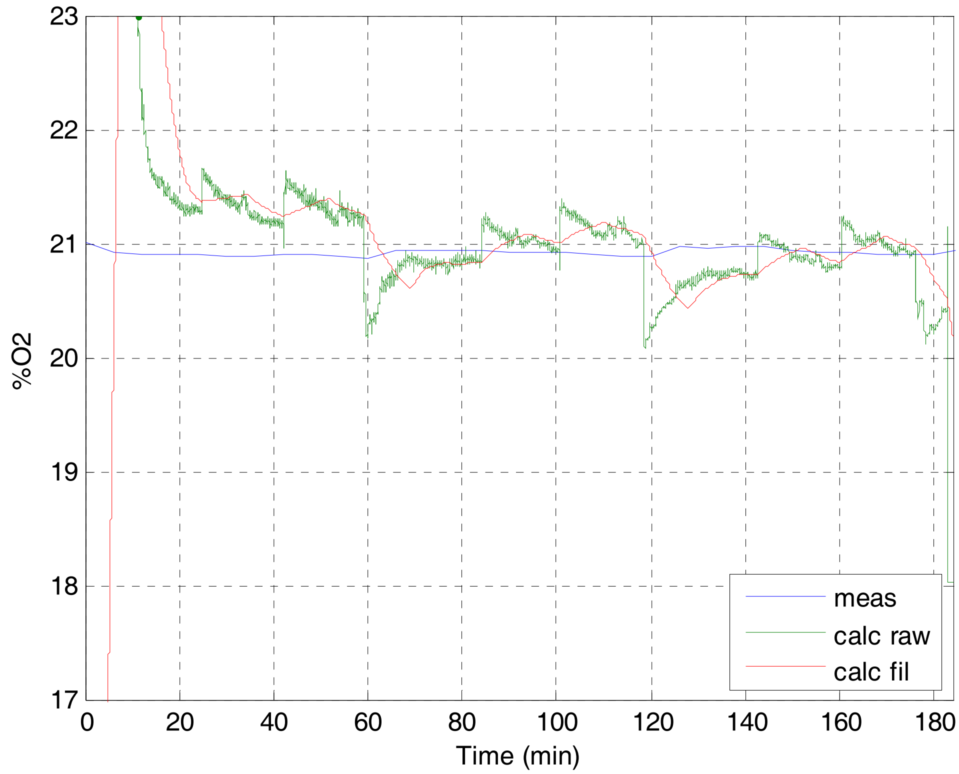

Figure IV.8: Measured and estimated O2 concentration for test T.

For test T, in which the garage bay door was open 24" and did not result in any oxygen depletion, the discontinuities of the calculated raw O2 trace are more apparent. Here it can more easily be observed that the estimated O2 sharply increases at times that correspond to load increases in the load profile. Correspondingly, the estimated O2 sharply decreases at the one-hour and two-hour marks, when the load is dropped from 5500 watts to 0 watts at the repeat of the hourly cyclic load profile. The magnitude of the discontinuity is proportional to the magnitude of the load change. For this test with no oxygen depletion occurring, the filtered trace "softens" these discontinuities into a positive slope of the estimated O2 when the load is increasing and a negative slope when the load is decreasing.

For the raw data trace, it starts tracking the measured trace after about twenty minutes of generator operation, and 8 minutes after operation in CLC (evidenced by AFR data as provided in ref [4]), which is very similar to that found in test N. The filtered trace largely tracks the measured data after about 25 minutes of generator operation, which is also the same as that found in test N.

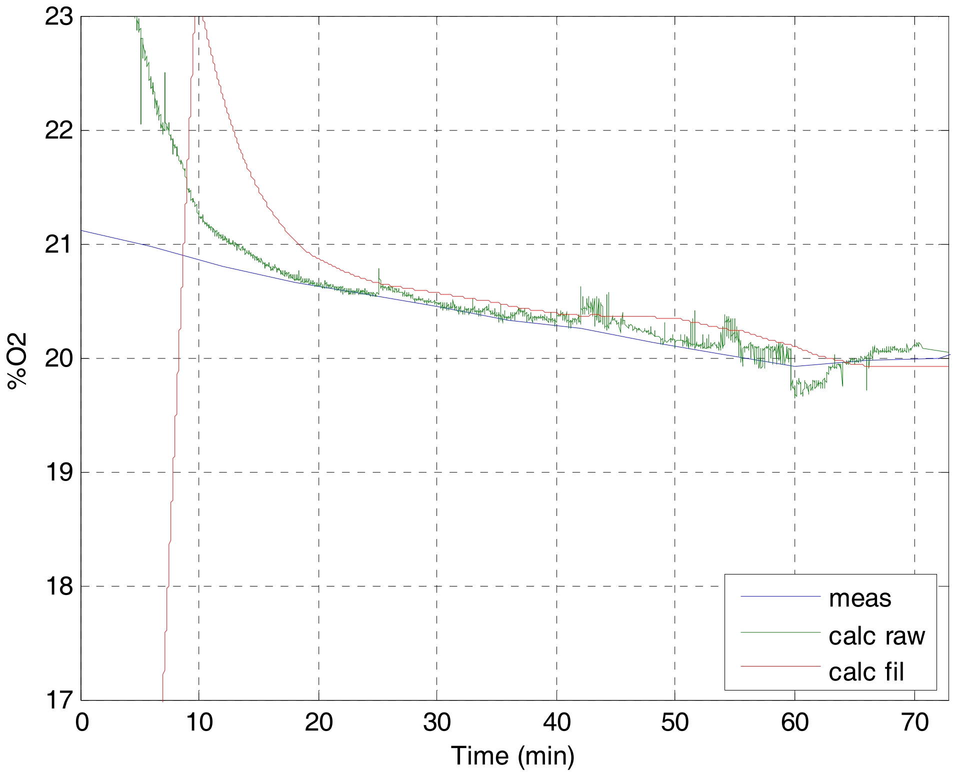

Figure IV.9: Measured and estimated O2 concentration for test Z.

For test Z, the software running on the laptop connected to the ECU that acquired the real-time ECU data "hung" shortly after the first hour of this nearly five hour test, so only the data in that initial time period is plotted. The garage oxygen level dropped by 1.6% over the course of the test. For the data that was acquired, both calculated traces appear to largely track the measured O2 trace, similar to test N but without the small offset between them. The duration of generator run times until the estimated O2 values track the measured values is nominally the same as those observed in tests N and T.

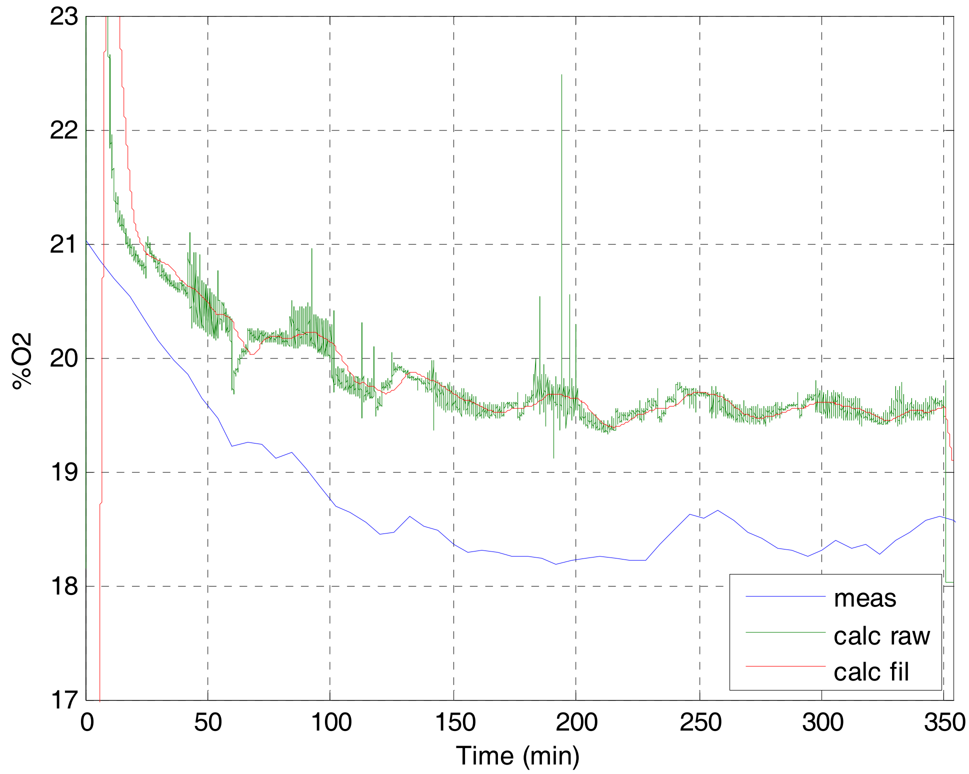

Figure IV.10: Measured and estimated O2 concentration for test W.

For test W, in which the garage oxygen level dropped by 2.8% over the course of the six hour test, both calculated traces appear to largely track the measured O2 trace after the same amount of generator run time as the previous tests, and with slightly larger offset between them as seen in test N.

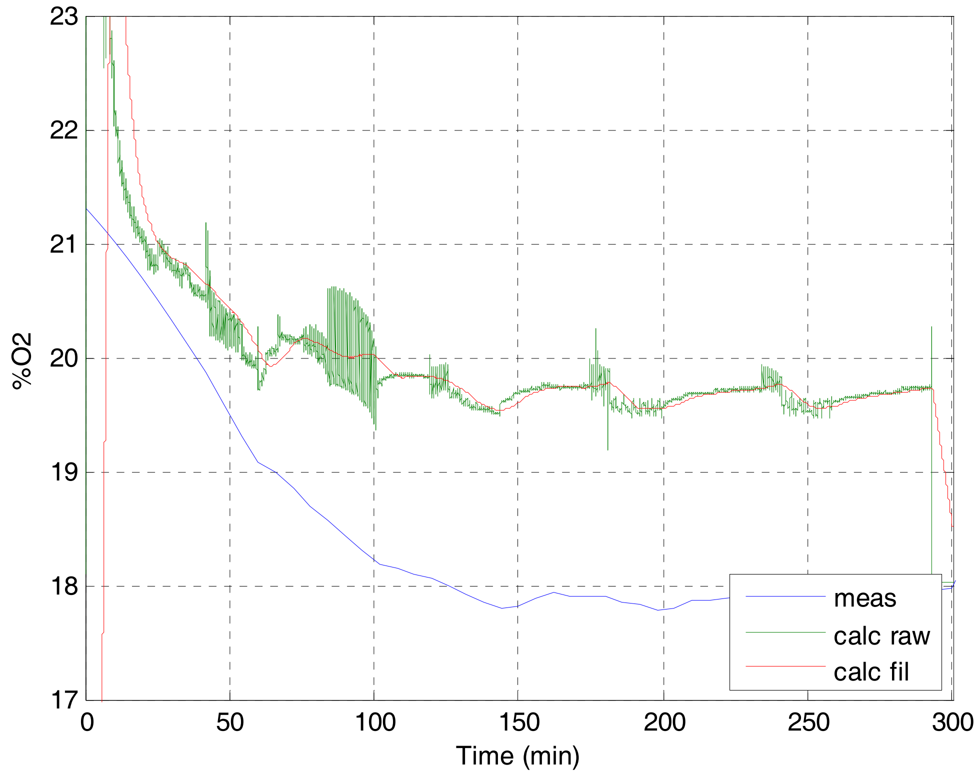

Figure IV.11: Measured and estimated O2 concentration for test AH.

For test AH, in which the garage oxygen level dropped by 3.5% over the course of the five hour test, both calculated traces appear to largely track the measured O2 trace after the same amount of generator run time as the previous tests, and with slightly larger offset between them as seen in tests N and W.

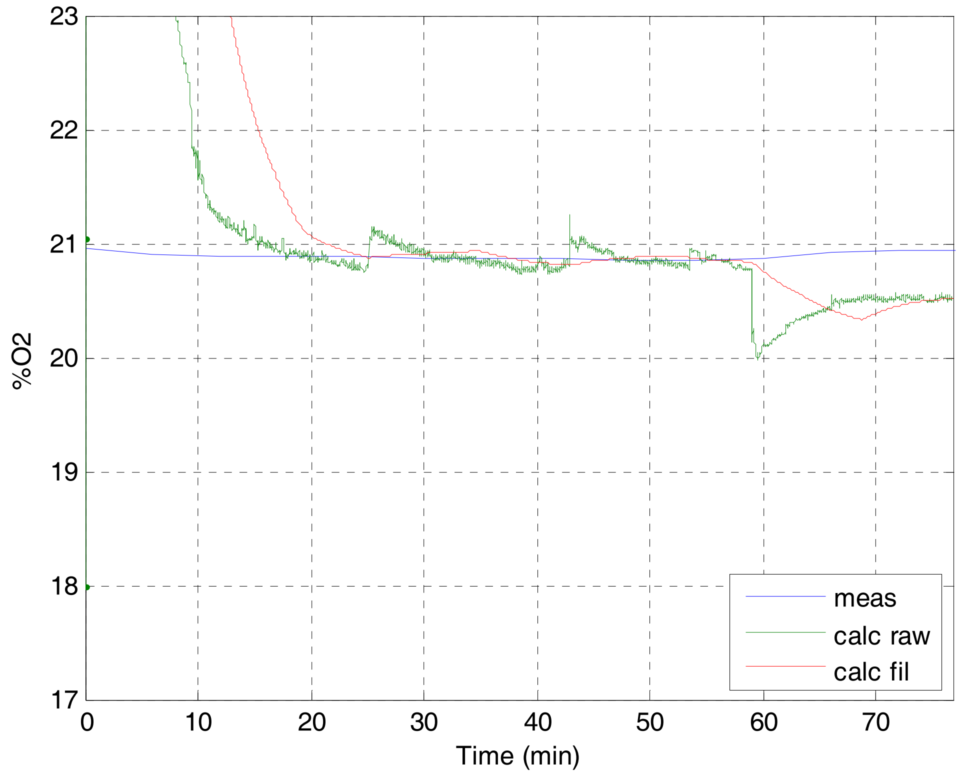

Figure IV.12: Measured and estimated O2 concentration for test U.

For tests U and V, shown in the above and following figures, the results are similar to those for Test T, all three of which were conducted with the garage bay door open 24" and not resulting in any oxygen depletion. Both calculated traces appear to largely track the measured O2 trace after the same amount of generator run time as all the previous tests.

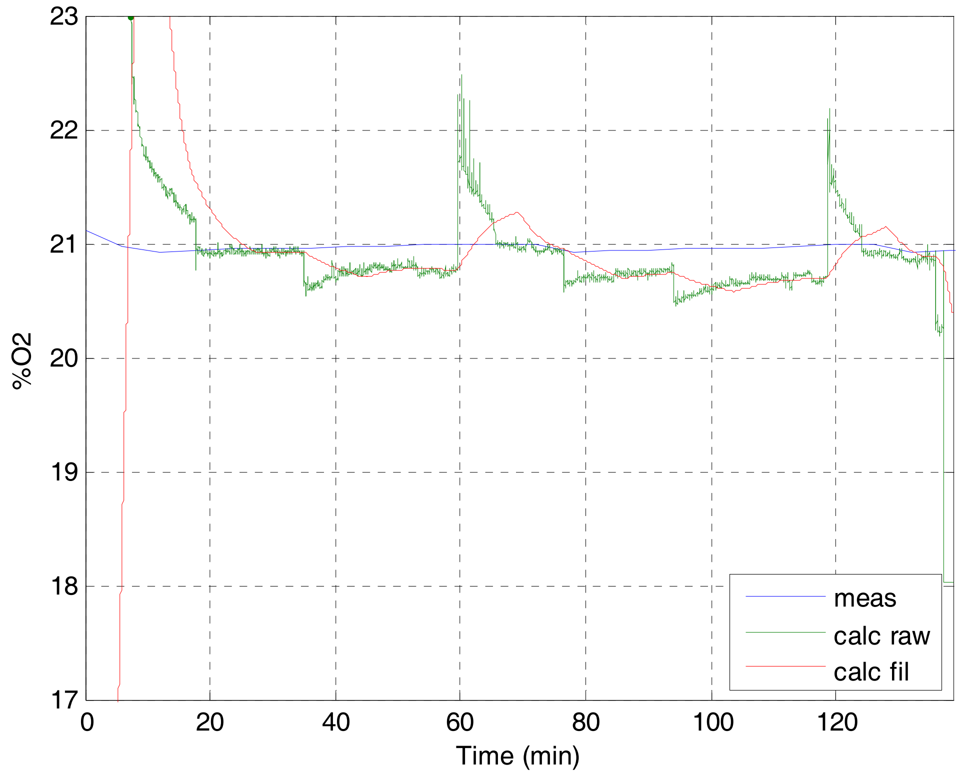

Figure IV.13: Measured and estimated O2 concentration for test V.

These 7 test cases indicate that the proposed method estimates the O2 concentration in the intake air reasonably well after nominally 20 minutes of generator operation.

The next step in the development of a shutdown strategy based on the O2 estimation method is to determine the criteria for shutdown. Various possibilities have been considered thus far. The first approach was focused on the O2 estimate trend, rather than the actual function. In other words, look for a consistently decreasing O2 concentration and a simultaneous increasing trend in MAP. The increasing trend in MAP would be needed to distinguish a decreasing O2 estimate due strictly to load changes from high to low, in which case MAP is decreasing. Under normal operation, MAP increases as load increases and also, as observed in the enclosure testing at UA, for a given load, MAP increases as O2 drops. However, it was determined by computing the derivative of the O2 estimate using the relationship used in (IV.3), that the closed-door and partially closed-door cases were indistinguishable. Refinement of the relationship so the estimated O2 more closely matches the measured O2 may prove successful since the derivatives of the measured O2 data appear sufficient to distinguish between tests in which oxygen depletion was and was not occurring. If a more precise relationship can be identified, consideration will need to be given to the fact that even when the generator is operating in an enclosed environment, the oxygen level may initially deplete but it could eventually reach equilibrium, as appears at least to nominally be the case in tests W and AH. Another possibility for shutoff criteria is focusing on the actual O2 estimate and the integral of the O2 estimate. This allows assessment of O2 concentration in terms of how far below some nominal value it may be as well as how long it has been below the nominal value.

V. Conclusions

This report has documented the hardware associated with prototype SO1. The prototype generator set is equipped with a muffler catalyst and engine control unit with an integral shutoff feature based on the initial algorithm developed. Furthermore the report has documented initial generator testing to assess the response of ECU variables to operation in an enclosed environment for the purpose of implementing the automatic shutoff feature preventing such operation. The initial shutoff algorithm presented above and implemented in hardware on prototype SO1 is effective; however, it does have significant limitations. Nevertheless, SO1 represents a significant proof of concept in demonstrating the capability to shut off the engine when a shutoff decision is rendered. An advanced approach to a shutoff algorithm, based upon estimating the O2 concentration in the intake air, appears to hold the most promise to date.

Suggestions for Possible Algorithm Strategy Utilizing Additional Sensors

While the work reported above adhered to CPSC's requirement that the shutoff feature use no additional sensors, two observations reported in the testing at UA and NIST provide another possible strategy that would violate this requirement. It was discussed previously that during UA's closed-door enclosure testing with fixed loads, MAP increases as the intake air oxygen level drops. Additionally, NIST reported in ref[4] that in all of the tests in which oxygen depletion occurred that as the oxygen level decreased, the generator's delivered electrical output decreased, with the higher loads showing greater sensitivity to decreasing oxygen content than the lower loads. A strategy that uses a power transducer (actually comprised of both voltage and current transducers) added as an input to the ECU to measure the electric power output for comparison with engine power output, as inferred by MAP, could be explored. In cases where MAP continually indicates increasing engine output but the electrical output is decreasing, it would be reasonable to assume operation in an enclosed environment. This option also appears to be a simple but highly effective strategy.

Since this strategy requires additional sensors, another obvious strategy that also requires an additional sensor, one employing a CO detector that provides a single shutoff signal to the ECU when CO is detected in the intake air, deserves attention. This strategy is not considered to be feasible for a number of reasons. We believe these sensors will have reliability issues when continually exposed to the wide range of environmental conditions in which portable generators are operated as well as stored. We also believe this strategy will impact the utility of the product by causing nuisance shutoffs during a variety of conditions of outdoor operation. Furthermore, these devices have a limited life span and are expensive.

VI. References

[1] Puzinauskas, Paulius V., et. al., *Low Carbon Monoxide Prototype Portable Generator – Build Description and Performance Evaluation*, July, 2011.

[2] Smelser, Jennifer Beasley, *Oxygen Depletion Shutdown Algorithm for Portable Gasoline Generators*, MS Thesis, University of Alabama, 2009.

[3] Nabinger, Steven and Andrew Persily, *Airtightness, Ventilation, and Energy Consumption in a Manufactured House: Pre-Retrofit Results*, NISTIR 7478, National Institute of Standards and Technology, U.S. Department of Commerce, May 2008.

[4] Emmerich, S.J., et. al., *Interim Report - Measured CO Concentrations at NIST IAQ Test House from Operation of Portable Electric Generators in Attached Garage*, July 6, 2011.

APPENDIX

Initial Algorithm Technical Development and Performance

Theoretical Background

This Appendix provides the theoretical development of the initial enclosed operation detection strategy. The governing heuristic principles that dictated the following development were presented in the main body of this report. When the engine is running with a fixed load in a confined space, the fuel pulse width (FPW2) increases, the pulse width correction factor (FBLMCOR) decreases, and the intake air temperature (IAT) increases. Under operation with a fixed load in the open enclosure, the fuel pulse width and pulse width correction factor do not simultaneously change in this manner. Thus, FPW2, FBLMCOR, and IAT are the target variables for this algorithm.

The algorithm is based upon a moving average of the collected data to calculate a pseudo-derivative for each signal. The pseudo-derivative is then used in the comparison logic to establish the trend of each signal. IAT and FPW2 will show increasing trends, and hence positive pseudo-derivatives, and the FBLMCOR will show a decreasing trend, and hence a negative pseudo-derivative under confined space operating conditions. Since a derivative is employed on physical signals with inherent noise, the input signal is filtered through the fixed-width window moving average. Although the algorithm does not actually calculate the average, the following set of equations illustrates how the concept of the moving average is used in the pseudo-derivative calculation. Equation (A.1) shows an average calculation of an array x over n points. As a new data point enters the array, the window slides, and a new average can be calculated according to (A.2).

$$\hat{x}_n = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n} \tag{A.1}$$

$$\hat{x}_{n+1} = \frac{x_2 + x_3 + x_4 + \cdots + x_{n+1}}{n} \tag{A.2}$$

Equations (A.3) and (A.4) illustrate how the pseudo-derivative, Δx, is calculated from (A.1) and (A.2).

$$\Delta x = \hat{x}_{n+1} - \hat{x}_n = \frac{x_2 + x_3 + x_4 + \cdots + x_{n+1}}{n} - \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n} \tag{A.3}$$

$$\Delta x = \frac{x_{n+1}}{n} - \frac{x_1}{n} = \frac{x_{n+1} - x_1}{n} \tag{A.4}$$

The calculation of (A.5) shows the pseudo-derivative, δx, as an approximation of the derivative over a number of samples. Note that the term pseudo-derivative is employed since the difference is numerically calculated and the time difference is not considered. Ultimately, stated more physically, if a sample taken now is higher than a sample taken much earlier, then the signal is increasing. Furthermore, the magnitude of the derivative is not of interest, just the sign to indicate a trend.

$$\delta x = x_{n=1} - x \tag{A.5}$$

In order for this algorithm to work in the existing ECU software, new variable initializations had to be made for the IAT, FPW2, and FBLMCOR pseudo-derivative signals, which can be found in Table A.1. The variables listed in Table V.3 are used to process the IAT, FPW2, and FBLMCOR signals through the algorithm, and they must be restored to zero upon system restart. The default parameters listed in Table A.1 are those selected based on the UA initial test data. In essence, the algorithm was executed with the collected data, and parameters were varied until all test cases were properly classified.

Table A.1: Confined space detection and shutoff algorithm variables.

Variable	Type	Description	Default
Npts	Integer	Number of points in averaging window	512
Flagcnt	Integer	Size of sample window over which the acceptable and unacceptable hit are compared	128
FthreshIAT	Integer	The number of unacceptable to hits that must be exceeded in a comparison window to set the trip flag for VIAT	85
FthreshBPW	Integer	The number of unacceptable to hits that must be exceeded in a comparison window to set the trip flag for FPW2	85
FthreshPWC	Integer	The number of unacceptable to hits that must be exceeded in a comparison window to set the trip flag for FBLMCOR	85
Tlim	Floating	The default change in intake air temperature that must be exceeded between samples to result in an unacceptable hit	2.048
COen	Binary	Enable bit for the confined space detection and shutoff algorithm	1

Table A.2: Confined space detection and shutoff algorithm process variables.

Variable	Type	Description	Restore Value
dVIAT	Floating	Intake air temperature pseudo-derivative	0
dFPW2	Floating	Base pulse width pseudo-derivative	0
dFBLMCOR	Floating	Block learn memory correction factor pseudo-derivative	0
BPWpos	Integer	Number of positive base pulse width derivative points	0
PWCneg	Integer	Number of positive pulse width corr. derivative points	0
IATpos	Integer	Number of positive intake air temp. derivative points	0
BPWflag	Binary	Flag indicating base pulse width increasing	0
PWCflag	Binary	Flag indicating pulse width correction decreasing	0
IATflag	Binary	Flag indicating intake air temp. increasing	0
COflag	Binary	Flag to shut down engine	0

Once initialization of the above variables has occurred, the algorithm buffers the incoming data from the IAT, FPW2, and FBLMCOR signals into three arrays, respectively, until 512 data points have been collected. The algorithm continues to buffer the incoming data through the array by pushing the current data point in, popping out the first element, and computing the pseudo-derivative. The comparison logic for each signal uses the respective pseudo-derivative to perform a comparison, and if the comparison is true, the signal's fail counter will be incremented by one count. The signal's fail counters are then compared to their respective thresholds listed in Table A.1 and if all three counters have reached their threshold point before FODSC resets to zero, the FODDET flag will be set to true resulting in engine shutdown. Engine shutdown is accomplished by disabling fuel injection, i.e. the fuel pulse width is set to zero and locked to this value.

Once shutdown has occurred, the ECU must be turned off to clear the FODDET flag before restarting the engine. Upon restart, the variables used to process the IAT, FPW2, and FBLMCOR signals will be reset to zero. The confined space detection algorithm pseudo-code, as originally developed based on initial UA test data, is shown below:

1. Set point counter, PCNT=0
2. On update to VIAT, FPW2, and FBLMCOR
    a. PCNT=PCNT+1
    b. Buffer (Npts long, FIFO) Npts samples of VIAT, FPW2, and FBLMCOR
        i. VIAThold(PCNT)=VIAT
        ii. FPW2hold(PCNT)=FPW2
        iii. FBLMCORhold(PCNT)=FBLMCOR
    c. If PCNT<Npts, GO TO 2
3. WINCNT=0
4. On update to VIAT, FPW2, and FBLMCOR
    a. WINCNT=WINCNT+1
    b. dVIAT=VIAT-VIAThold(1)
    c. dFPW2=FPW2-FPW2hold(1)
    d. dFBLMCOR=FBLMCOR-FBLMCORhold(1)
    e. PUSH VIAT into VIAThold buffer
    f. PUSH FPW2 into FPW2hold buffer
    g. PUSH FBLMCOR into FBLMCORhold buffer
    h. If dVIAT>Tlim, IATpos=IATpos+1
    i. If dFPW2>0, BPWpos=BPWpos+1
    j. If dFBLMCOR<0, PWCneg=PWCneg+1
    k. If WINCNT=Flagcnt
        i. If BPWpos>FthreshBPW
            1. BPWflag=1
            2. Else, BPWflag=0
        ii. If PWCneg>FthreshPWC
            1. PWCflag=1
            2. Else, PWCflag=0
        iii. If IATpos>FthreshIAT
            1. IATflag=1
            2. Else, IATflag=0
        iv. COflag=BPWflag&PWCflag&IATflag
        v. WINCNT=0
        vi. BPWpos=0
        vii. IATpos=0
        viii. PWCneg=0
        ix. If COflag&COen=1, **SHUT DOWN ENGINE (Disable Fuel Injection)**
    l. GO TO 4

It is important to recognize that the algorithm is tuneable based upon user data for all of the variables listed in Table A.1, which are flashed into memory for initialization. The buffer size, counter thresholds, and absolute thresholds all significantly affect the algorithm performance. During subsequent phases of testing with SO1, these parameters were tuned to optimize performance, resulting in different default parameters than those presented in Table A.1. The refined parameters are discussed later and presented in Table A.3.

Algorithm Validation on Existing Test Data

The developed algorithm, as defined in the previous pseudo-code, was implemented for simulation in the computer software MATLAB. MATLAB is a product of MathWorks and provides a computational platform and programming environment for extensive and rapid algorithm development and data analysis as well as simulation. It is widely recognized as a standard tool in both engineering and the sciences.

The data from the previously presented test cases (3 load settings under open- and closed-door conditions for a total of 6 different scenarios) was post-processed through the MATLAB simulation of the shutdown algorithm with the parameter values defined in Table A.1. None of the open-door test data sets produced any trips, and all of the closed-door data sets tripped as expected. Please note that the absence of a trip event with open-door test data should not be misunderstood to imply that it is safe to operate a portable gasoline generator in a shed just because the doors are open.

For illustration of the algorithm and to show the nature of the internal variables, the closed-door, 5500 W load scenario was selected. Figure A.1 displays the intake air temperature, base pulse width, and block learn memory correction factor versus time as well as the moving averages of these variables. Note that the algorithm is not enabled until the moving averages have tracked to the real-time signals. In this case, it can be seen that the intake air temperature and base pulse width are increasing while the correction factor is decreasing.

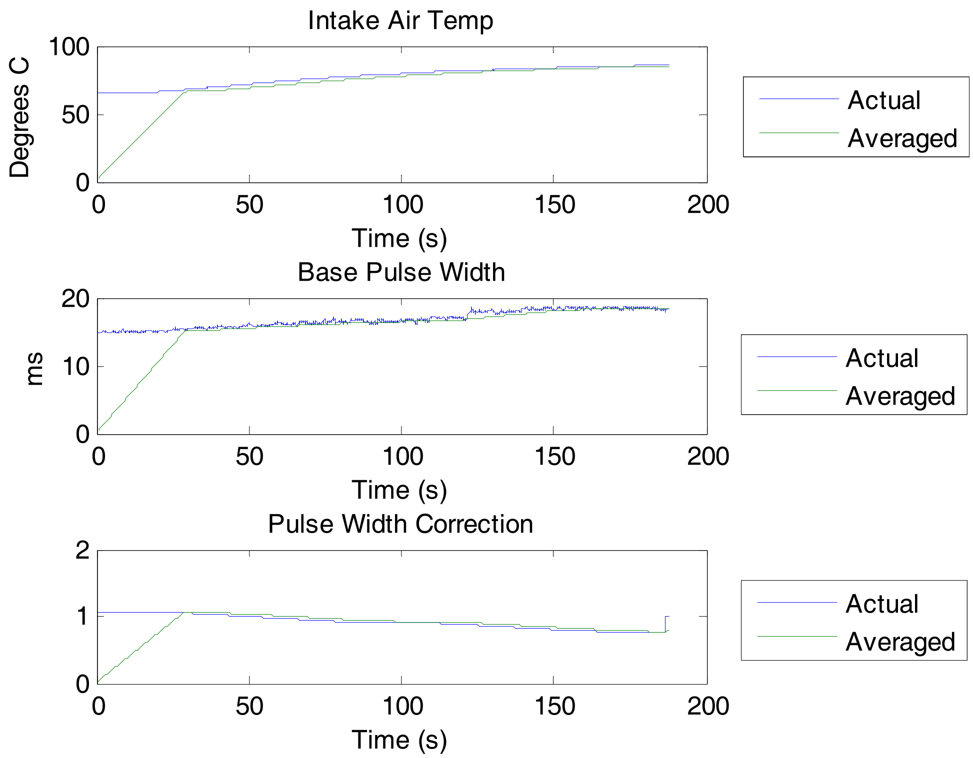

Figure A.1: Key signals for the 5500 W, closed-door case.

Figure A.2 shows the intake air temperature, base pulse width, and correction factor pseudo-derivatives calculated within the algorithm. Since the difference is not divided by the time step, the magnitude of these signals has little meaning. Furthermore, the units associated with the pseudo-derivatives remain the same as the original variables. Of interest for these signals is their sign.

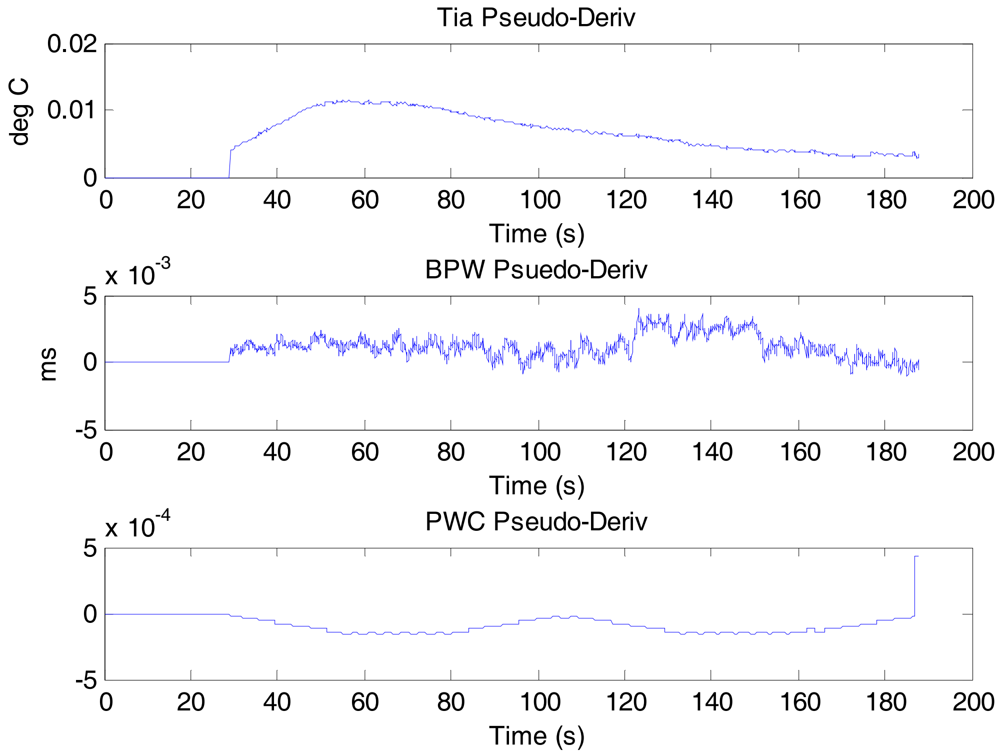

Figure A.2: Pseudo-derivatives for the 5500 W, closed-door case.

Figure A.3 displays the values of the counters that are tracking the number of times the respective pseudo-derivative signals meet the conditions indicating operation in an enclosed environment. The term "fail hit" is employed to imply that the pseudo-derivative conditional test for continued operation has been failed.

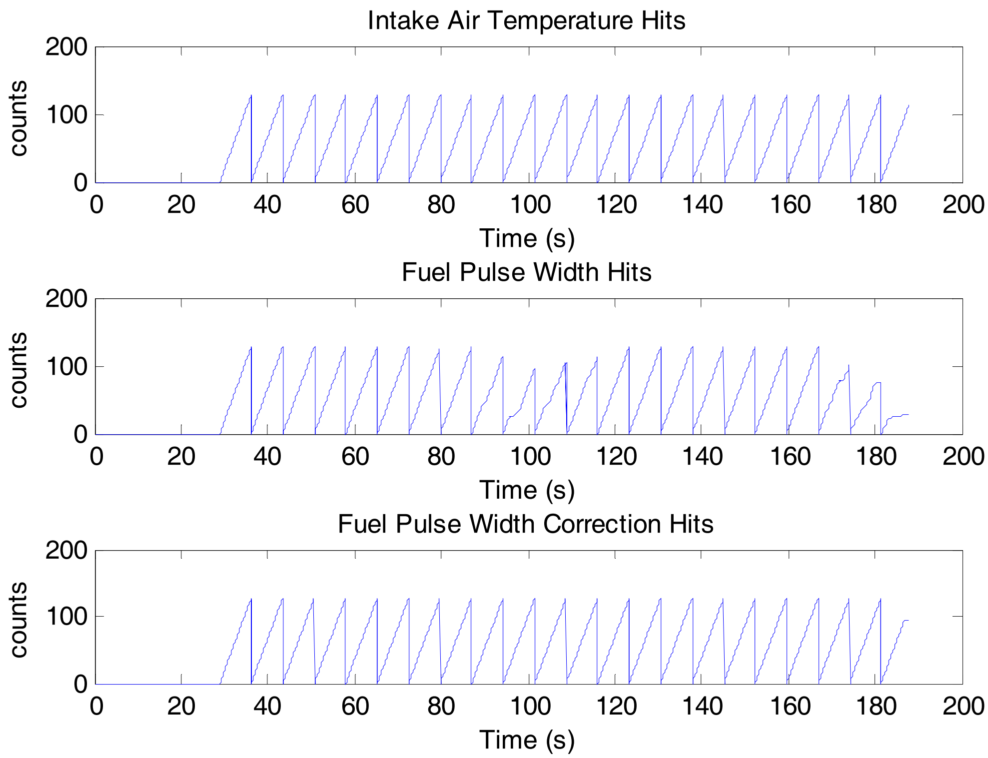

Figure A.3: Fail hits for the 5500 W, closed-door case.

Finally, Figure A.4 shows the three trip flags and shutoff signal based upon the counters. Again, the trip flag status is determined by whether or not the number of "fail hits" exceeds the user defined threshold. Just like the trip flags, the shutoff signal has allowable values of 0 or 1. A 0 value means continue operation, and a value of 1 indicates a shutoff. This signal requires that all three trip flags be equal to 1.

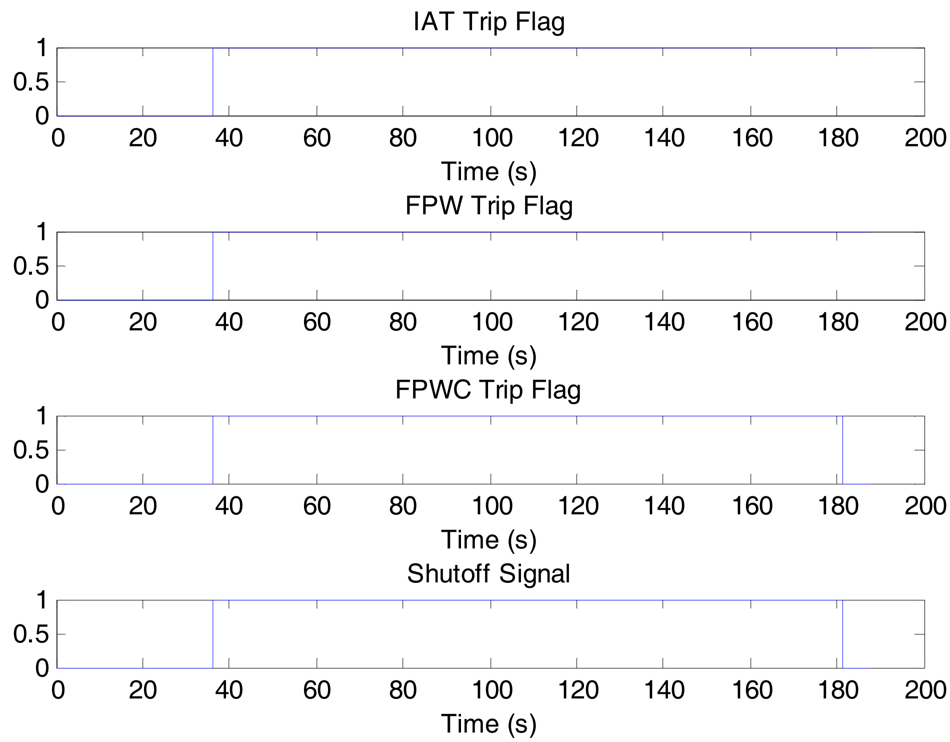

Figure A.4: Fail hits for the 5500 W, closed-door case.

Although the data is not plotted here, a number of interesting points that were uncovered during data analysis are worth mentioning here. All of the open door tests indicated a slightly increasing intake air temperature, which was sometimes adequate to set the IAT trip flag. Also, the variations in fuel pulse width and block learn memory correction factor were adequate to set their trip flags as well. However, the conditions were never sufficient to have all three trip flags equal to 1 at the same instant of time. Thus, by employing all three signals and setting appropriate thresholds on fail hits, random noise and signal variations resulting from normal and expected operation were not allowed to trip the algorithm. However, the figures pertaining to the closed-door test conditions showed that the variations in all three signals were adequate to run the fail hit counters high enough to exceed the trip thresholds and resulted in all three trip flags being set to 1 simultaneously. This resulted in the shutoff signal transitioning from 0 to 1, indicating that the engine should be shut down.

With the algorithm validated on the existing data, discussions with the ECU manufacturer were initiated to implement the algorithm to run in real-time on the ECU platform. In working with the manufacturer to implement the algorithm in conjunction with the existing control software, a number of minor implementation details and variable names were implemented. To document those changes such that the pseudo-code and initialization routines match the software implementation, the revised pseudo-code is presented below, and Tables A.3 and A.4 show the variable names and default values. As previously stated, the default parameter values differ from those originally employed based on results from the initial phase of NIST testing. Furthermore, the variable EngineTempThreshold was added to determine when the algorithm would start execution after the engine was started. Recall that the ECU manufacturer set the threshold temperature for closed-loop control at 60 ^{o}C. However, it was determined that allowing the algorithm to start slightly before this, at a temperature of 50 ^{o}C resulted in acceptable operation.

1. Set the buffer counter, FODBC=0
2. Upon update of VIAT, FPW2, and BLMCOR
    a. FODBC++
    b. Begin initial buffer of VIAT, FPW2, and FBLMCOR (BufferSize long, FIFO)
        i. IAT(FODBC)=VIAT
        ii. FPW(FODBC)=FPW2
        iii. BLM(FODBC)=FBLMCOR
    c. If FODBC<BufferSize
        i. GO TO 2
3. FODSC=0
4. Upon update of VIAT, FPW2, and BLMCOR
    a. FODSC++
    b. dVIAT=VIAT-IAT(1)
    c. dFPW2=FPW2-FPW2(1)
    d. dBLM=FBLMCOR-BLM(1)
    e. PUSH current VIAT value into the buffer
    f. PUSH current VIAT value into the buffer
    g. PUSH current VIAT value into the buffer
    h. If dVIAT>IAT_FailThreshold
        i. FODIATC++
    i. If dFPW2>0
        i. FODFPWC++
    j. If dFBLMCOR<0
        i. FODBLMC++
    k. If FODSC=Flagcnt
        i. If (FODIATC>IAT_FailCounter)&(FODFPWC>FPW_FailCounter)&(FODBLMC>BLM_FailCounter)
            1. FODDET=1, **Disable Fuel Injection (SHUT DOWN ENGINE)**
        ii. Else
            1. FODSC=0
            2. FODIATC=0
            3. FODFPWC=0
            4. FODBLMC=0
    l. GO TO 4

Table A.3: Confined space detection and shutoff algorithm variables.

Variable	Type	Description	Default
BufferSize	Integer	The number of points in the averaging window for IAT, FPW, and BLM arrays	512
Flagcnt	Integer	The size of the sample window over which the IAT, FPW, and BLM counters are compared to their respective counters	128
IAT_FailCounter	Integer	The number of hits that must be exceeded by the IAT comparison logic in the sample window to trip the IATflag	32
FPW_FailCounter	Integer	The number of hits that must be exceeded by the FPW comparison logic in the sample window to trip the FPWflag	64
BLM_FailCounter	Integer	The number of hits that must be exceeded by the BLM comparison logic in the sample window to trip the FPWCflag	64
IAT_FailThreshold	Floating	The change in IAT between samples that must be exceeded to result a hit in the IAT comparison logic	0.5
COen	Binary	The enable bit for the O_2 depletion algorithm	1
EngineTempThreshold	Integer	The minimum oil temperature, in °C, that allows the confined space detection and shutoff algorithm to be enabled	50

Table A.4: Confined space detection and shutoff algorithm process variables.

Variable	Type	Description	Restore Value
FODBC	Integer	Used to buffer the IAT, FPW, and BLM signal arrays	0
FODSC	Integer	Used in the logic for which the IAT, FPW, and BLM counters are compared to their respective thresholds	0
FODIATC	Integer	Counter used in the IAT comparison logic and increments when the comparison is true	0
FODFPWC	Integer	Counter used in the FPW comparison logic and increments when the comparison is true	0
FODBLMC	Integer	Counter used in the BLM comparison logic and increments when the comparison is true	0
dVIAT	Floating	Pseudo-derivative for the IAT	0
dFPW2	Floating	Pseudo-derivative for the FPW	0
dFBLMCOR	Floatin	Pseudo-derivative for the BLM	0
FODDET	Binary	Flag used to shut down the engine	0

NIST Testing

Once the UA testing of the confined space detection and shutoff algorithm (described in section III of the report main body) was complete, the next phase of testing could begin. The generator was sent to the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland for the purpose of verifying and optimizing the performance of the algorithm in more realistic scenarios known to cause consumer fatalities. NIST is equipped with an Indoor Air Quality Testing Facility, which is illustrated in Figure A.5. This facility is a 1500 square foot double-wide manufactured home. Details on the facility can be found in reference [3].

The garage, located on left end of the test house from the presented view, is where the generator was set up for testing. The test house is equipped with sample ports, in a number of different locations, providing samples of room air to the gas analyzers for measuring exhaust emission concentrations. The O2 and CO concentrations in the garage were the focus of the UA effort.

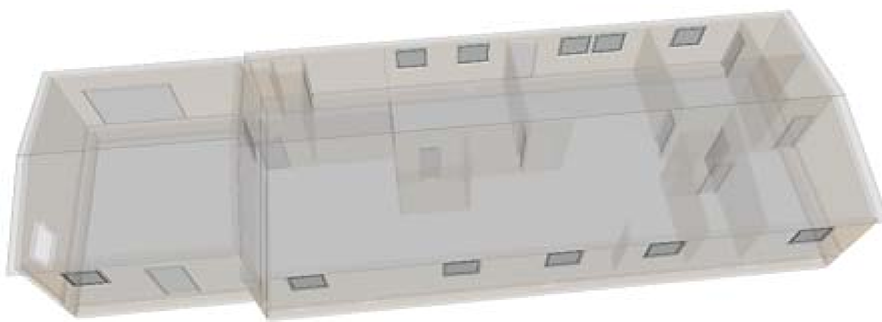

Figure A.5: NIST indoor air quality test house.

Upon set up at NIST, as previously discussed, the algorithm parameters were tuned for more realistic operation rather than for a laboratory setting. Basically, the algorithm was somewhat desensitize by increasing the trip thresholds to reduce nuisance tripping, and the parameters presented in Table A.3 were established. The generator loading was accomplished by NIST personnel using a resistive load bank connected to the 240 V receptacle on the generator. Though a tremendous amount of data exists, the following list represents a number of illustrative scenarios tested in the NIST test house with the algorithm initialized with the default values provided in Table A.3:

- Warm start, fully open bay door, 5500 W
- Warm start, fully closed bay door, 5500 W
- Warm start, bay door open 24 in., 5500 W
- Warm start, fully closed bay door, 2500 W
- Warm start, bay door open 24 in., 2500 W

Note that all tests presented here were performed from a warm start. Under cold start conditions, the algorithm would shut the engine down very quickly after CLC was enabled since the CO content in the exhaust was extremely high while the engine was running rich before CLC was enabled. Though the algorithm is in fact responding properly under these conditions, i.e. shutting down when the engine is in a high CO environment, the transient nature of the condition does not warrant a trip. In a production application, a time delay could be inserted prior to starting the algorithm rather than using an oil temperature as the algorithm start signal. The idea would be to allow the engine to operate for a longer period of time in CLC at 14.6 AFR and the CO concentration in the intake to drop back down before the algorithm starts to function. To do so in this prototype would have required reprogramming the ECU and a long delay in testing.

Figures A.6 through A.15 present the results. These tests produced the expected results: the open bay door tests did not produce any trips, and the closed bay door tests caused the engine to trip. The 5500 W test tripped faster than the 2500 W test, due to the high load, which produces more heat and emissions. When the engine is operating at mid-to-low loads, the algorithm does not respond as quickly as it does at high loads. It was discovered at the NIST facility that under no load and lightly loaded conditions, the engine can run for periods up to 3 hours before the algorithm, initialized with the Table A.3 parameter default values, shuts down the engine.

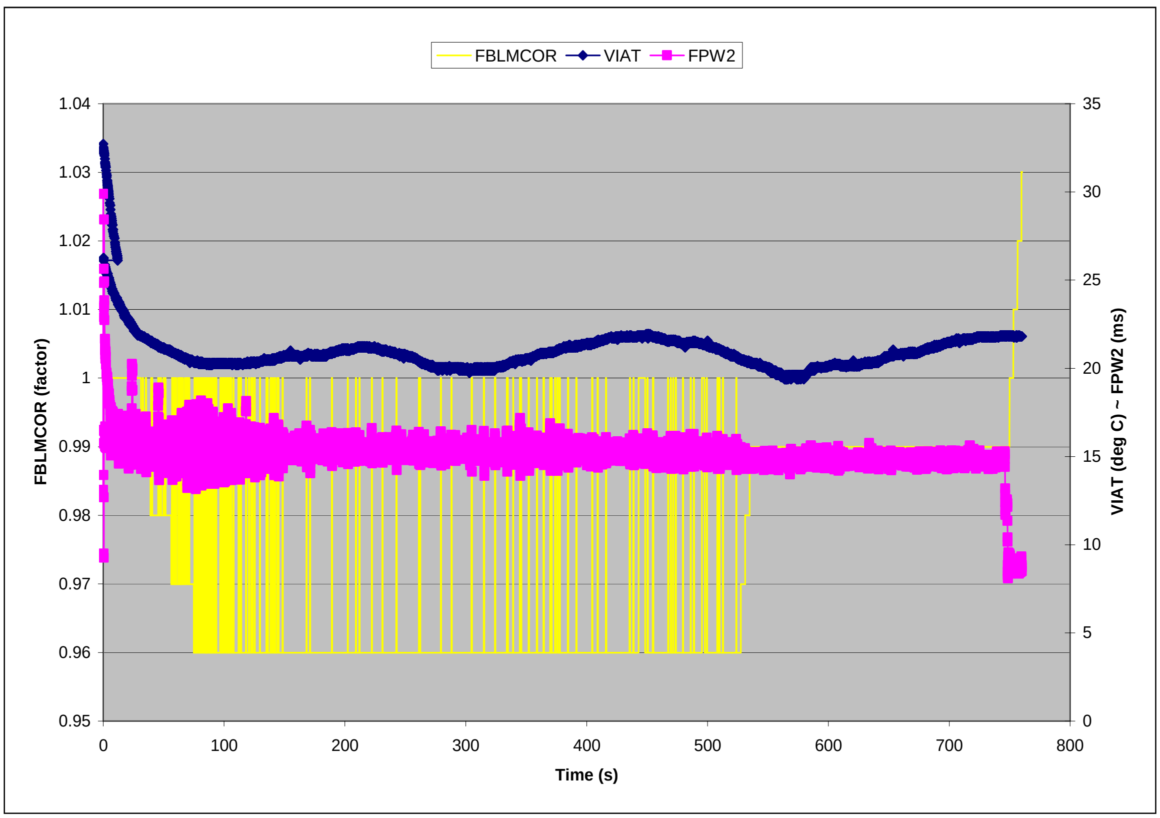

Figure A.6: Enclosed operation detection parameters, open-door, warm start, 5500 W.

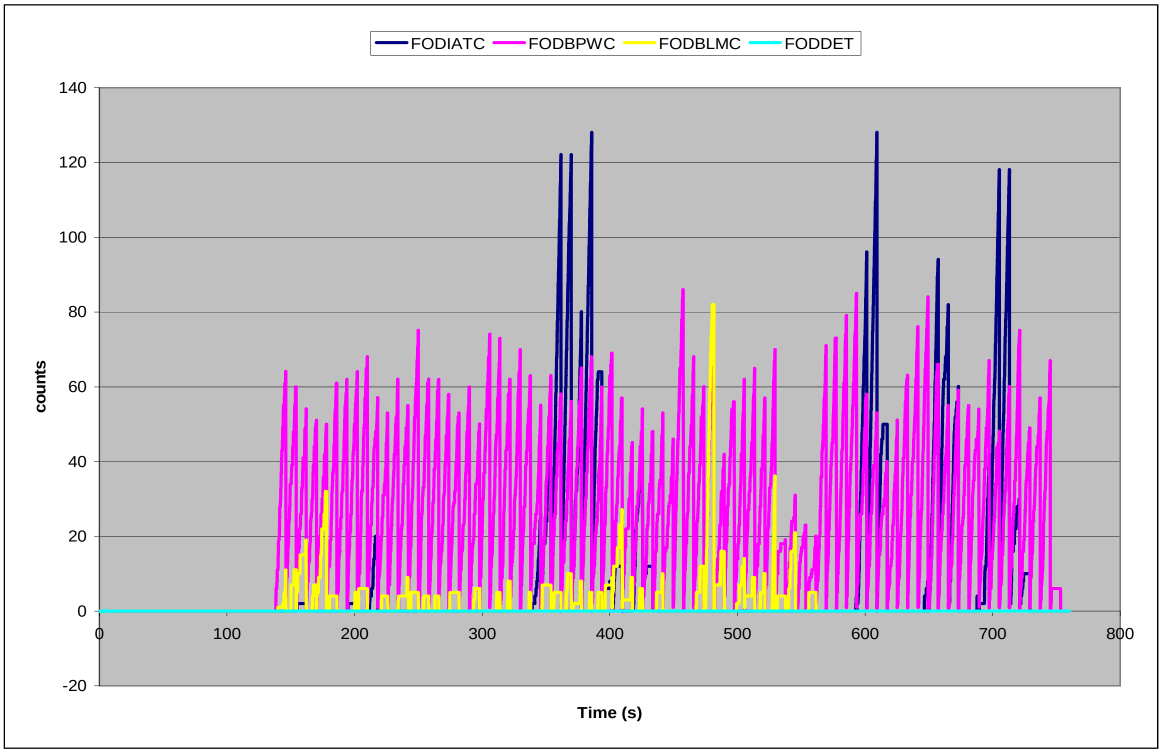

Figure A.7: Algorithm fail counters and trip flag, open-door, warm start, 5500 W.

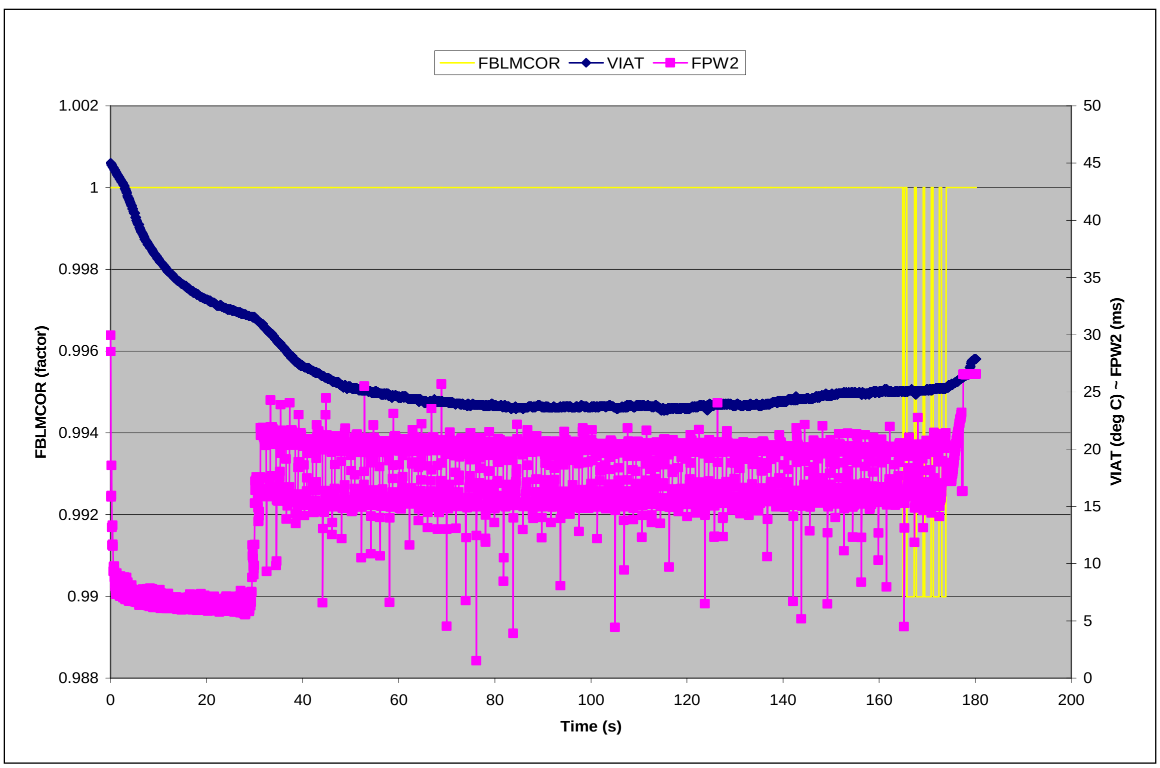

Figure A.8: Enclosed operation detection parameters, closed-door, warm start, 5500 W.

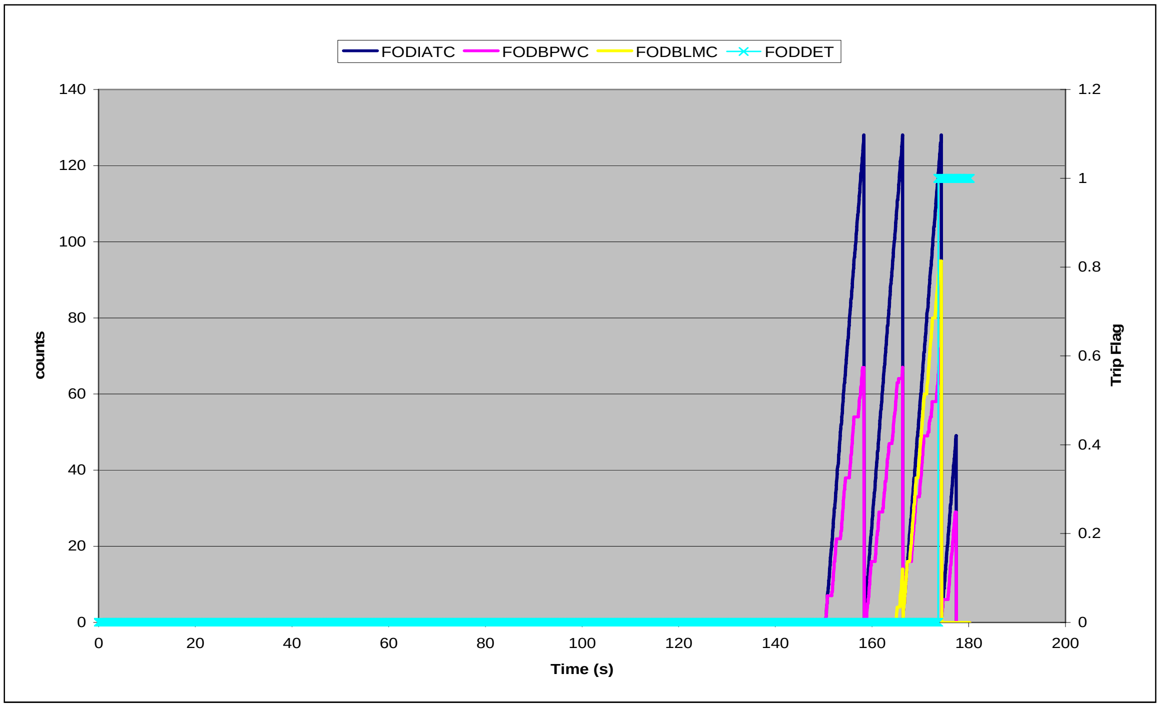

Figure A.9: Algorithm fail counters and trip flag, closed-door, warm start, 5500 W.

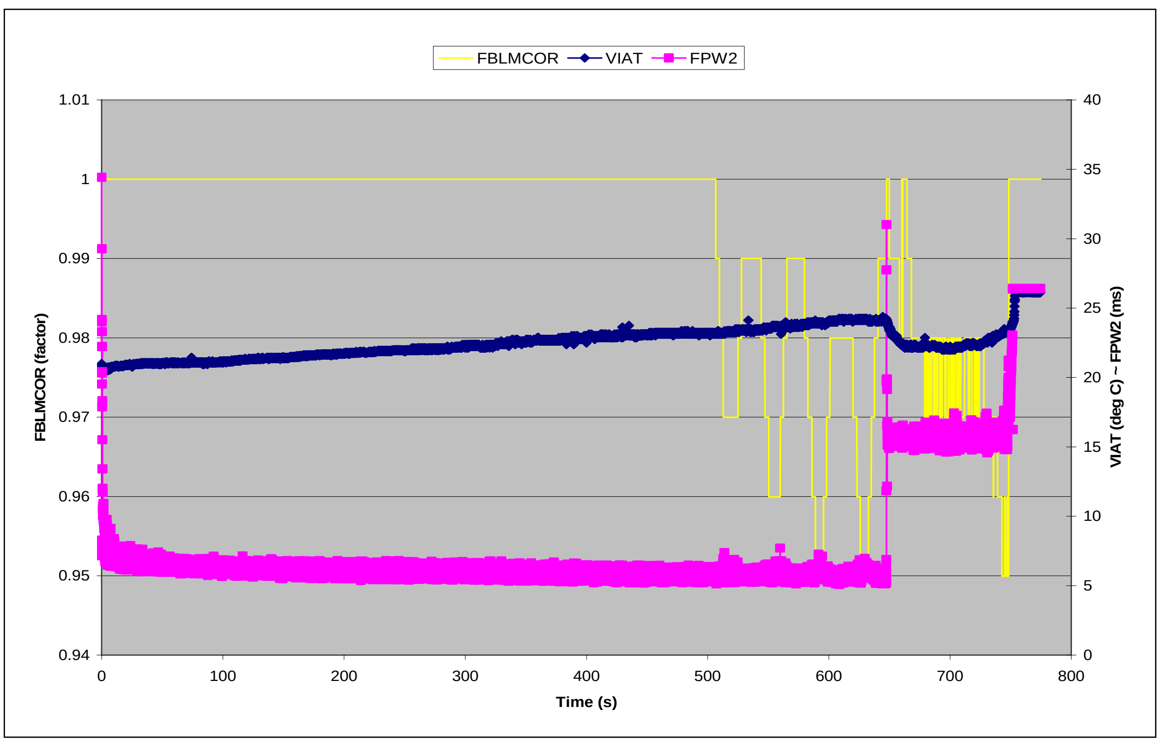

Figure A.10: Enclosed operation detection parameters, door open 24 in., warm start, 5500 W.

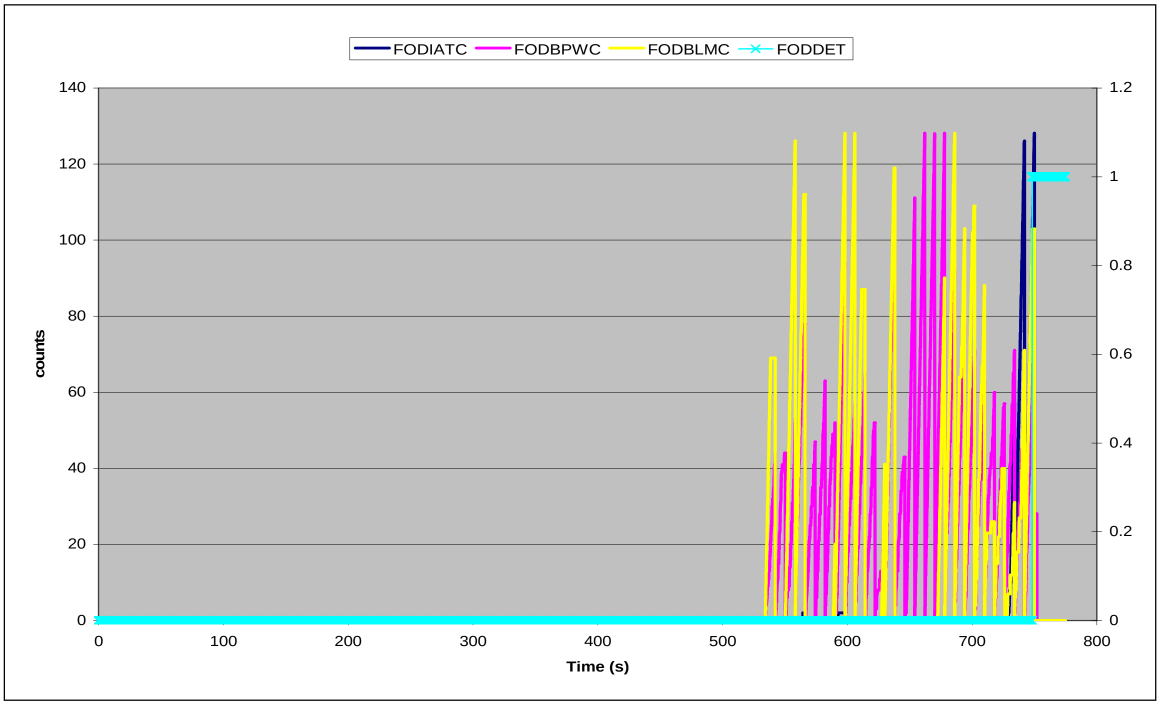

Figure V.11: Algorithm fail counters and trip flag, door open 24 in., warm start, 5500 W.

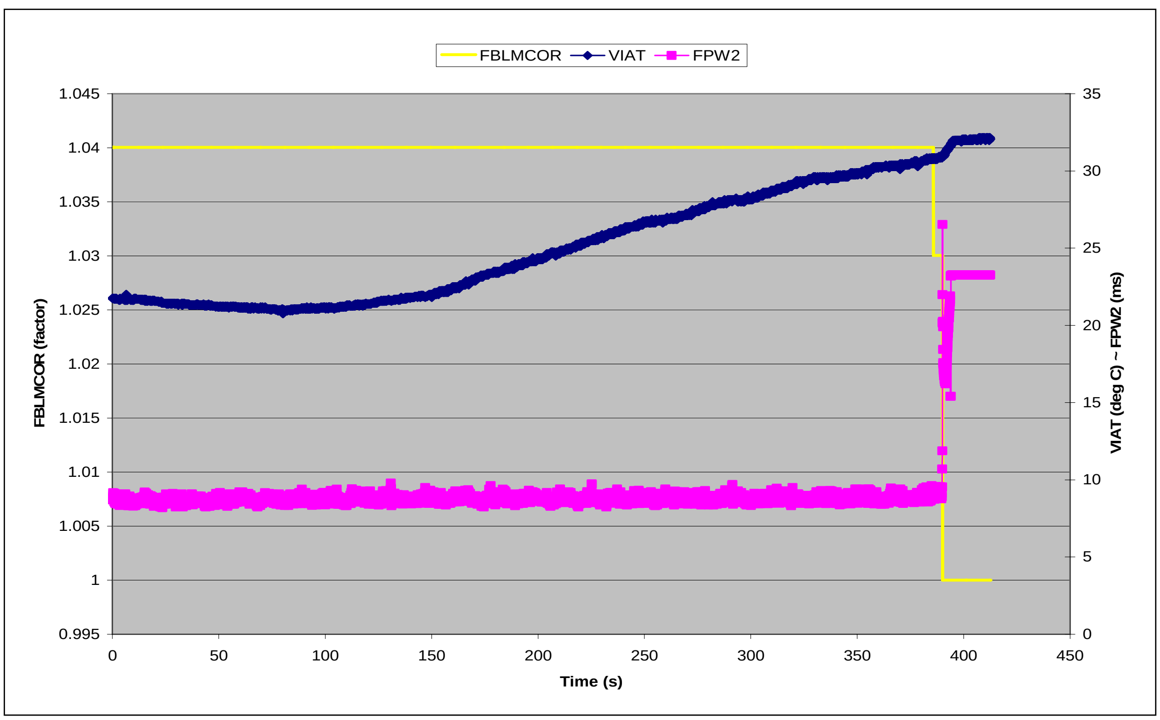

Figure A.12: Enclosed operation detection parameters, closed-door, warm start, 2500 W.

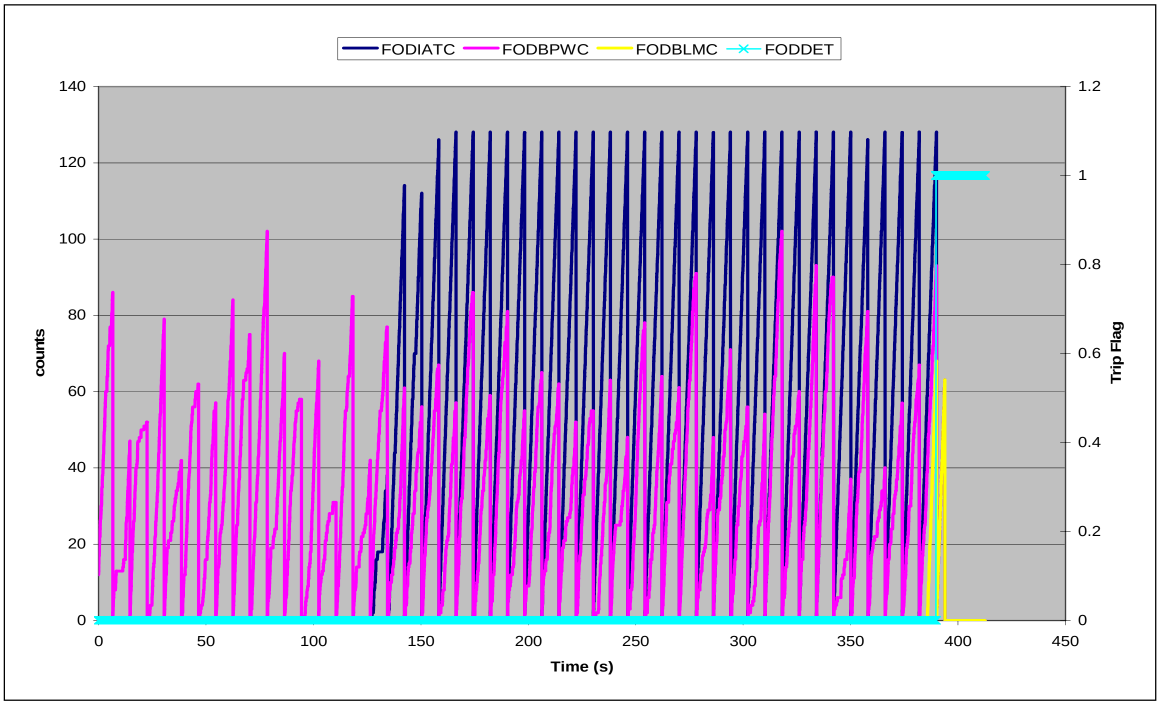

Figure A.13: Algorithm fail counters and trip flag, closed-door, warm start, 2500 W.

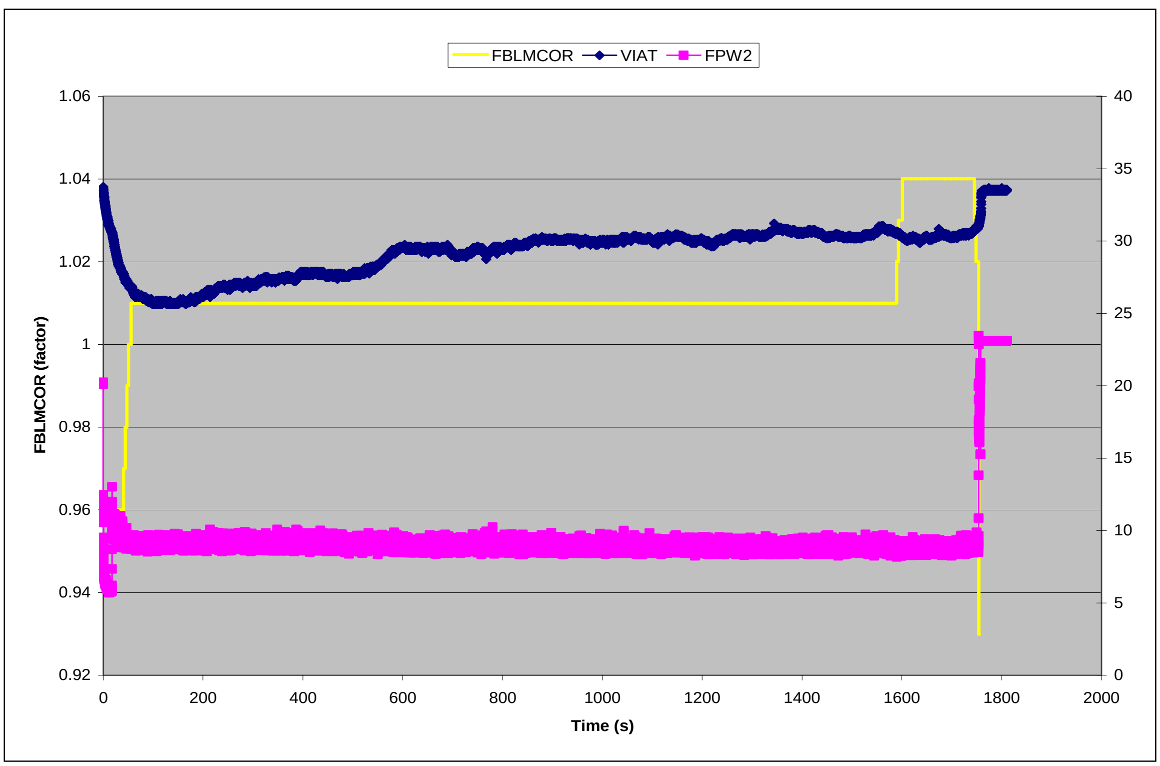

Figure A.14: Enclosed operation detection parameters, door open 24 in., warm start, 2500 W.

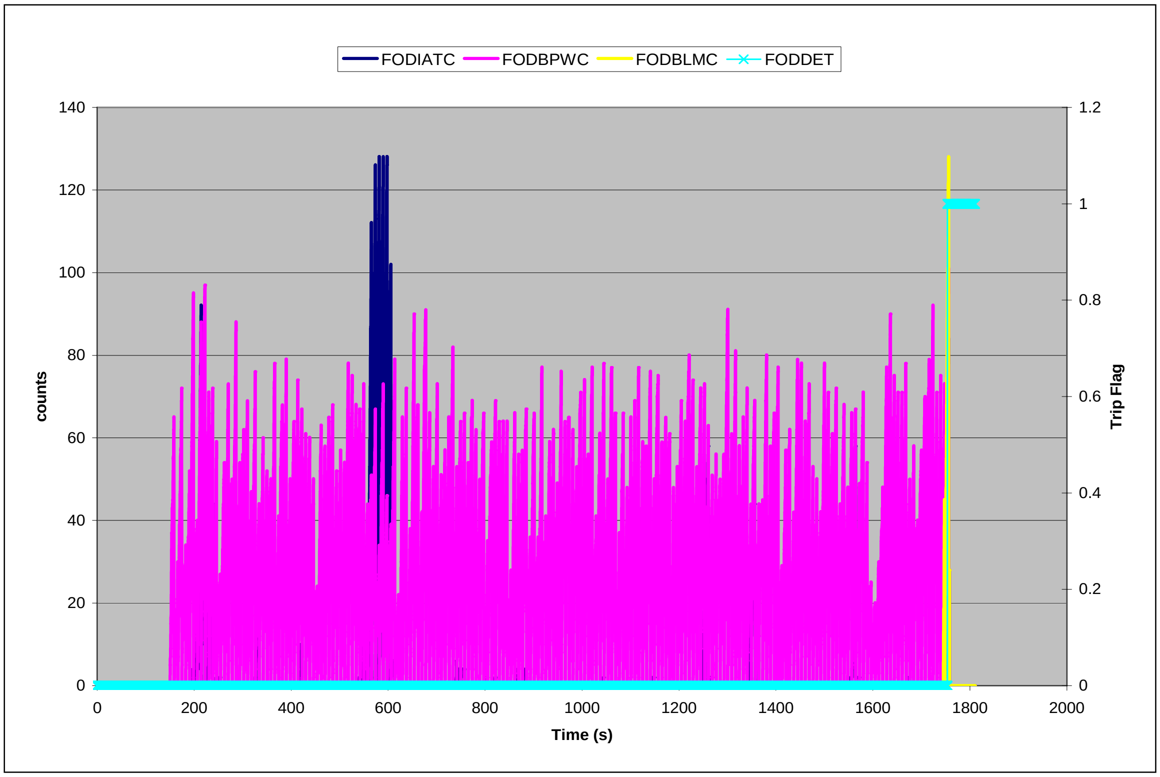

Figure A.15: Algorithm fail counters and trip flag, door open 24 in., warm start, 2500 W.

The lightest loads were found to be problematic for the shutoff algorithm to capture when the generator was running in an enclosed environment. In an attempt to improve algorithm sensitivity, a number of additional tests were performed at the NIST facility with variations in the algorithm tuning parameters. During the second phase of NIST testing, the BLMC, BPWC, and IATC counters were set to 256 so the algorithm would not trip under any conditions and data could be gathered to further improve the algorithm's shutoff capabilities. In addition to varying the counter thresholds, two different sampling intervals were also used during this phase of testing. The sampling interval is the amount of time that passes between capturing the variable of interest to perform the necessary calculations. Although the BLMC, BPWC, and IATC counter thresholds were varied, it was determined that 85, 85, and 16, respectively were the most consistent, produced no nuisance trips, and were only problematic at the lightest loads. These counter values were verified against previous test data where the counters were set to 64, 64, and 32.

The goal was to make sure the algorithm would not produce any trip conditions in open or outdoor spaces, but also capture the lowest load conditions in enclosed spaces. Please note that the desire to eliminate trips in open spaces should not be interpreted to imply that operation in an open shed or garage is acceptable. Table A.5 shows the results of the single and double sample interval tests performed at NIST during this second phase of testing. Be aware that the real-time data was captured with high counter thresholds to disable the algorithm and then post-processed so that many parameter variations could be investigated with one set of data. The definition of a load sweep is a steady progression, either up or down, through the six load modes. A random load test is one in which the load is randomly switched to any number of different loads, independent of the 6 modes, at random intervals.

Table A.5: NIST test scenarios.

Sample Interval	Test	Trip Result
Normal (0.062 s)	LoadSweep-Outdoor	No Trip
	LoadSweep-ClosedDoor	Trip
	LoadSweep-OpenDoor	No Trip
	500W-ClosedDoor-Test1	No Trip
	2500W-ClosedDoor	Trip
	5500W-ClosedDoor	Trip
	500W-ClosedDoor-Test2	No Trip
	500W-OpenDoor	No Trip
	RandomLoad-OpenDoor	No Trip
	RandomLoad-Outdoor	No Trip
Double (0.125 s)	5500W-OpenDoor	No Trip
	500W-ClosedDoor	Trip
	RandomLoad-OpenDoor	Trip
	500W-ClosedDoor	No Trip
	RandomLoad-Outdoor	Trip
	RandomLoad-OpenDoor	No Trip
	500W-OpenDoor	No Trip
	2500W-OpenDoor	No Trip
	5500W-OpenDoor	Trip
	RandomLoad-ClosedDoor	Trip
	2500W-ClosedDoor	Trip
	LoadSweep-Outdoor	No Trip
	500W-ClosedDoor-Test1	Trip
	500W-ClosedDoor-Test2-P1	No Trip
	500W-ClosedDoor-Test2-P2	No Trip
	5500W-ClosedDoor	Trip

Undesirable trips in Table A.5 are shaded. The results from Table A.5 show that using the double sample interval results in a number of nuisance trips and trip failures. The algorithm did produce a trip during the closed-door 500 W test, but only in two out of the five times the test was performed. It was determined that the single sample interval scenarios produced the best results, without any trips outdoors or with the door fully open; however, the algorithm rarely produced a trip for the 500 W closed-door test. The following figures show the outdoor load sweep and closed-door 500 W single sample interval scenarios as well as the outdoor random load and closed-door 500 W double sample interval scenarios. In the case of the two single sample interval tests shown below, the outdoor test did not trip as required, but 500 W closed-door test should have tripped.

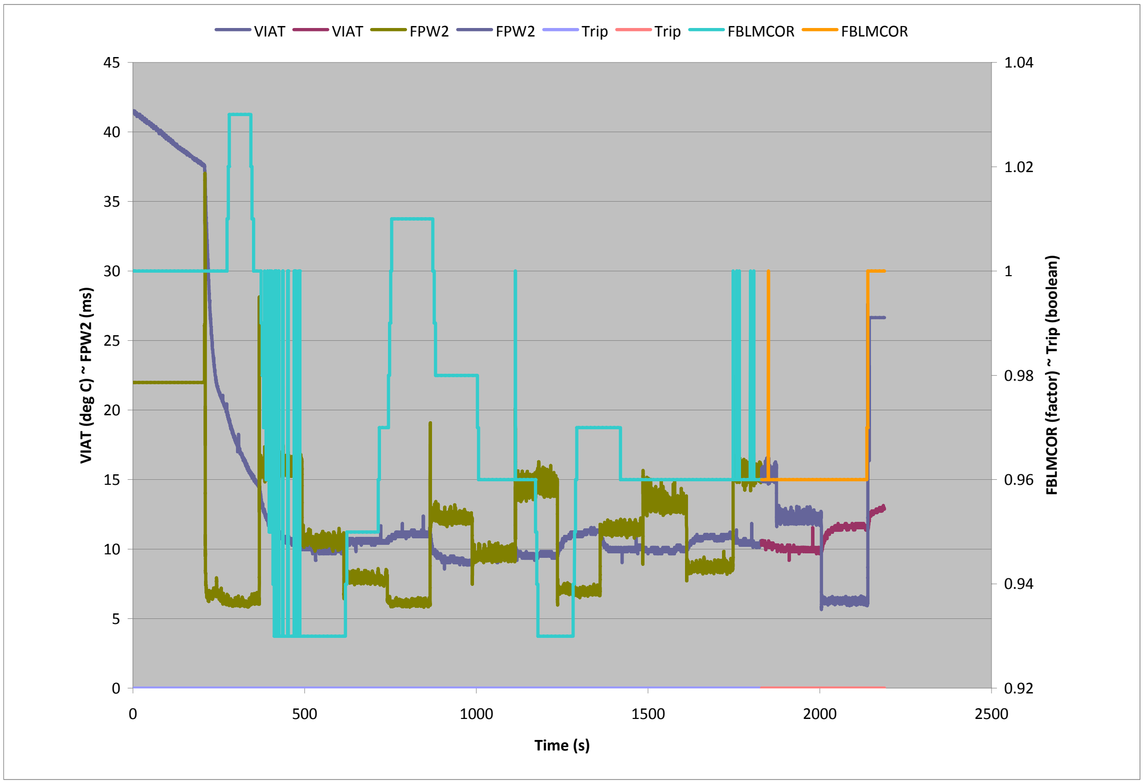

Figure A.16: Outdoor, random load, single sample interval test, no trip.

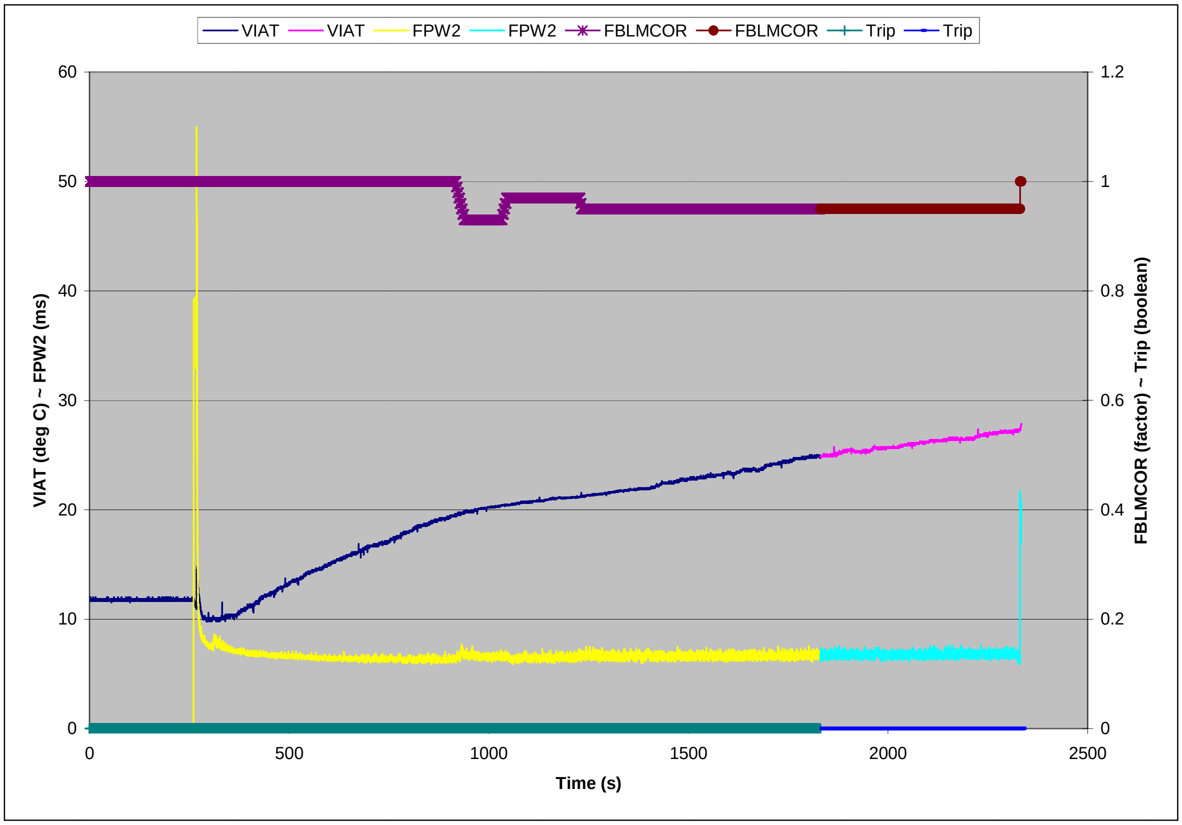

Figure A.17: Closed-door, 500 W, single sample interval test 1, no trip.

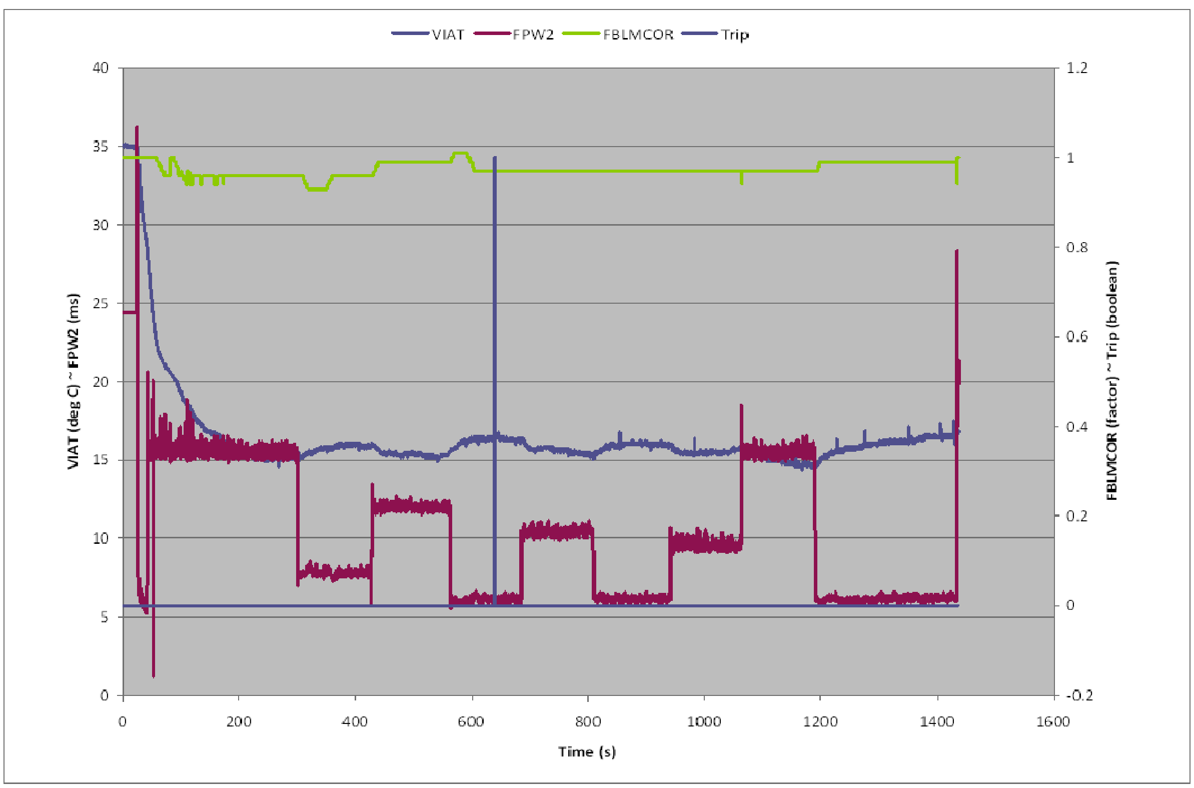

Figure A.18: Outdoor, random load, double sample interval test, tripped.

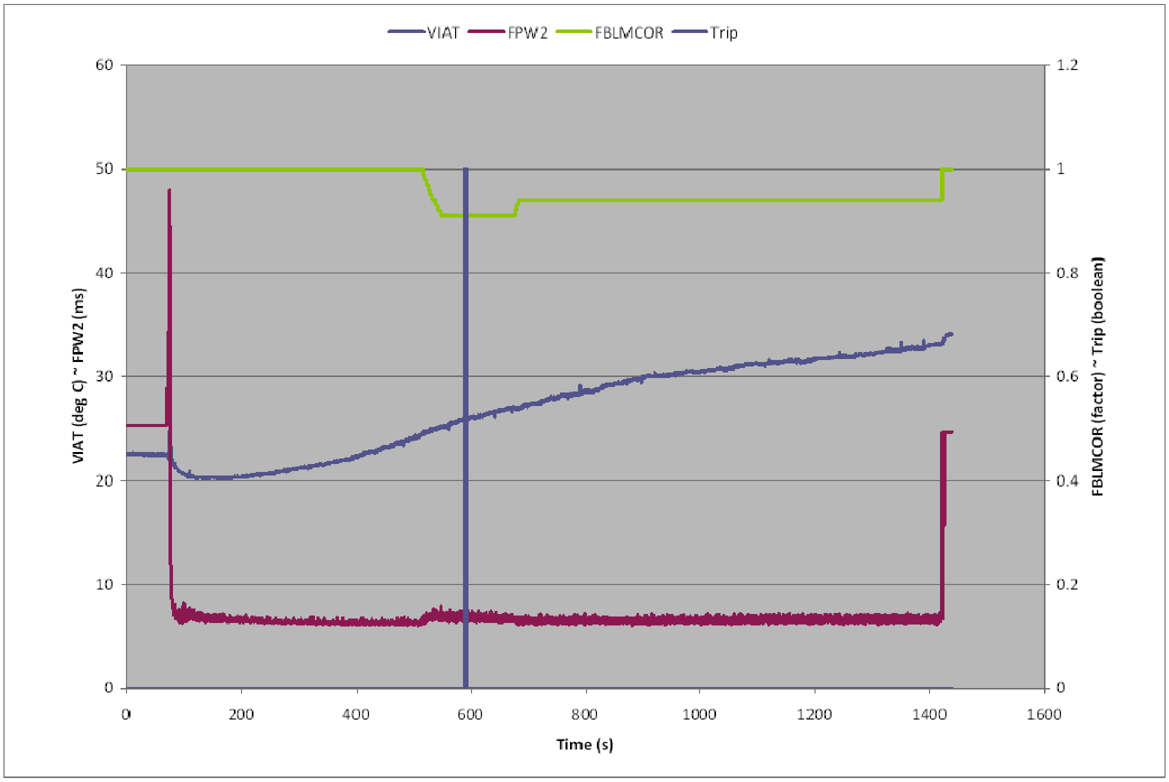

Figure A.19: Closed-door, 500 W, double sample interval test 1, tripped.

Limitations of Existing Algorithm

This project has resulted in a proof of concept demonstration for an algorithm capable of shutting off a portable gasoline-powered generator when operated in an enclosed space if equipped with an engine control module. CPSC specifically requested that the algorithm be integrated into an existing ECU, using data already existing in the ECU, and without using any additional sensors. However, the developed algorithm, implemented within existing hardware, does have shortcomings. Specifically, during testing subsequent to that previously presented in this report, three specific issues sporadically surfaced:

1. With sudden and significant load changes, as well as constant load, the algorithm will sometimes nuisance trip.
2. Rarely will the algorithm trip in an enclosed environment with extremely light loads.
3. Rarely, but even with high load, the algorithm will not trip when operating in an enclosed environment.

In an attempt to address this issue, it was hypothesized that examining the frequency content in some of the engine control module signals may provide another indicator of outdoor operation. Specifically, intake air temperature (IAT), manifold absolute pressure (MAP), and fuel base pulse width (FBPW2) were analyzed. Four specific cases were considered:

- CASE 1: 5.5 kW load, operated in garage with door fully closed.
- CASE 2: 5.5 kW load, operated outdoors.
- CASE 3: Cyclic load pattern, operated in garage with door fully closed.
- CASE 4: 1.5 kW load, operated outdoors.

Figures A.20 through A.23 display the ECU data for these four test cases.

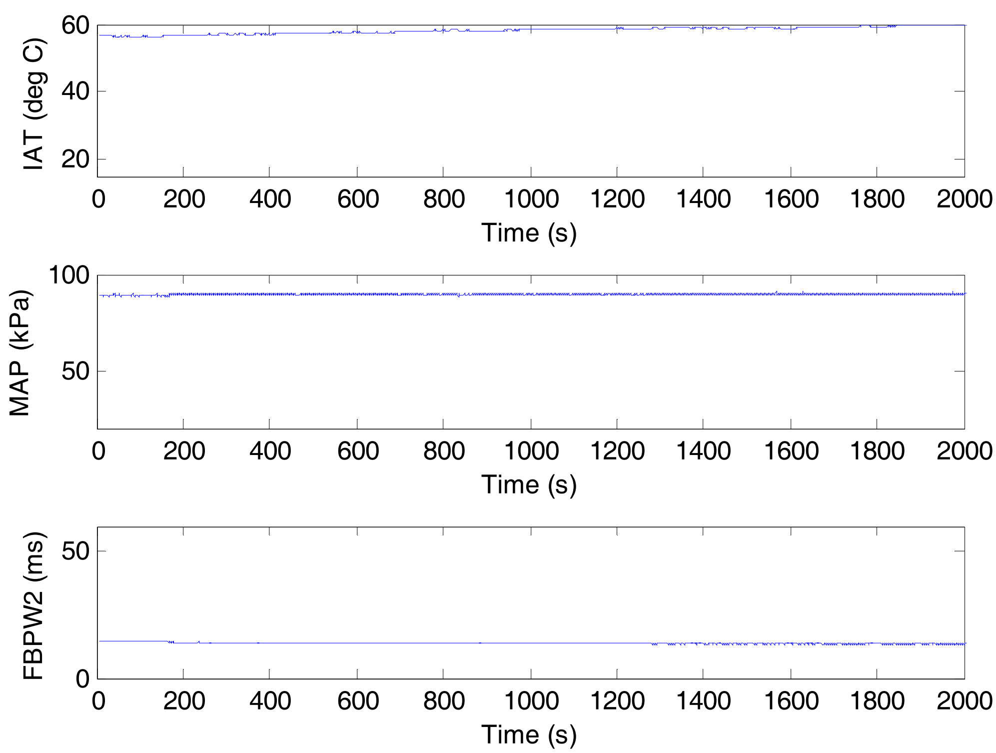

Figure A.20: Case 1 real-time ECU data.

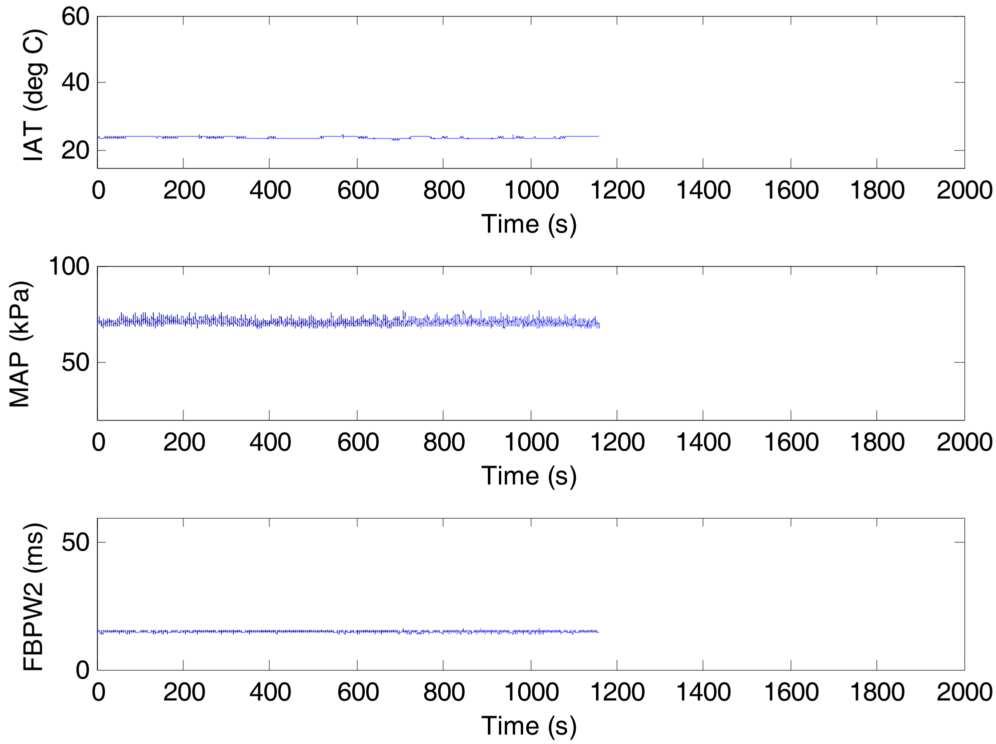

Figure A.21: Case 2 real-time ECU data.

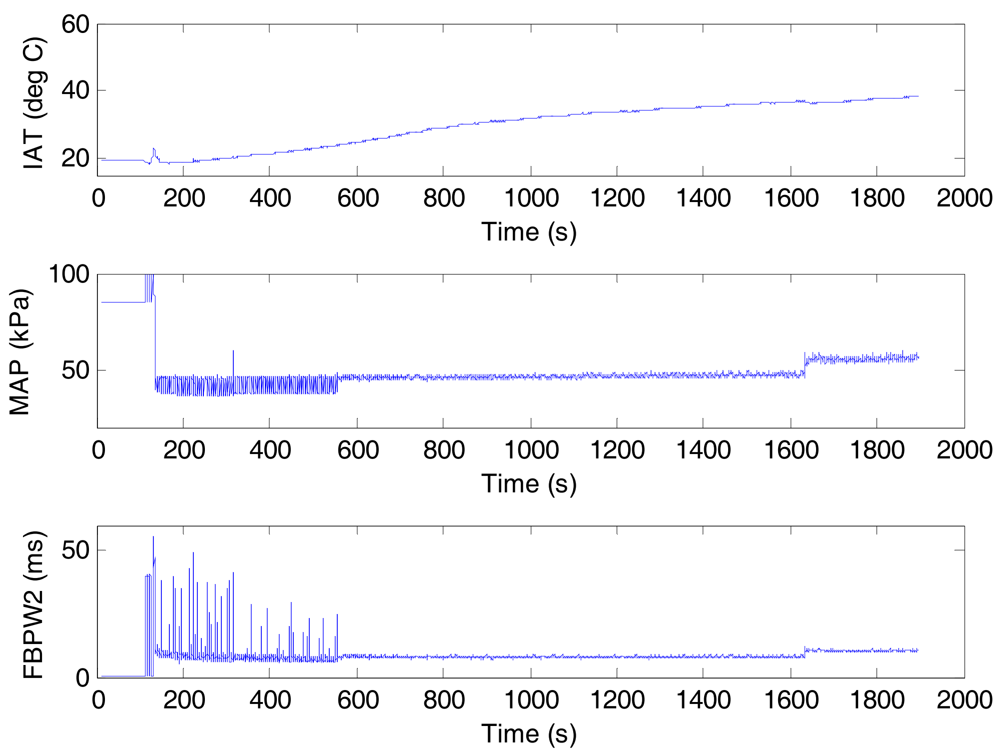

Figure A.22: Case 3 real-time ECU data.

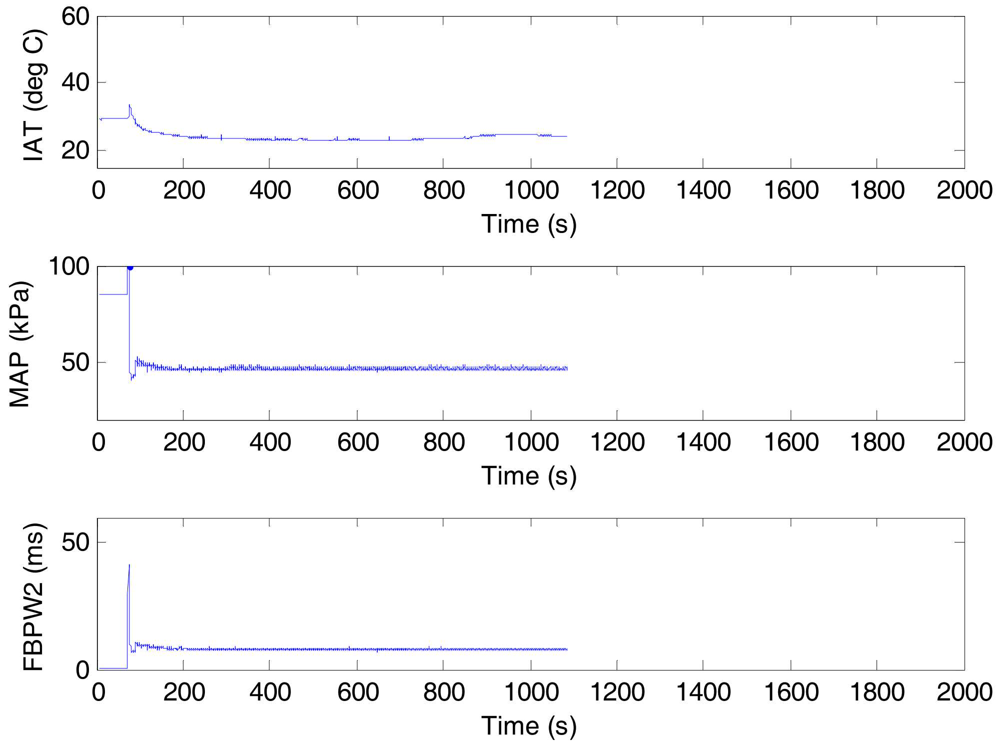

Figure A.23: Case 4 real-time ECU data.

Analysis of cases 1 and 2 provides a direct comparison indoors and outdoors for the same load conditions. In both of these tests, the shutoff algorithm was disabled to allow full sampling of the data regardless of whether the algorithm would or would not have shut down the engine. Through post-processing, it was determined that case 1 would not have tripped, though a trip would have been desired. Also, case 2 would have tripped, but it would have been a nuisance trip. Cases 3 and 4 present two other options for comparing harmonic content in indoor versus outdoor settings. A portion of case 3 is also performed at the same load setting as the entirety of case 4.

The sampling period of the ECU data in each case is approximately 50 ms to 60 ms. The minor variation occurs as a result of the processor requiring different time periods for various control computations and writing output data only when otherwise idle. For analysis, the average time step was assumed between all data points. Thus, the sampling frequency is always in the range of 16.67 Hz to 20 Hz. By employing the discrete Fourier transform (DFT), the harmonic content of each signal could be computed from the dc (average) value up to components around 10 Hz.

The DFT processes a fixed period of data collected in the time domain into its corresponding frequency content. The length of time over which the DFT was computed for this study was either 30 seconds or 5 minutes. Assuming the 30 second period, the DFT was computed for the first 30 seconds of data, then for the next 30 seconds of data, and so on. For each time period, then, a spectrum of data exists. Note that the emphasis here is on magnitude only, not phase.

Figures A.24 through A.27 show the magnitude spectra for each test case with a sampling window of 30 seconds. Note that case 2 shows a pronounced spike in MAP and FBPW2 around 8 Hz while case 2 does not. Though this may appear as an indicator of indoor versus outdoor operation, analyses of cases 3 and 4 both show a similar spike.

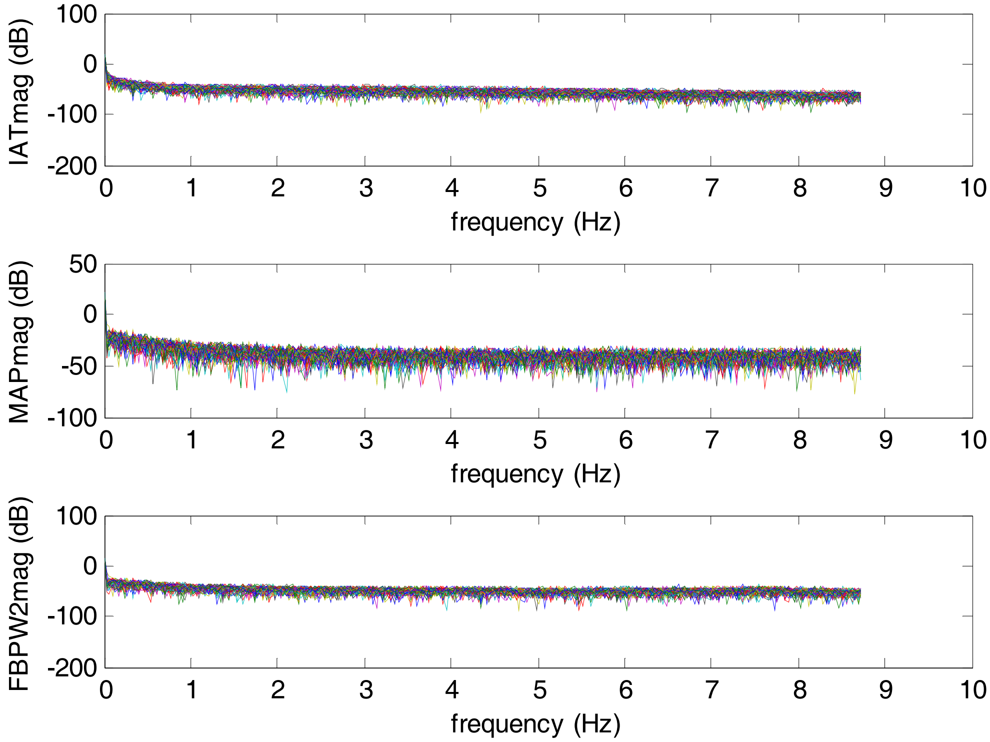

Figure A.24: Case 1 with 30 second sampling window.

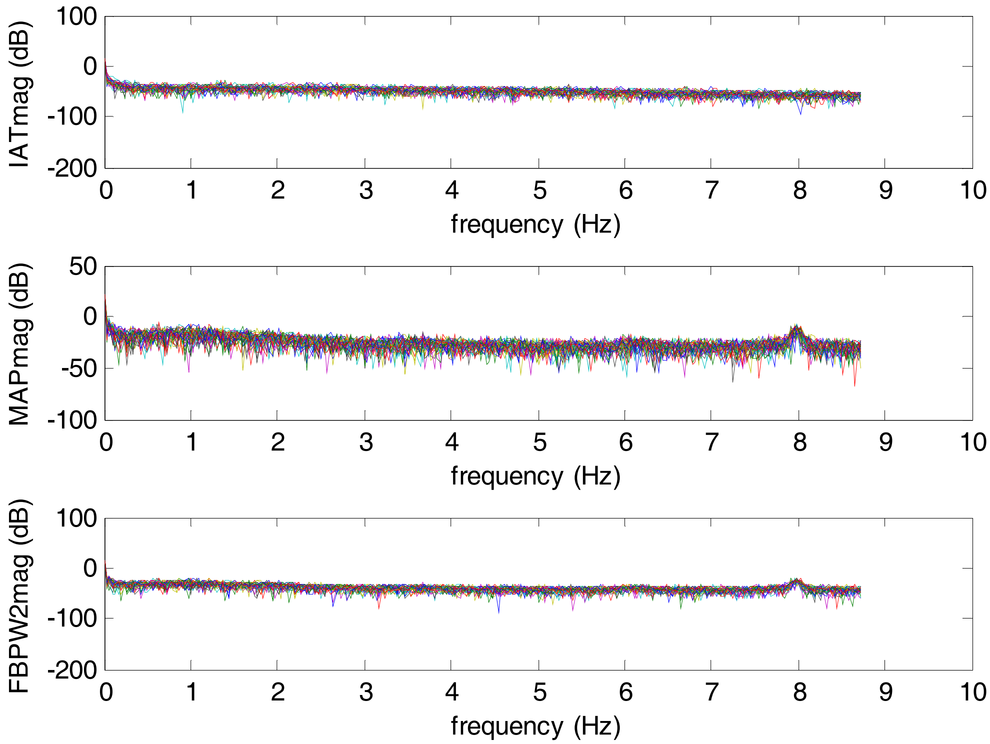

Figure A.25: Case 2 with 30 second sampling window.

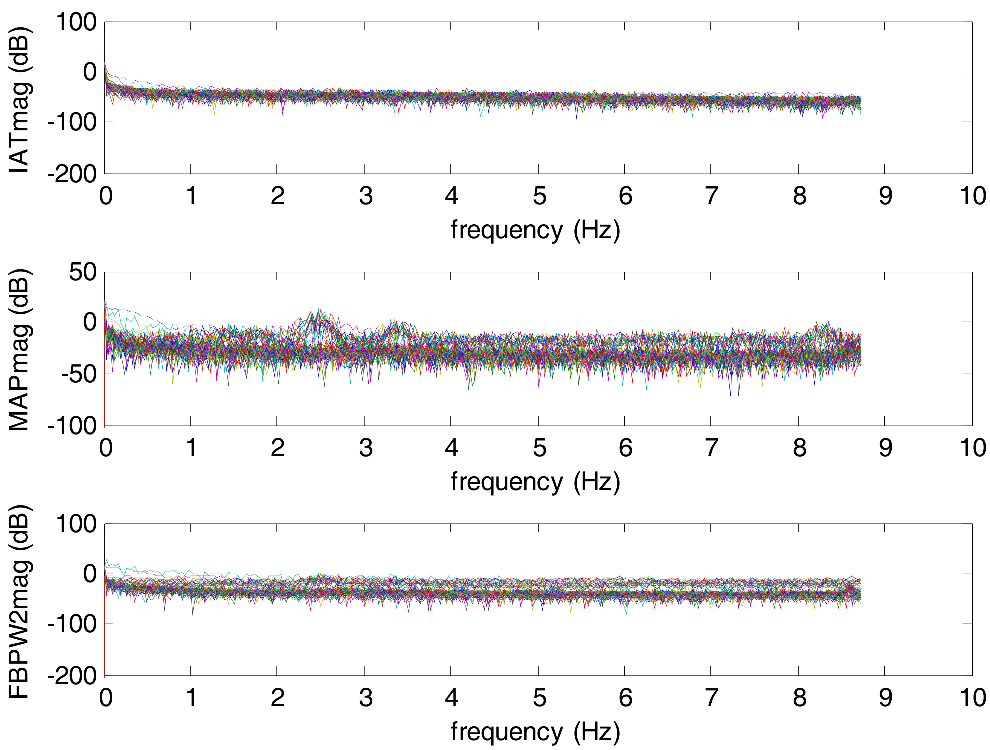

Figure A.26: Case 3 with 30 second sampling window.

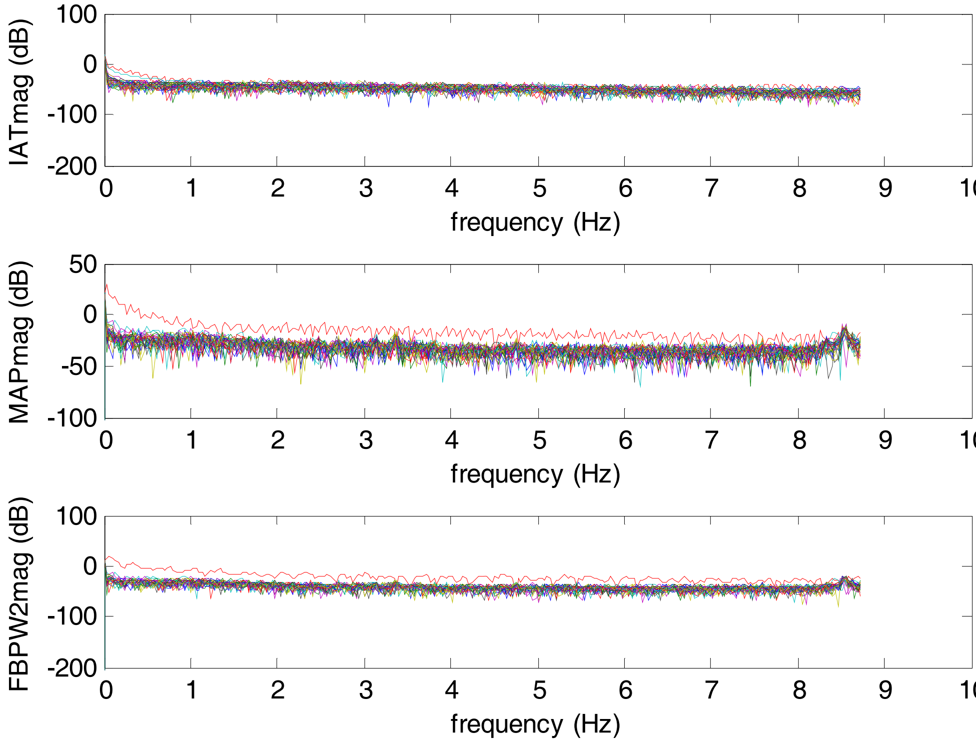

Figure V.27: Case 4 with 30 second sampling window.

Since no clear signature can be seen to delineate between indoor and outdoor operation with a 30 second sampling window, a larger window was employed. Figures A.28 through A.31 display the magnitude spectra for the four test cases with a 5 minute sampling window.

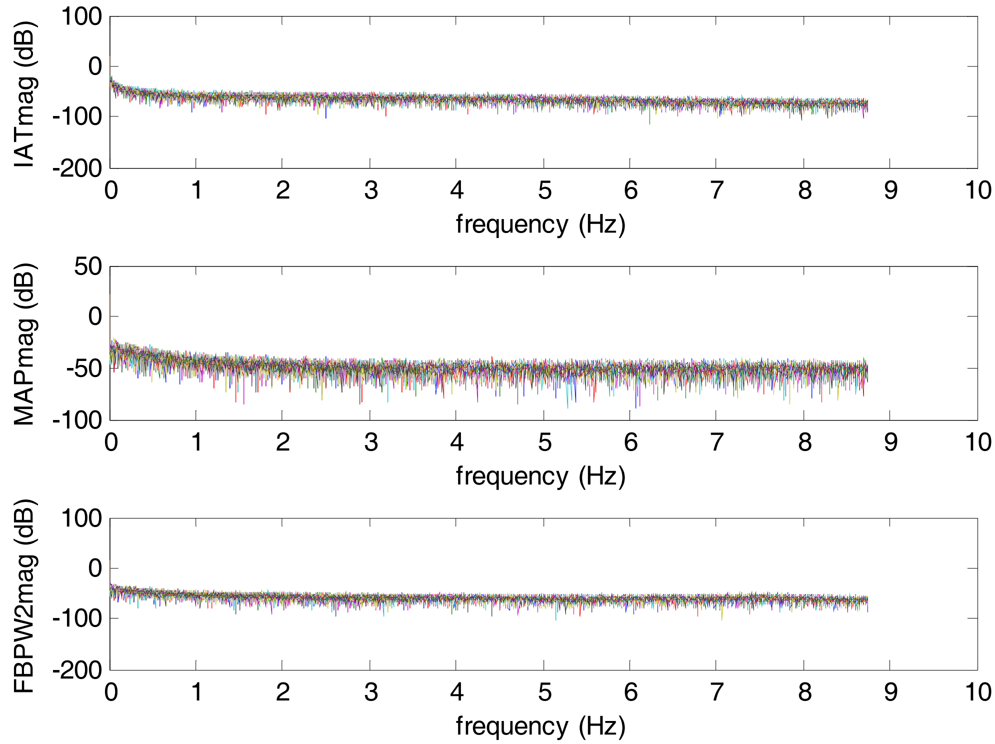

Figure A.28: Case 1 with 5 minute sampling window.

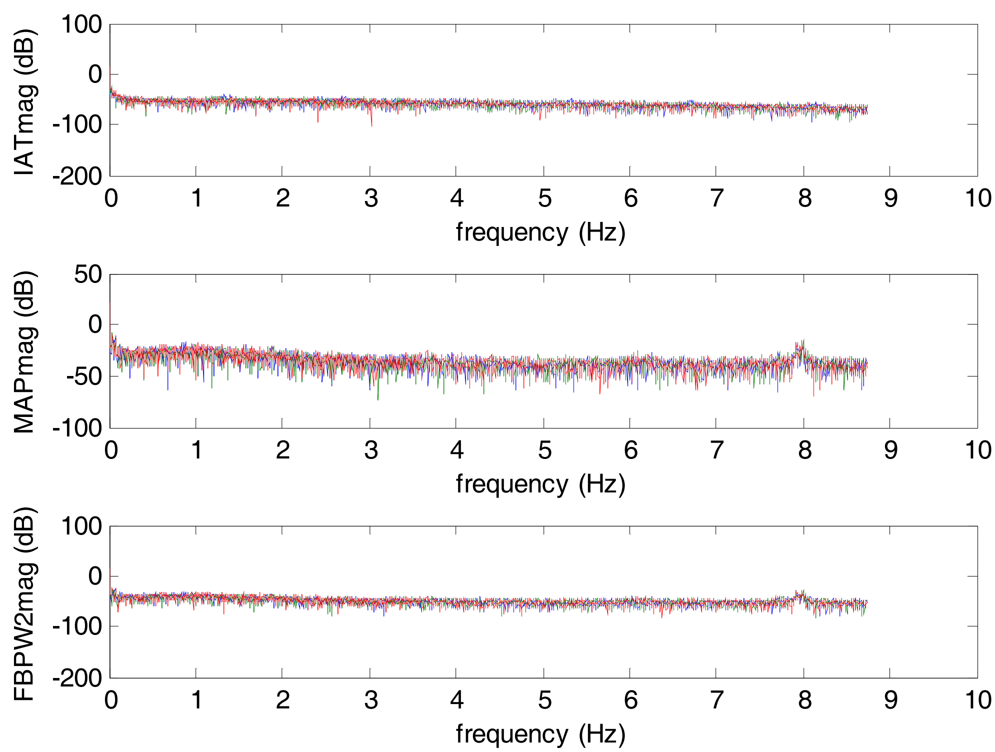

Figure A.29: Case 2 with 5 minute sampling window.

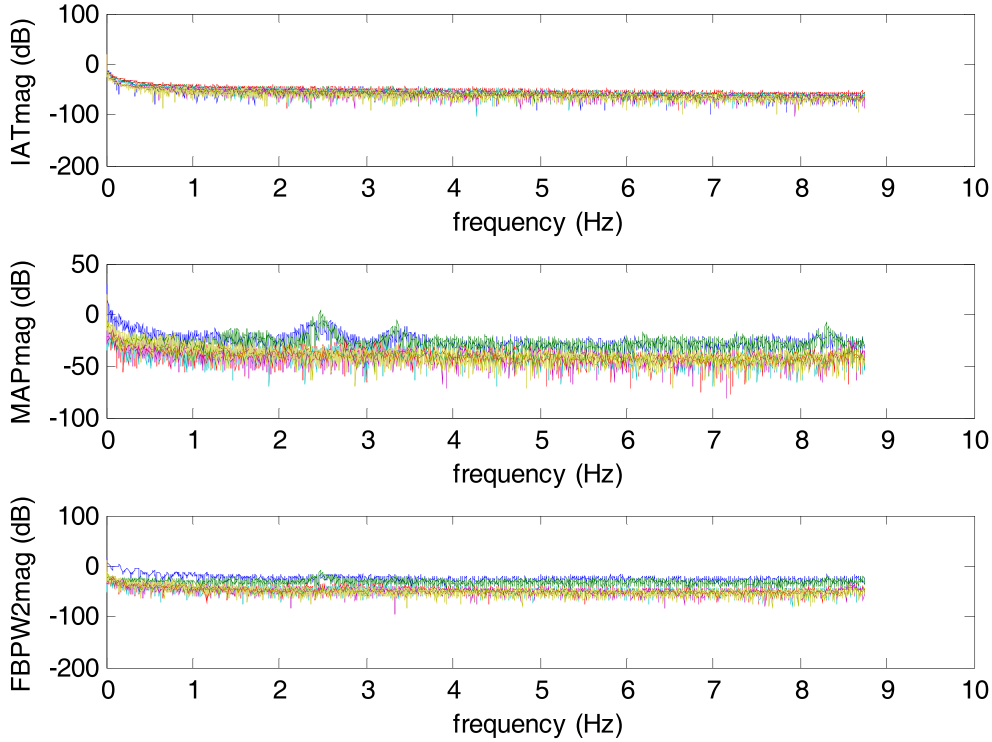

Figure V.30: Case 3 with 5 minute sampling window.

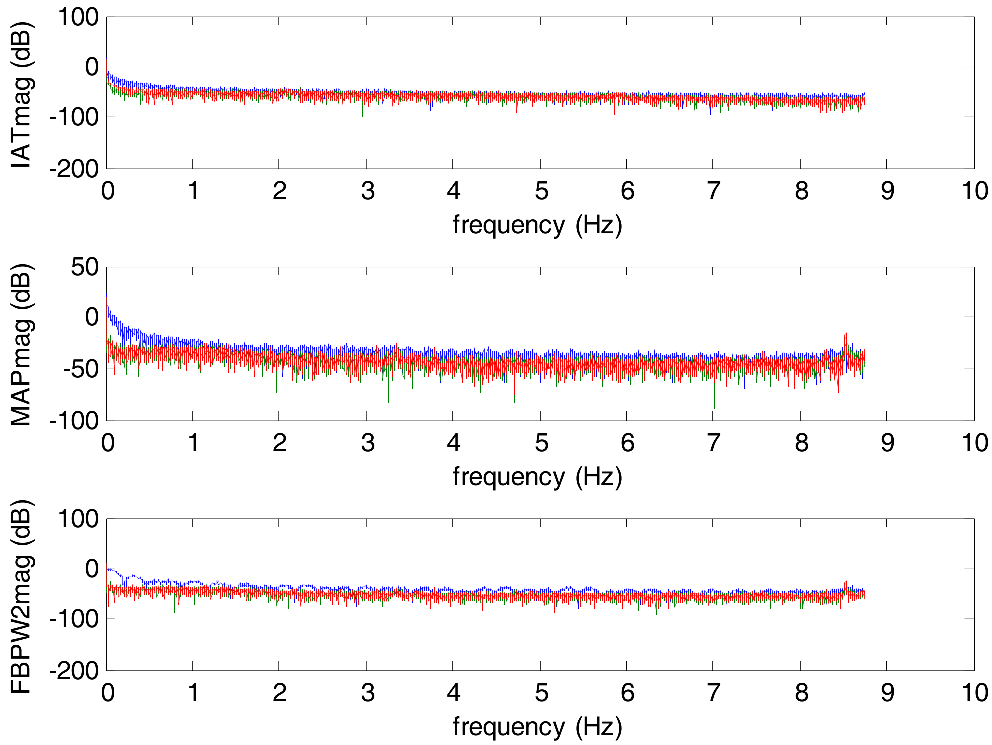

Figure V.31: Case 4 with 5 minute sampling window.

Unfortunately, no clear indicator for indoor versus outdoor operation exist with the 5 minute sampling window either. To be certain, analysis on power spectral density and total harmonic distortion were performed as well, but nothing remarkable was found.

TAB G

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: August 13, 2012

TO: Janet Buyer, Project Manager, Portable Generators
Division of Combustion and Fire Sciences, Directorate for Engineering Sciences

Through: Mary Ann Danello, Ph.D., Associate Executive Director,
Directorate for Health Sciences (HS)
Lori E. Saltzman, M.S., Division Director, HS

FROM: Sandra E. Inkster, Ph.D., Pharmacologist, HS

SUBJECT: A comparison of the carbon monoxide (CO) poisoning risk presented by a commercially available portable gasoline-powered generator versus a prototype "reduced CO emissions" generator, based on modeling of carboxyhemoglobin (COHb) levels from empirical CO data.

1. Objective

The primary objective of this Health Sciences (HS) staff memorandum is to provide an assessment of whether a prototype portable gasoline-powered generator can offer any significant safety gains for consumers to reduce the risk of high-severity or fatal carbon monoxide (CO) poisoning presented by current generator designs. It should be noted clearly that it is not CPSC staff's objective to encourage unsafe consumer behavior by trying to develop a generator that can be used safely inside living spaces. Rather, in the event that a poorly informed consumer[1] decides to operate a generator in an inappropriate location, the aim is to allow occupants a greater chance of recognizing that a hazardous CO poisoning situation is developing, by slowing the rate at which CO levels rise in the immediate area where the generator is located, and consequently, further slowing and reducing the CO infiltration into any attached living spaces. It is reasoned that this approach could provide occupants with a longer window of opportunity to escape before incapacitating, life-threatening CO levels develop; but it is obviously dependent on consumers recognizing that a problem exists and reacting appropriately to the developing CO hazard. Ideally, appropriate reactions could be prompted by individuals realizing that the onset of slowly worsening, nonspecific

[1] "Poorly informed consumer" can include one who is heeding instructions, provided by some manufacturers, to use a short extension cord and/or who tries to keep the unit from getting wet because these recommendations inherently conflict with appropriate outdoor placement of a generator at a sufficient distance from a home to avoid the CO hazard.

symptoms is indicative of CO poisoning, or recognizing that a CO alarm has been activated. However, appropriate responses—such as seeking fresh air and/or calling 911—can be prompted by an individual's growing awareness that their slowly worsening symptoms mean "something is wrong"; and those appropriate responses do not necessarily require any understanding by the consumer that CO is the underlying cause.

This report assesses the expected onset, progression, and severity of CO poisoning symptoms in healthy adults who are exposed to exhaust emissions from an unmodified, original equipment as manufactured (OEM) generator[2] with an advertised rated power output of 5.0 kilowatts (kW) (representative of currently marketed OEM generator designs that use a carbureted engine), or a reduced-CO emissions prototype unit, operated in a test house setting.

To conduct this comparative assessment, as in previous related HS memoranda (Inkster, 2004; Inkster, 2006), a nonlinear version of the theoretical Coburn-Forster Kane (CFK) model was used to predict the rising level of carboxyhemoglobin (% COHb[3]) in the blood. The % COHb level serves as a useful, though inexact, approximation of acute CO uptake by the body, and of symptom severity. Previously, HS staff modeled COHb profiles for occupants located in different areas of a theoretical single-family home, assuming a generator operated in the home's basement area, under a constant load setting (no load, partial load, or full load), for 6 hours (estimated engine operation time on a full tank of gas for a specific generator unit). The theoretical CO input data used in these earlier HS reports were generated using an indoor air quality (IAQ) modeling program to model CPSC Laboratory Sciences (LS) staff's experimentally derived CO emission rates for an unmodified, 5.5 kilowatt engine-driven portable generator. In contrast, this current report is based on empirical CO time course data collected in a test house facility while a generator was operated in the attached garage, for varying durations, under a cyclic load profile. The tests were designed to provide information on how different environmental conditions operating in a home structure affect: (i) performance and CO emissions of unmodified and prototype generators units, and (ii) the dynamics of CO accumulation in the garage space and infiltration into residential living spaces, and ultimately, to estimate the relative risk of CO poisoning throughout the test house.

2. Background

There is increasing concern about the serious risk of fatal and nonfatal, high severity CO poisoning presented by portable gasoline-powered generators. The number of annual generator-related CO poisoning fatalities has risen significantly since

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[2] A generator's *rated power outage* and *engine power rating* describe different generator product characteristics and their respective kW values should not be confused as meaning the same thing since the former will always be less than the latter. Throughout this report, the unmodified unit refers to an OEM generator with a manufacturer's advertised power output of 5.0 kilowatts (kW) as powered by an engine having a manufacturer's advertised power rating of 8.2 kW; in prior HS memoranda, a 5.5 kW generator (rated power outage) was powered by a 7.46 kW engine.

[3] % COHb reflects the percentage share of the body's total hemoglobin pool occupied by CO.

1999. It is notable that, for the four most current annual estimates available, generators have overtaken and more than doubled furnace numbers to become the single product **type** responsible for the largest **estimated** number of annual, nonfire-related CO poisoning fatalities (current estimates are 88, 85, 62, and 86 deaths for the years 2005, 2006, 2007, and 2008, respectively) (Hnatov, December 2011). Staff does not have current sales/exposure data to assess whether the rate of generator-related CO poisoning fatalities is increasing. However, staff reasons that, based on past numbers of units in use (Smith, 2006) and different usage patterns (*i.e.,* daily furnace use for several months versus more occasional use of generators in power outage situations that are often unplanned), the relative risk of CO poisoning is considerably greater for generators than for furnaces. Regarding minimal death counts (not annual estimates), as of April 20, 2012, CPSC databases contained reports of at least 755 generator-related CO poisoning deaths from 1999 to 2011. Sole use of a generator was responsible for 695 of these deaths, and the remaining 60 deaths involved concomitant use of a generator and another combustion product. The majority of victims were male (560, 74%) and 620 victims (86%) were adults over 24 years old (Hnatov, 2012).

Most of these generator-related deaths (551 of 755) occurred at various fixed-structure residential settings, including traditional houses, mobile homes, apartments, townhomes, and structures attached to a home. Of these 551 fatalities, just over half (284, 51.5%) occurred when a generator was operated in an attached garage, enclosed carport, or attached barn (131 deaths), or in a basement or crawlspace of a home (153 deaths). At least 232 deaths occurred when a generator was operated in other areas inside a home, *i.e.,* in recognized living spaces (173 deaths), closets (13 deaths), doorways (6 deaths), or other unspecified indoor spaces (40 deaths). In addition to these 551 deaths in various fixed-structure home settings, another 49 deaths were reported at residential sites where generators were operated in separate structures, such as sheds and detached garages. At least 13 more deaths are reported to have occurred when generators were operated outdoors, but close enough to a home to allow lethal levels of CO-rich exhaust fumes to infiltrate nearby rooms via windows, doors, air vents or other openings. The generator location was not known in another 22 deaths at fixed-home sites. It is clear from this data that, despite growing public awareness of the danger and safe use, some consumers intentionally operated generators in unsafe residential locations. The reasons why they chose to do so were not always clear, but apparently, they were unaware of the generator-related CO poisoning hazard, did not fully understand the meaning of “adequate ventilation”, and/or did not realize how quickly lethal levels of CO can develop when generators are operated in unsafe locations.

3. Summary Information on Carbon Monoxide Pathophysiology

This section is provided as a reference summary on CO pathophysiology. More detailed information on how CO acts as a gaseous chemical asphyxiant, and key parameters influencing the rate of uptake of CO and attainment of equilibrium at different CO exposure levels, can be found in previous HS staff memoranda (Burton, 1996; Inkster, 2004; Inkster, 2006), and other authoritative sources (Chale,1998; US EPA, 2010; ATSDR, 2009).

Essentially, during acute exposures, inhaled CO rapidly diffuses from the lungs into the bloodstream, where it blocks uptake of oxygen and impedes oxygen delivery to tissues by binding 210 to 250 times more avidly to hemoglobin to form carboxyhemoglobin (COHb). In addition to the specific CO exposure level, the rate of CO uptake (and elimination) is greatly influenced by an individual's activity level because both the amount of air (and CO) inhaled into the lungs and the volume of blood passing through the lungs per unit time increase as the body's energy expenditure increases. As reflected by the progression of symptoms, tissues with the highest oxygen demands will be the first affected (brain, heart, then exercising muscles). The % COHb level can serve as a useful approximation of expected CO poisoning severity in healthy adults during ***acute*** uptake of CO, although it is recognized that the relationship is not absolute, and there is variation among individuals due to different physiological characteristics and/or health status. It should also be noted that measured COHb levels are influenced by the timing of the COHb measurement, relative to cessation of the CO exposure, and by provision of any oxygen therapy in the intervening period. Notwithstanding these caveats, increasing % COHb levels are generally related to progressively worsening symptoms (Table 1).

Table 1. Approximate Correlation Between Acute %COHb Levels and Symptoms in Healthy Adults

% COHb	Symptoms
<10%	No perceptible ill effects*
10–20	Mild headache, labored breathing, decreased exercise tolerance
20–30	Throbbing headache, mild nausea
30–40	Severe headache, dizziness, nausea, vomiting, cognitive impairment
40–50	Confusion, unconsciousness, coma, possible death
50–70	Coma, brain damage, seizures, death
>70	Typically fatal

(Source: Burton, 1996) ***** *Some studies have reported adverse health effects in some cardiac patients at 2–5 % COHb*

It is convenient to categorize CO poisoning severity by discrete COHb levels, but in reality, the CO poisoning symptoms in Table 1 should be regarded as a continuum of health effects with overlapping transitions. Furthermore, in situations where COHb levels rise steeply and suddenly, causing rapid, severe oxygen deprivation (hypoxia), or even virtual anoxia (total oxygen deprivation), it is possible for exposed individuals to experience extremely quick onset of confusion, loss of muscular coordination, loss of consciousness, and death, without having first experienced milder CO poisoning symptoms associated with low- or slowly rising CO-induced hypoxia. With prolonged CO exposures above an ill-defined critical level, there is also significant transfer of CO from COHb to other nonvascular body components (*e.g.*, myoglobin proteins in muscle, certain cellular proteins, and cytochrome enzymes), which will further impair physiological function. This partly explains why, in prolonged sub-lethal CO exposure situations, even if the environmental CO elevation and the corresponding equilibrium % COHb level remain constant, symptom severity can worsen to some degree.

Binding of CO to hemoglobin is reversible, and CO is eliminated from the body primarily via exhaled air, but the rate of elimination is very much slower than the rapid rate of CO uptake. The half-life of CO in a healthy adult breathing fresh air (~21% oxygen) at normal atmospheric pressure is around 4 to 5 hours, which means that an individual's % COHb level is expected to drop by 50 percent every 4 to 5 hours. Individuals who have moderate CO poisoning are typically treated with 100 percent normobaric oxygen, which will reduce the CO half-life to about 80 minutes. Ideally, severely poisoned patients should be treated in a special hyperbaric oxygen (HBO) chamber because this will further increase the CO elimination rate by reducing the CO half-life to about 20–30 minutes. This is not always possible because other concerns with a poisoned individual's health status can cause the risks involved in HBO treatment to outweigh the benefits, or because no HBO chamber is available in nearby medical facilities.

For some individuals who survive serious prolonged COHb elevations, the resulting brain hypoxia, and any consequent associated damage, may ultimately result in the phenomenon of delayed neurological sequelae (DNS). DNS is typically manifested within a few days or weeks after apparent recovery from the initial CO exposure. Symptoms can include emotional instability, memory loss, dementia, psychosis, Parkinsonism, incontinence, blindness, hearing loss, paralysis, and peripheral neuropathy. Some symptoms of DNS may respond to HBO therapy and/or may resolve spontaneously over a 2-year period, but victims exhibiting the most severe symptoms, such as Parkinsonism, blindness, and paralysis are often permanently affected (US EPA, 2000). Loss of consciousness is more likely to be associated with more serious outcomes, but it is not necessary to have lost consciousness to sustain DNS from CO exposures. Although current understanding of DNS does not allow very accurate prediction of DNS occurrence in nonfatal CO poisoning cases, some authorities regard 20% COHb as an approximate lower threshold of concern for DNS (EPA, 2001; ATSDR, 2009). Given the extremely high CO levels in exhaust from current portable generator designs, HS staff believes that survivors of generator-related CO poisoning incidents can be at significant risk of developing DNS, particularly if the incident is known also to have involved a death.

4. Reduced CO Emissions Prototype Generators

A). Summary of Initial Prototype Development Work

As is detailed in this current briefing package, a significant part of CPSC staff's recent efforts to counter the ongoing surge of generator-related fatal carbon monoxide poisonings (and an undetermined, but sizeable number of high-severity injuries) has focused on an approach to reduce CO emissions produced by generator engines. Under a CPSC contract, the University of Alabama (UA) developed prototype generator units, equipped with design modifications to reduce CO emissions, from commercially available models. As part of the testing to assess prototype durability, an OEM unit and a prototype generator unit were operated under cyclical load conditions for a total of 500 hours, which is the manufacturer's expected useful life of the engine. During this time, exhaust emissions were monitored periodically to assess whether there was any sign of obvious degradation in engine performance. The generator prototype was also monitored for any other obvious signs of excessive product wear or malfunction. After 500 hours of operation, the OEM and prototype generators were sent to an independent, experienced, private test facility and were tested for compliance with the EPA's relevant regulations for exhaust emissions from small engines, using established protocols. The prototype's impressively reduced CO emissions easily met EPA's Phase 2 CO emissions standard applicable to the OEM unit's engine, and were significantly reduced compared to the OEM's engine's original certification data (EPA's Phase 2 CO limits were not changed in its now current Phase 3 engine emissions standard). However, the prototype did not meet EPA's applicable Phase 2 emission standard for hydrocarbon and nitrogen oxides (HC+NOx) unless fitted with a catalyst-containing muffler (referred to as a *cat muffler*). With the cat muffler present, the prototype complied with EPA's Phase 2 and current, more stringent, Phase 3 HC+NOx engine emissions standard (see briefing memo, Buyer, 2012).

B) NIST Test House Generator Test Overview

As a parallel part of CPSC staff's proof-of-concept testing of "reduced CO-emissions" generator prototypes, unmodified generator units and additional UA prototype generator units were tested by National Institute of Standards and Technology (NIST) staff under a CPSC-funded interagency agreement (IAG No. CPSC-1-06-0012). For one component of this IAG with NIST, unmodified and prototype generator units were operated in the attached garage of NIST's Indoor Air Quality (IAQ) manufactured test house (referred to as the *NIST test house*[4]), for multiple hourly load cycles, under seven controlled test house configurations. The house configurations targeted three controllable factors that are considered key influences on the accumulation of the CO in the garage, and its migration into the living spaces of the house. These factors are: (1) the degree of opening of the garage bay door to the outdoor environment (*tested while either closed or open 24 inches*); (2) the degree of opening of the door connecting the garage to the living space (*tested while either closed or open 2 inches*); and (3) the operating status of the home's heating ventilating air conditioning (HVAC) system's fan (*tested while either off or on*).

During each test, in addition to measuring CO levels in the garage and living spaces of the test house, concomitant measurements of other important environmental factors (wind speed, ambient temperature) and some key indicators of generator engine performance were also made. Details of the NIST test materials and methods, and the findings from 16 specific tests, are documented in an interim report to the CPSC (*Emmerich, July 2011).* Table 2 of the NIST report provides a useful test reference guide identifying each of the 16 tests by a unique letter ID, and indicating for each test,

[4] The NIST test house is a single story 1,500 ft^2 (12,000 ft^3) 3 bedroom manufactured home, to which a 320 ft^2 (3,200 ft^3) attached garage was added for testing generators for CPSC (see Emmerich, 2011, and Nabinger and Persily, 2008).

the specific generator unit tested, specific house configuration settings (identified by number code 1 through 7), applicable CO analyzer line locations, and prevailing outdoor temperature and wind speeds. Table 3 of the NIST interim report provides a summary overview of the test results during the time of engine operation (engine run time), and where applicable, including any natural decay period allowed. The relative performance of the unmodified and prototype generator(s) in each of the 7 house configurations is expressed in terms of: (1) the peak CO concentration of CO attained in the garage (where microliters/liter [µl/L] is equivalent to parts per million [ppm]); (2) the percentage reduction of the prototype's peak CO level reached in the garage relative to the unmodified generator unit; and (3) the peak CO concentration measured in the home's living space (µl/L, equivalent to ppm).

In this memorandum, HS staff has used the same test letter and number ID codes as NIST to identify specific tests, house configurations, and test house areas, respectively. This assessment was limited to 14 tests of the 16 NIST tests that represent 7 paired tests comparing CO emissions from the original unmodified OEM generator unit *(referred to as Unmod GenX)* to emissions from the second generation prototype unit (*referred to as SO1*). Two NIST tests (O and R) of UA's first generation prototype (*referred to as ModGenX*) are not discussed here.[5] The SO1 prototype unit was tested in two slightly different configurations, either with a catalyst present in the muffler (*referred to as SO1-cat*), or without the catalyst present (*referred to as SO1-noncat*); the purpose of the catalyst muffler design is to further reduce CO levels present in the prototype unit's engine exhaust (*i.e.,* a post-engine modification). Details of the specific differences between Unmod GenX and SO1 prototypes and the cat muffler specifics are reported elsewhere in this package (Buyer, 2012).

NIST staff provided CPSC staff with voluminous, electronic, raw data files for each of the generator tests conducted in the NIST test house. Both staffs worked together closely to produce the graphs showing the CO time course profiles, in both the garage and the home locations, for each of the generator tests conducted. The floor plan of the NIST test house (Fig. 2, Emmerich 2011) shows that the family room (FAM) is the living space closest to the internal door connecting the house to the garage. Not surprisingly, in all tests, the highest CO level in living spaces was recorded in the FAM. There was less consistency between tests regarding the living space with the lowest peak CO level (see NIST report). In some tests (B, D, F), the master bedroom (MBR)

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[5] As noted in the briefing memo (J. Buyer, 2012), the original generator model used for the ModGenX prototype was no longer available when a second unit was commissioned. CPSC Engineering Sciences (ES) staff and UA decided to use a generator unit made by the same manufacturer of the original Unmod GenX unit, for the second generation SO1 prototype. Importantly, the 8.2 kW engine component of this SO1 unit was the same as the 8.2 kW engine used on Unmod GenX, even though the generator product had a higher advertized rated power output than the Unmod Gen X product (7.0 kW versus 5.0 kW, respectively). (Note: the *engine's power rating* and *generator's rated power output* describe different generator product characteristics and should not be confused as meaning the same thing). Later, due to constraints in the NIST IAG test program, staff elected to focus remaining resources on the SO1 unit, which also had improved prototype technology (see Buyer, 2012). The decision not to include the duplicate Mod GenX test results in this HS analysis is intended, not to "hide" data, but simply to omit data that would add little to the health assessment and would further complicate an already complicated analysis. The Mod GenX CO data for the test house studies are available (Emmerich, 2011).

clearly had very much lower peak CO levels than all other living spaces, reflecting uneven air distribution in the test house with the HVAC fan off. In other tests, the range of CO peak values in different house areas was small, and technically, the lowest CO peak value was recorded in either bedroom 2 or bedroom 3 (BR2, BR3), but the relatively small differences were evaluated by HS staff to be of minimal significance in terms of related health effects. As a general approach, HS staff modeled COHb levels for the garage, FAM, and MBR. For all 14 tests, the garage CO content is considered the primary determinant influencing CO infiltration into living spaces of the NIST test house.

As detailed in the 2011 NIST interim test report, in order to cover the broad range of CO levels that could be expected in the generator tests, CO analyzers with different threshold limits and sensitivities were used. The measured CO levels ranged from about 0 to 23,000 ppm in the garage location, and from about 0 to 10,600 ppm in the living spaces. Generally, the most sensitive CO analyzers were considered to provide the most reliable data for assessing early buildup of COHb at up to 1,000 ppm (RM and TE analyzers) or 2,000 ppm (N3 analyzer). The less sensitive mid-to-high range CO analyzers, N1 and N2, which each had high and low range settings (covering 0 to10,000 ppm and 0 to100,000 ppm), were used for making COHb predictions when considered more appropriate (*i.e.,* typically if the range of TE, R1, or N3 analyzers was exceeded). The CO sampling setup used in the NIST test house means that, for each analyzer line, CO measurements in each house location were measured at 6-minute intervals, and the measurement sampling sequence between the separate analyzer lines was staggered by 1-minute intervals.

5. Modeling of COHb Levels Using Empirical CO Data from NIST Generator Tests.

A) Coburn-Forster-Kane (CFK) Model for Predicting COHb Levels

HS staff modeled the COHb profiles from appropriate analyzer data using a nonlinear version of the Coburn-Forster-Kane (CFK) differential equation (Coburn, Forster, Kane, 1965). The nonlinear CFK equation is a physiologically-based, mechanistic model that is widely regarded by authoritative sources as the most reliable of the various theoretical models for predicting CO uptake and COHb formation by humans that has been validated by empirical data (US EPA, 2000; ATSDSR, 2009). Although some interesting theoretical models that attempt to account for burden of CO found in nonvascular body compartments have recently been published, the Environmental Protection Agency's (EPA) Integrated Science Assessment for Carbon Monoxide, (US EPA, 2010), which is an update of its comprehensive Air Quality Criteria for Carbon Monoxide review document (US EPA, 2000), reaffirms that the nonlinear CFK is still considered the most broadly applicable, validated COHb prediction model available.

Previous HS staff memoranda have described a customized, computer-based, nonlinear CFK modeling program that staff developed for modeling COHb levels from rising CO profiles. The program allows staff to customize input values easily for key physiological variables that influence the rate of CO uptake and COHb formation. In particular, the respiratory minute volume (RMV), which is the amount of air inhaled per minute, can be set to reflect expected activity levels *(Appendix 1 provides greater perspective as to how different activity levels affect COHb formation prior to attainment of equilibrium or death)*. As was done for a recent HS staff generator-related memorandum (Inkster, 2006), in this study, COHb levels were modeled using two RMV values to reflect breathing rates expected in healthy adults engaged in light-to-moderate indoor activities (15 L/min [liters per minute]) or while sleeping/resting (6 L/min). These RMV values are based on information for (1) expected amount of time an average person spends indoors during a 24 hour period, and (2) expected inhalation rates relevant to indoor settings, by age and sex, and activity level, as documented in tables 5.17 and 5.16 of EPA's Exposure Factors Handbook (US EPA, 1997). The EPA indicates that an average person spends 20.4 hours/day indoors, with 19.64 hours (96 percent of estimated indoor time) being spent at resting or light activity levels (9.82 hours at each level), and only 0.76 hours at higher activity levels. For these estimates, the EPA defined "light activity" as: *"Includes most domestic work, attending to personal needs and care, hobbies, and conducting minor indoor repairs and home improvements,"* and it defined "resting activity": *"Includes watching television, reading, and sleeping."*

The EPA's inhalation rate values for adult males, females, and average adults at resting and light activity levels are shown in Table 2 (note: HS staff converted EPA's inhalation rates, expressed as cubic meters/hour (m^3/h), to L/min, as used for the RMV variable in the CFK model).

Table 2. Inhalation Rates Relevant to Expected Indoor Activity Levels*

	Resting Activity			Light Activity		
	No. Subjects	m3/h	**L/min**	No. Subjects	m3/h	**L/min**
Adult male	454	0.7	**11.7**	102	0.8	**13.3**
Adult female	595	0.3	**5.0**	786	0.5	**8.3**
Average adult	1049	0.5	**8.3**	888	0.6	**10.0**

** Based on Table 5.16, EPA Exposure Factors Handbook, 1997*

HS staff considers that use of a 15L/min RMV represents a reasonable upper bound value for calculating COHb formation over several hours in individuals who are located in indoor residential settings. In some power outage scenarios where generator use is common, consumers are likely to spend some time above light activity levels when dealing with the cause of the power outage, and/or its consequences, particularly if related to severe weather conditions. It is reasoned that, even if trying to engage in higher level activity (RMVs >15 L/min), any significant CO exposure that elevates COHb levels above 10 percent is expected to reduce an individual's exercise capacity, which would automatically reduce their RMV, and therefore, slow uptake of CO. Both CO uptake and elimination increase as RMV increases.

Although some older studies have been published in which subjects were briefly exposed to particularly high CO levels under controlled circumstances that prevented

COHb levels from exceeding 20 percent (Peterson and Stewart, 1973; Tikuisis, Buick, Kane, 1878; Benignus, Hazucha *et al*., 1994), it is acknowledged that the CFK model has not been validated by empirical data for **prolonged**, extremely high, life-threatening CO exposures, as is expected with current generator carbureted engine emissions. Ethical considerations prevent collection of such comparative controlled human data, and knowledge of such exposure outcomes is based on incident reports of intentional and unintentional CO poisoning and case studies documented in the medical literature. In situations of rapidly rising, extremely high CO levels (several thousand ppm), when predicted COHb levels quickly exceed approximately 80 to 90% COHb, depending on the modeling time interval used, the iterative CFK model can become unstable, and instead of maintaining plateau levels between 90 to 100% COHb, can predict some erratic, impossible values that intermittently spike above 100% COHb. Although not ideal, this error is considered inconsequential from a health effects perspective because any exposed individuals would already be dead. As indicated by Table 1, death becomes increasingly likely in healthy adults as COHb levels rise from 40 to 70% COHb, and any acute elevation that exceeds 60% COHb is generally considered to be lethal without rescue, with death considered virtually unavoidable at 70% COHb. Where erratic predictions above 90% COHb occurred (in a few cases with Unmod GenX), staff "smoothed" the upper section of the COHb profile curves shown in Appendix 2 figures to represent the realistic lethal percent COHb plateau level predicted by COHb values from values on either side of impossible predicted spike values above 100% COHb. However, aside from noting predicted peak % COHb levels from smoothed curves (or non-smoothed curves), no COHb data above 70% COHb were used when calculating COHb-based measures of health risk (described later) used in this study to compare performance of Unmod GenX and SO1 generators.

B). Specific NIST Tests Analyzed

To present the results of the COHb modeling studies in a logical order from a health risk perspective within living spaces, HS staff rearranged the test pair order used in the NIST interim report, as indicated in Table 3. The revised order represents the expected sequential progression of the paired tests of Unmod GenX and SO1 units through the seven house configurations, starting with the worst case scenario for CO poisoning in the living spaces of the house (*closed* garage bay door and *open* door connecting the garage to the house) and ending with the least dangerous of the test scenarios (*open* garage bay door and *closed* door connecting the garage to the house). The specific influence of the HVAC fan was considered to be worst case when the fan was off, on the basis that, without the fan running, highest peak CO levels would be expected to occur in the living areas closest to the CO source (family room [FAM] and kitchen). In contrast, operation of an HVAC fan is expected to reduce the highest peak CO levels in the living space by distributing the CO more evenly within the house.[6]

[6] The influence of the HVAC fan's operational status is not clear-cut and could be viewed from an opposite perspective, *i.e.,* if very high CO levels are present, an operating HVAC fan would quickly redistribute high CO levels nearest the source location more evenly throughout a home, presenting a serious CO poisoning risk in all areas. As noted in relevant test results, the influence of the HVAC fan's operational status on CO distribution in the NIST test house was not always consistent with expectations (reasons unclear).

The generator test order used to present HS staff's COHb modeling results is shown in Table 3, along with details of the corresponding test order and related figures featured in the NIST interim report.

Table 3. Details of 14 Generator Tests Conducted in the NIST Test House with Unmod Gen X *(unmodifed)* and *SO1* (prototype) Portable Generators*: revised NIST test order (Table 2, Emmerich. 2011) reflecting decreasing CO poisoning risk expected in living spaces (not garage) for 7 house configurations tested.*

Generator Unit	Test ID	House Config-uration	Test Date	Garage Bay Door	Garage to House Door	HVAC fan status	CO Analyzers in Garage	CO Analyzers in House	Test Order in NIST Report	Related Figs - NIST Report
Unmod Gen X	B	1	04/22/08	Closed	Open	OFF	N1	N2, N3	1	3 a,b,c
SO1 - cat muffler	N	1	04/01/10	Closed	Open	OFF	N2, N3	N1, R1	3	5 a,b,c
Unmod Gen X	I	3	05/15/08	Closed	Open	ON	N1	N2, N3	7	9 a,b,c
SO1 - noncat muffler	Z	3	05/05/10	Closed	Open	ON	N2, N3	N1, R1	8	10 a,b,c
Unmod Gen X	D	5	04/30/08	Closed	Closed	OFF	N1	N2, N3	11	13 a,b
SO1 - noncat muffler	AH	5	05/13/10	Closed	Closed	OFF	N2, N3	N1, R1	12	14 a,b,c
Unmod Gen X	J	4	05/21/08	Closed	Closed	ON	N1	N2, N3	9	11 a,b
SO1 - cat muffler	W	4	04/29/10	Closed	Closed	ON	N2, N3	N1, R1	10	12 a,b,c
Unmod Gen X	K	7	05/23/08	Open	Open	OFF	N1, T1	N2, N3	15	17 a,b
SO1 - noncat muffler	V	7	04/23/10	Open	Open	OFF	N2, N3	N1, R1	16	18 a,b,c
Unmod Gen X	G	6	05/07/08	Open	Open	ON	N1	N2, N3	13	15 a,b
SO1 - cat muffler	U	6	04/22/10	Open	Open	ON	N2, N3	N1, R1	14	16 a,b,c
Unmod Gen X	F	2	05/06/08	Open	Closed	OFF	N1	N2, N3	4	6 a,b
SO1 - cat muffler	T	2	04/14/10	Open	Closed	OFF	N2, N3	N1, R1	6	8 a,b,c

6. Approach Used for Analysis of the Empirical CO Data and Modeled COHb Data

A) Projected Symptom Onset, Progression, and Outcome (Test Duration-Specific)

In terms of assessing health risks, comparative analysis of the NIST test results is not a straightforward matter of simply comparing peak CO and projected COHb levels reached. In the 14 NIST tests examined in this report, the generator engines ran for different times, varying from about 2 to 4 hours for Unmod GenX, and from about 2 to 6 hours for SO1. In some paired tests (specifically tests B and N; F and T), the prototype unit was operated for significantly shorter times than the unmodified unit, while in other paired tests, the opposite was true (specifically tests pairs I and Z; D and AH; J and W). To some degree, the different engine operation times complicates the assessment of comparative performance within test pairs, and between all the separate tests; but even if all tests were run for 6 hours or more, the peak CO and COHb are not considered the most useful outcome measures for CPSC staff's specific objective to provide consumers a greater chance of recognizing a problem and escaping from a developing hazardous CO exposure. It is important to understand that, in tests when death is predicted while the generator was still running, the timing of the maximal COHb level is relatively inconsequential, and the more important measures are the times at which CO exposure is expected to have reached a potentially incapacitating point, and a lethal point of no return.

Comparative test analysis is further complicated because in most tests, when the generator run time ended, forced mechanical venting of the test house was immediately implemented; but in five tests, a variable period of natural decay was allowed. Specifically, natural decay was monitored for 45 minutes in test N, 60 minutes in test I, 45 minutes in test AH, 30 minutes in test U, and 60 minutes in test F. Staff notes that at the time the engine stops, if acute **sub-lethal COHb** levels below 60% COHb are predicted for occupants in each house area, the CO decay period can have significant impact on predicted health outcomes of occupants in each area. The impact of the decay period depends on whether: (1) decay occurs naturally or is forced (or in incident scenarios increased by opening windows and doors); (2) the relative CO levels in each area are low enough to cause COHb levels to start declining immediately; or (3) CO levels are high enough to continue driving further COHb formation for a while longer, although at a reduced rate. Formation of COHb will continue until area CO levels decay sufficiently to reverse the CO concentration gradient between the blood and inspired air. Only then can more CO than is absorbed in the lungs' capillary bed, diffuse out from the blood to be eliminated during exhalation. It is specifically emphasized that, unlike test house CO levels that drop precipitously and are rapidly cleared from the home within minutes after forced mechanical venting begins, even if all CO is removed from inhaled air, elevated blood COHb levels will drop much more slowly over several hours, due to COHb's aforementioned 4 to 5 hour half-life. For example, after removal from a CO exposure, at breathing rates between 6 to 15 L/min RMV (and without any supplemental oxygen), a 40% COHb level will take at least 8 to 10 hours to decline to 10% COHb.

It is also noted that in tests where the HVAC fan was turned off, and where lethal exposure levels are not predicted in the living spaces during the generator run time, the variable time lag[7] in the infiltration of CO into the different living spaces can result in staggered timing of COHb profiles, with later, reduced-peak COHb levels being attained after the engine stops, in living spaces that are furthest away from the garage and/or have the lowest natural air circulation. When modeling COHb profiles, in order to capture any delayed COHb profiles and peaks and/or reflect COHb elevations maintained above specific percentile COHb levels of concern (see Tables 5 and 6 below) after the engine stopped, where considered appropriate, HS staff used useful[8] relevant raw test data supplied by NIST staff to model COHb for times that extend beyond those shown in area CO profile figures documented in the 2011 NIST interim report. As used in this memorandum, the term "run time" refers specifically to the generator engines' operation time, whereas, test duration includes run time plus relevant data collected immediately after run time, during the subsequent natural decay period, and/or to a limited extent, during the early minutes of forced mechanical venting.

To address staff's objective of providing occupants a greater window of opportunity to escape from generator-related CO exposures, staff decided to focus first on comparisons between matched test pairs of Unmod GenX and the SO1 units, before attempting any comparisons across all seven pairs of tests. The specific approaches and measures considered most useful are as follows:

- estimate times to key health effects points, such as initial symptom onset, recognition of obvious symptoms/concern for lasting impairment, probable incapacitation, and death, and
- estimate timing and duration of a "*window of opportunity to escape a developing CO hazard,"* based on predicted time from engine start up to obvious symptom onset, and the interval between obvious symptom onset and progression to incapacitation, which shows rate of symptom progression.
- comparison of the COHb levels predicted at specific matched time points common to all tests,
- where considered appropriate, comment on projected outcomes for each test based on available CO and COHb time profiles, with consideration of likely outcome if engine run times were extended.

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[7] Variable time lag is a function of the amount and concentration of CO accumulated in the garage, house configuration, and other weather-related factors.

[8] The NIST interim report figures show only data CO collected during the generator engine run time plus any period of natural decay, whereas, NIST staff generally continued collecting data until garage CO levels were reduced to background levels. When considered appropriate, HS staff modeled "useful" CO test data collected in living space areas for a short period beyond the test time ranges shown in the NIST report figures. This was done in order to account for prolonged durations of significantly elevated COHb levels resulting from: (a) the delayed CO infiltration within the test house that was particularly staggered in tests where the HVAC fan was turned off, and (b) the long COHb half-life that can maintain abnormally high COHb elevations above specific threshold COHb values of concern despite declining garage CO levels. Staff understands that if COHb levels continue to rise for a short period after initiation of forced venting, predicted levels will be minimum underestimates of those that would result under natural decay.

B) CO alarms

To put into perspective the *window of opportunity to escape a developing CO hazard* insofar as potential protection afforded by CO alarms, HS staff estimated the times when the CO levels in each test home area would first reach any of the mandatory alarm activation criteria for residential CO alarms, and then related these times to the estimated times for symptom recognition, incapacitation, and death. Note: the CPSC recommends that consumers install at least one ANSI/UL or CSA-listed CO alarm that has a battery backup power supply on each level of a home, outside of sleeping areas (http://www.cpsc.gov/info/co/coalarms.html).

Table 4 shows the CO alarm activation criteria based on the sensitivity test limits for residential CO alarms documented in Table 39.1 of ANSI/UL 2034, the *Standard for Safety for Single and Multiple Station Carbon Monoxide Alarms* (Underwriters Laboratories (UL), 2008). The ANSI/UL mandatory alarm activation criteria are intended to prevent development of perceptible CO poisoning symptoms in healthy adults, and are reported in the standard to be "*based on a 10% COHb level.*"[9]

Table 4. Alarm Activation Criteria for Residential CO Alarms (ANSI/UL 2034)*

	CO concentration (ppm)	Permissible Alarm Threshold (minutes)	Mandatory Alarm Threshold (minutes)
Sensitivity Test Points (based on Table 39.1)	70 ± 5	60	240
	150 ± 5	10	50
	400 ± 5	4	15
Normal Operation Test (based on 36.3)	600		Instantaneous alarm must sound for 12 hours

**Based on UL 2034, 2008, Table 39.1 and clause 36.3*

To estimate approximate NIST test times when CO alarm activation was required in each area, HS staff simply examined the relevant CO profiles to determine if, and when, the first of UL's mandatory alarm activation test point criteria thresholds (70, 150, 400, and 600 CO) would be reached, and compared these to its own predicted times to attainment of 10% COHb derived using the nonlinear CFK model with a 15L/min RMV. Staff did not attempt to calculate expected CO alarm times based on exceeding the 10% COHb curve shown in Fig. 39.1 of the UL 2034 standard using Steinberg and Nielsen's relatively simplistic, linear model using their "heavy work effort."

[9] It should be understood that the 10% COHb curve used as the basis of the UL 2034 alarm criteria is based on the *"heavy work effort"* classification of Steinberg and Nielsen (1977), equivalent to an RMV of 30 L/min. If lower RMVs of 15 L/min and 6 L/min are used with the UL 2034 mandatory alarm test points, predicted COHb levels are generally less than 10% COHb, which means that UL 2034 provides a conservative level of protection for healthy adults. In addition to the specific mandatory alarm performance test points documented in table 39.1, clause 36.3 of UL 2034 reports a normal operation test requirement that states *"The maintenance of approximately 600 ppm of carbon monoxide in the alarm chamber shall result in the operation of the alarm in its intended manner for at least 12 hours."* HS staff interprets this to mean that UL-listed CO alarm products are required to activate a near-instantaneous alarm signal if CO levels reach or exceed 600 ppm. It is of note that when UL 2034 was first developed in the early to mid 1990s, portable generators were rarely known to cause residential CO poisoning, and generators were not considered as likely causes of life-threatening CO elevations in residential settings.

C) Health Effects, COHb Thresholds, and Time Intervals

Compared to defining times when CO alarm activation criteria are reached, defining the times for expected symptom onset, incapacitation, and death in healthy adults is more difficult and less accurate because, as noted, the expected CO poisoning health consequences result from the characteristics of the entire CO exposure, *i.e.,* the size of the COHb peak level, the rate at which it is reached, the duration for which it is sustained, and the rate at which it decays. Furthermore, significant variation in individual response to a hazardous CO exposure is expected in terms of perception of symptoms, recognition "that something is wrong," and any subsequent behavioral response taken. Staff recognizes that responses to symptom perception could range from appropriately leaving the area immediately and/or calling 911, to taking no action, or in worst cases, entering the generator location to try and rescue a loved one or turn the engine off, or mistaking symptoms for flu-like illnesses and then retiring to bed. Clearly, multiple factors influence the expected onset, progression, and severity of CO poisoning in exposed individuals, and their likelihood of escaping or surviving a dangerous exposure.

In an earlier memorandum (Inkster, 2004), the approximate times at which hypothetical victims (in a theoretical home model) would attain COHb levels of 20 percent, 40 percent, and 60 percent, were used to assess health effects of CO emissions from a representative, commercially available generator; that approach is also used here, with some additional considerations. HS staff generally uses the 20 percent COHb level to represent the approximate threshold level at which adverse (but nonspecific) symptoms should be obvious to all conscious individuals, DNS might occur in surviving victims, and lucid decision making could be impaired in prolonged CO exposures. Acute attainment of 40% COHb is considered to reflect severe cognitive impairment of victims and likely loss of consciousness, with death possible for prolonged exposures. A 60% COHb level is considered to represent a level at which a fatal outcome is likely without rescue. A 70% COHb level is expected to be a fatal exposure level (COHb levels can continue rising while the individual is dying). To provide some perspective: about 900 to 950 ppm CO represents the approximate minimum exposure that can eventually result in 60% COHb at equilibrium; about 1,350 to 1,400 ppm CO is the approximate minimum exposure that can result in 70% COHb at equilibrium; and 1,200 ppm is the CO level defined by the National Institutes of Occupational Safety and Health (NIOSH) as being *Immediately Dangerous to Life and Health (IDLH).*[10]

To use a convenient, systematic approach to evaluate expected health outcomes for hypothetical victims in specific NIST test house locations during NIST generator tests, HS staff extracted predicted times after engine start up to reach threshold

[10] The NIOSH IDLH is defined as "*An acute respiratory exposure that poses an immediate threat of loss of life, immediate or delayed irreversible adverse effects on health, or acute eye exposure that would prevent escape from a hazardous atmosphere within 30 minutes."*

percentile COHb values that approximate acute symptom categories and descriptors shown in Table 5.

Table 5. Threshold % COHb Values Used to Categorize Predicted Health Outcome in Healthy Adults in Generator Test-Related CO Poisoning Scenarios

COHb Level	Lower Threshold for Acute CO Poisoning Symptoms	Symptom Descriptor used to Categorize Test Outcome
<10%	Symptoms not usually perceived in acute scenario	No or low severity symptoms
10%	Onset of perceptible symptoms	Low severity symptoms,
20%	Adverse symptoms obvious; lower limit for concerns of DNS and lasting impairment	Moderate symptoms
30%	Confusion probable	Moderate to severe symptoms
40%	Incapacitation; probable loss of consciousness	Incapacitation
50%	Death Possible	Death Possible
60%	Death Probable	Death Likely
70%	Death Expected	Death Expected

Furthermore, to provide some immediate comparative understanding of each generator's relative performance in terms of health effects, for each matched pair of tests and across all tests, a system was devised to estimate the relative speed of symptom onset, and progression through to incapacitation, and death, based on "Health Effects Time Intervals" (HETI) defined in Table 6, as calculated from the key COHb levels thresholds defined in Table 5.

Table 6. Definitions of "Health Effects Time Intervals" (HETI) Used to Compare Health Consequences of Generator CO Emissions in Healthy Adults

"HETI" Interval Descriptor	% COHb range	"HETI" Interval Definition
A	10% to 20%	window of earliest possible symptom perception and recognition
B	10% to 40%	interval between earliest possible symptom perception and incapacitation
C	10% to 60%	interval between earliest possible symptom perception and probable death
D	20% to 40%	interval between obvious symptom recognition and incapacitation
E	20% to 60%	interval between obvious symptom recognition and probable death
F	40% to 60%	interval between incapacitation and probable death

In terms of staff's objective to increase the window of opportunity for occupants to escape the CO hazard, HETI B represents the most favorable interval. However, staff recognizes that not all individuals will experience or perceive early adverse effects of CO poisoning as soon as 10% COHb is reached. Staff believes that by 20% COHb, most/all exposed individuals will be aware of adverse health effects; therefore, staff considers the shorter HETI D[11] to represent a more realistic window of opportunity to escape from acute generator-related CO exposure scenarios.

D) Cautionary Statement

Before presenting the COHb profiles and analysis of results, it is emphasized that although all the data in this report are presented as specific numbers, this should not be taken to mean the values are precise. Unless the CO exposures are very likely to be lethal (>60% COHb), some undetermined degree of tolerance is to be expected for the predicted COHb values and the corresponding projected health outcomes. **This means predicted values and projected outcomes should all be viewed as approximate comparative estimates rather than absolute values**. Reported times for CO and COHb levels are also, to some extent, limited by the 6-minute sampling interval between consecutive CO measurements from each CO analyzer. This is especially important when estimating rapid symptom onset and progression in Unmod GenX tests involving fast rising, high, CO levels, because staff had to derive time estimates by interpolating between relevant consecutive data points.

7. Results

A) COHb Modeling Results

Appendix 2 contains individual figures showing composite data for NIST staff's CO time course profiles and HS staff's corresponding modeled COHb profiles, for specific areas in each test (garage, FAM, and MBR areas of the NIST test house). The figures are presented as paired test sets in the order listed in Table 3; odd-numbered figures correspond to the Unmod GenX generator; and even-numbered figures correspond to the SO1 generator, which was fitted with the cat muffler in 4 of the 7 paired tests (tests N, W, U, and T). Generally, matched figures from each test pair are placed side-by-side to facilitate comparison. In most cases, for each specific house location, only data from the CO analyzer line considered most accurate for modeling COHb levels is shown

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[11] Although the underlying mechanisms for acute CO-related and altitude-related hypoxia differ, their impact is similar in terms of acute severe brain hypoxia and compromised brain function. The Federal Aviation Administration (FAA) has defined *Time of Useful Consciousness (TUC)* as "*the amount of time in which a person is able to effectively or adequately perform flight duties with an insufficient supply of oxygen.*" The TUC decreases with altitude, until eventually coinciding with the time it takes for blood to circulate from the lungs to the head usually at an altitude above 35,000 feet. Faster rates of ascent result in shorter TUC. (http://www.faa.gov/pilots/training/airman_education/media/AC%2061-107A.pdf, *see page 12-13)*. In situations of sudden aircraft decompression, the TUC at 40,000 feet is about 7 to 10 seconds, compared to 10 to 15 minutes at 18,000 feet. Conceptually, HS staff equates the FAA's TUC with HETI-D, the realistic window of opportunity to escape a developing CO hazard, as represented by time taken to progress from 20% to 40 % COHb. HETI-D decreases as CO levels increase; faster rates of CO increase result in shorter HETI-D.

(joint decision of NIST and CPSC staff),[12] although COHb profiles were modeled for each CO analyzer. For two closed-bay door tests of Unmod GenX (B, I) where the lower range CO analyzer threshold was exceeded, data from two analyzers were used to derive COHb values in the living spaces, and so two figures per location are shown. Readers are cautioned to pay attention to figure titles because, in these two cases, the pattern of placement of the figures is not totally consistent with other sets. To help avoid confusion, a consistent color scheme that differs between specific house areas is used for the COHb profiles in all tests. However, the colors of the CO profiles are not necessarily consistent between house locations and tests because the CO profile colors are indicative of the useful range of the respective CO analyzer data modeled and the analyzers' locations differed between the first series of tests conducted with Unmod GenX, and the subsequent series conducted with SO1 prototype, as shown in Table 3. It is also important to be aware that the scales used for CO and COHb levels in each figure are optimized to provide detail, so they do not necessarily match between paired tests of Unmod GenX and SO1 generators.

B) Analysis of Empirical CO Data and Modeled % COHb Data

A composite summary table was prepared for each pair of matched tests of UnMod GenX and SO1 tests. For each of the 14 generator tests, the relevant raw data and figures for CO and COHb profiles were carefully examined, and key data, derived from the CO analyzer lines judged most appropriate, were extracted for the garage, FAM, and MBR locations. The "Health Effects Time Intervals" (defined in Table 6) specific to each location were also calculated, where appropriate. For any HETI that was not completed during any particular test, "NA" (not applicable) is used in the summary table to denote that it was not possible to define the HETI as a specific number of minutes for the particular test duration. Additionally, for each area, the specific time, or time ranges, at which the CO levels would be expected to activate a UL-listed CO alarm in the FAM or MBR were identified by examination of the individual raw data files for the most relevant CO analyzers. For information purposes only, the tables include alarm times for a hypothetical CO alarm located in the garage, but no related discussion of this is included because placement of CO alarms in garages is not recommended by CO alarm manufacturers and is not considered likely.

All data and "HETI" calculations concerning COHb levels are based on values modeled using a 15L/min RMV (note: rounding effects explain any apparent 1 minute differences between values shown in the tables for timing of specific percentile COHb values and calculated HETI values). For the MBR, each summary table also includes information on the predicted size and timing of peak COHb levels when modeled using a 6L/min RMV representative of sleeping or sedentary individuals. *(For all tests, the Appendix 2 figures show predicted COHb profiles for both the 15 L/min RMV and the 6L/min RMV, which provides immediate perspective on how the activity level affects onset and progression of CO poisoning before equilibrium or death is reached.)* **CPSC**

[12] The CO profiles for each analyzer did not transition smoothly, so for the few relevant cases, CPSC and NIST staff elected not to splice data together. Generally, staff used data from the lower range, but more sensitive, CO analyzer for timing the buildup of COHb up to ~60%, and where appropriate, used a higher range CO analyzer for estimating the maximum test-specific COHb level reached.

staff's objective is to increase the window of opportunity to escape (HETI-D), and in the paired test discussion of results, bolded text is used to highlight summary findings specific to this critical interval. To help perspective, the summary tables include HS staff's assessment of likely health outcomes for hypothetical victims who remain in the NIST test house garage, FAM, and MBR locations for the entire test-specific generator run times, and where relevant, natural decay period and/or early minutes of forced venting.

For simplicity, the terms "bay door" and "house door" are used to refer to the garage bay door, which opens to the outdoors, and the internal door between the garage and the utility room, which connects the garage to the house living spaces.

Table 7. Paired Test Results: UnMod GenX Test B and SO1-cat Test N

SUMMARY DATA FOR TESTS B AND N						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	B	N	B	N	B	N
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door Position	closed	closed	closed	closed	closed	closed
House Door Position	2"	2"	2"	2"	2"	2"
HVAC fan status	OFF	OFF	OFF	OFF	OFF	OFF
Engine Run Time (min)	185	138	185	138	185	138
Decay (min) v Forced Venting	FV	D (45)	FV	D (45)	FV	D (45)
Test Duration	210	210	210	210	210	210
CO ppm at 60 min	7130	300	1050	60	480	50
CO ppm at 120 min	12770	260	3530	120	1840	120
CO ppm at 180 min	17860	110	6380	130	3330	130
CO ppm at 240 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
CO ppm at 300 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Peak CO ppm	19520	260	6620	140	3540	150
Time of Peak CO ppm	189	120	186	150	186	144
% COHb at 60 min	92	8	18	2	4	1
% COHb at 120 min	94	13	81	5	41	5
% COHb at 180 min	94	16	91	9	83	9
% COHb at 240 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
% COHb at 300 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Peak % COHB	95	16	92	9	84	10
Peak exceeded 70% COHb	yes	no	yes	no	yes	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	*44*	168	*107*	192	*150*	210
Time to 10% COHb - mins	20	76	47	*>210*	76	210
Time to 20% COHb - mins	26	*>210*	64	*>210*	93	*>210*
Time to 30% COHb - mins	30	*>210*	75	*>210*	107	*>210*
Time to 40% COHb - mins	34	*>210*	83	*>210*	118	*>210*
Time to 50% COHb - mins	37	*>210*	91	*>210*	126	*>210*
Time to 60% COHb - mins	40	*>210*	99	*>210*	136	*>210*
Time to 70% COHb - mins	44	*>210*	107	*>210*	150	*>210*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	6	*NA*	17	*NA*	17	*NA*
B: 10% to 40% COHb	14	*NA*	36	*NA*	42	*NA*
C: 10% to 60% COHb	20	*NA*	52	*NA*	60	*NA*
D: 20% to 40% COHb	8	*NA*	19	*NA*	25	*NA*
E: 20% to 60% COHb	14	*NA*	35	*NA*	43	*NA*
F: 40% to 60% COHb	7	*NA*	16	*NA*	18	*NA*
Predicted Outcome at test-specific run time	DEATH Expected	Low severity symptoms	DEATH Expected	Low level symptoms if any	DEATH Expected	Low level symptoms if any
CO alarm times (first alarm point(s) reached highlighted)						
600 ppm instant alarm	13.5	*NA*	44	*NA*	69	*NA*
400 ppm time +15 minutes	12-27	*NA*	31-46	*NA*	55-70	*NA*
150 ppm time + 50 minutes	9-59	6-56	17-67	*NA*	41-91	*NA*
70 ppm time + 240 minutes	12-252	6-246	12-252	72-*312*	12-252	72-*312*
Peak % COHB @ 6 L/min RMV					60	5
Time to Peak % COHb @ 6 L/min RMV					198	204
Predicted Outcome at test-specific run time at 6L/min RMV					DEATH Probable	Low level symptoms if any

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 7
Test B: Unmod GenX *(189 min. run time, forced venting); Figs. 1a, 1b(i), 1b(ii), 1c(i), 1c(ii)*
Test N: SO1-cat (*138 min. run time, 45 min. decay time); Figs. 2a, 2b, 2c.*
House configuration 1: bay door closed, house door open, HVAC fan off,

Unmod Gen X

In this worst case house configuration, Unmod GenX produced rapidly rising CO levels that were still climbing when the run time ended at 189 minutes after three load cycles. At this time (~186 to 192 minutes), the approximate CO peak levels were 19,500 ppm in the garage, 6,620 ppm in the FAM, and 3,530 ppm in the MBR. The corresponding COHb profiles show that death (~60% COHb) would be expected to result much earlier in the test, at approximately 40 minutes in the garage, 99 minutes in the FAM, and 136 minutes in the MBR. At these times, corresponding CO levels in each area had already reached about 4,850 ppm, 2,660 ppm, and 2,170 ppm, respectively. At 136 minutes, the MBR CO levels were significantly lower than other living space areas (where CO levels were between 3,500 and 4,500 ppm), showing how natural air flow pathways in the test house cause uneven, progressive distribution of the garage CO content into each house area when the HVAC fan is off. This explains why, in living spaces, symptom onset is delayed (by about 27 minutes in the FAM and 56 minutes in the MBR), and progression take a little longer, compared to the garage.

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance of perceptible adverse symptoms to their expected appearance, starts about 20 minutes after generator start up, and only lasts about 6 minutes *(which matches the 6-minute interval between consecutive readings for the CO analyzer, i.e., limit of resolution for time estimates).* **After 26 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 8 minutes (HETI-D),** and the interval between incapacitation and probable death is only about 7 minutes (HETI-F). In test B, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific,[13] symptoms (~20% COHb) to probable death (~60% COHb) is estimated at about 14 minutes (HETI-E).

In the FAM, the window of symptom perception (HETI-A) starts about 47 minutes after generator start up, and only lasts about 17 minutes. **After 64 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 19 minutes (HETI-D),** and the interval between incapacitation and probable death is only about 16 minutes (HETI-F). In test B, for the FAM, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (~20% COHb) to probable death (~60% COHb) is estimated at about 35 minutes (HETI-E).

[13] At ~20% COHb, exposed individual are expected to feel strange or unwell and are likely to understand that something is wrong; they might recognize CO as the underlying cause, but they might also confuse the nonspecific symptoms with rapid onset of a viral illness, such as influenza.

In the MBR, the window of symptom perception (HETI-A) starts about 76 minutes after generator start up, and only takes about 17 minutes. **After 93 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation about 25 minutes later (HETI-D),** and the interval between incapacitation and probable death is only about 18 minutes (HETI-F). In test B, for the MBR, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (~20% COHb) to probable death (~60% COHb) is estimated at about 43 minutes (HETI-E).

Comparative performance of SO1-cat

When assessing the comparative performance of the SO1-cat generator, it should be noted that in test N, the prototype operated under a cyclical load for only 114 of the total 138-minute engine run time,[14] followed by a 45-minute period of natural decay. Despite the premature termination of this test, HS staff modeled the NIST CO data collected over 210 minutes to capture the delayed, staggered infiltration of CO into the home, which particularly affected predicted COHb levels of MBR occupants. In the MBR, projected COHb levels were low, but they continued to rise for more than an hour after the engine was turned off, throughout the period of natural decay, and during the early minutes of forced venting. Even though the engine run times were shorter than planned, the data show that the SO1-cat prototype's dramatically reduced CO emissions result in an obvious delay in symptom onset and progression in all spaces. Approximate CO peak levels of about 300 ppm[15] were reached in the garage, and peak CO levels of about 137 ppm in the FAM, and 145 ppm in the MBR, were measured slightly later at (at 150 and 144 minutes, respectively). The garage CO profile clearly shows the prototype engine's cyclical production of CO during each load cycle; the cyclical pattern was less obvious in the living space CO profiles where CO levels were generally lower than garage levels, but still climbing when the test was ended. In the garage, only 13% COHb is predicted at 2 hours, rising to 16% by 168 minutes, before starting to decline during the natural decay period. After running for 2 hours, the prototype's CO emissions are not expected to elevate COHb levels above 10 percent in FAM or MBR. (At 6 L/min RMV, MBR levels only reached 5% COHb after 204 minutes).

During the relatively short 138-minute run time of SO1-cat in test N, COHb levels predicted in all areas did not reach the 20 percent COHb lower threshold of HETI-D, where the appearance of obvious symptoms might be expected. In the living spaces, low COHb levels continued climbing slowly during the 45 minutes of natural decay, and into the early phase of forced venting (started183 minutes into test), just about reaching the 10% COHb threshold, where symptom perception might begin around 3 hours after the test started. In contrast, in comparative Unmod GenX test B,

[14] The NIST interim report informs that during test N, the applied load dropped at 114 minutes; the SO1-cat unit, therefore, was turned off prematurely at 138 minutes, and a subsequent 45-minute period of natural decay was allowed before forced venting was implemented. ES and NIST staff advised that the cause of the unexpected load drop at 114 minutes was subsequently traced to a blown fuse on the load bank rather than any issue with the SO1-cat prototype.

[15] The two consecutive load cycle CO peaks were ~300 ppm CO (at 60 minutes) and ~258 ppm CO (at 114 minutes when the fuse blew).

lethal exposures were reached at 40, 99, and 136 minutes after engine startup in the garage, FAM, and MBR, with progression from obvious symptoms to death taking about 14, 34, and 43 minutes in each area, respectively.

Although test N was prematurely shortened, the comparative results of tests B and N provide evidence that the SO1-cat prototype can significantly delay symptom onset and can slow the progression of CO poisoning to incapacitation in living spaces and garage test house locations.

CO Alarms

Examination of the CO profiles indicate that in test B of Unmod GenX, a CO alarm would be expected to activate[16] at about 44 to 46 minutes in the FAM, and at 69 to 70 minutes in the MBR, which could allow a short but adequate window of opportunity (~39 minutes) for occupants in each respective area to exit the home before being incapacitated by the fast-rising CO levels. However, at the time of CO alarm activation in the MBR,[17] individuals in the FAM (~25% COHb) would have a much-reduced 14-minute window of opportunity to escape (64% decrease). At the time of CO alarm activation in the MBR, the garage CO level was about 8,400 ppm and was rising quickly; any individual who entered the area in an attempt to rescue someone, turn off the OEM generator, or exit the home via the garage, is expected to be incapacitated within a few minutes by the sudden extreme hypoxia resulting from inhalation of the high, rising CO concentration.[18] In test N of SO1-cat, CO levels in the FAM and MBR did not reach the activation criteria required for an alarm during the shortened test time, although it is projected that an alarm activation would occur in these areas, at least by 312 minutes, assuming CO levels remained at least above 70 ppm.

For various reasons, individuals may not immediately egress the building when a CO alarm signal is activated, meaning in test B, the small window of opportunity to escape before incapacitation (HETI-D) will continue to shrink as the CO levels rise and symptoms worsen.

From Table 7, it can be seen that there is relatively good agreement between the estimated times of CO alarm activation and predicted attainment of 10% COHb in tests B and N, as should be expected. The slightly earlier CO alarm times at high-level exposures, in part, reflects the use of the conservative 30L/min RMV as the basis of UL 2034's 10% COHb alarm criteria, versus staff's use of a 15L/min RMV to model the generator test data.

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[16] Alarm activation: based on instant CO level ≥ 600 ppm and 15 minute CO exposure at ≥ 400 ppm

[17] CPSC advises consumers to locate CO alarms near sleeping areas.

[18] HS estimates that with a CO level of 8,400 ppm and 15L/min RMV, 20% COHb will be reached at about 3.25 minutes and will climb to 40% COHb by 6.5 minutes (*i.e.,* HETI-D interval from obvious symptoms to incapacitation is <3.5 minutes) for someone not previously exposed to CO. For generator scenarios, these estimates will be reduced considering that, at the time of an MBR CO alarm activation: (a) house occupants would have preexisting body burdens of COHb that differ depending on their house location, and (2) garage CO levels would continue rising and would increase the rate of CO uptake.

Table 8. Paired Test Results: UnMod GenX Test I and SO1-Noncat Test Z

SUMMARY DATA FOR TESTS I AND Z						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	I	Z	I	Z	I	Z
Generator Unit	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC
Bay Door Position	closed	closed	closed	closed	closed	closed
House Door Position	2"	2"	2"	2"	2"	2"
HVAC fan status	ON	ON	ON	ON	ON	ON
Engine Run Time (min)	245	281	245	281	245	281
Decay (min) v Forced Venting	D (60)	FV	D (60)	FV	D (60)	FV
Test Duration	373	311	373	311	373	311
CO ppm at 60 min	6780	450	1440	160	750	120
CO ppm at 120 min	11180	510	4470	250	3450	220
CO ppm at 180 min	15650	590	7820	320	6100	280
CO ppm at 240 min	18620	640	10380	360	8840	320
CO ppm at 300 min	9280	100	9970	*NA-*	9250	*NA*
Peak CO ppm	18630	640	10600	360	9770	340
Time of Peak CO ppm	241	240	246	246	270	264
% COHb at 60 min	92	14	18	4	7	3
% COHb at 120 min	94	25	86	11	74	9
% COHb at 180 min	94	34	97	18	90	16
% COHb at 240 min	94	40	97	25	92	23
% COHb at 300 min	DEAD (can-not decay)	43	DEAD (can-not decay)	*NA*	DEAD (can-not decay)	*NA*
Peak % COHB	94	43	96	30	92	28
Peak exceeded 70% COHb	yes	no	yes	no	yes	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	*42*	296	*94*	294	*117*	300
Time to 10% COHb - mins	16	42	47	114	67	132
Time to 20% COHb - mins	22	84	62	193	76	216
Time to 30% COHb - mins	26	151	65	294	85	*>311*
Time to 40% COHb - mins	30	241	72	*>311*	93	*>311*
Time to 50% COHb - mins	34	*>311*	79	*>311*	101	*>311*
Time to 60% COHb - mins	36	*>311*	86	*>311*	108	*>311*
Time to 70% COHb - mins	42	*>311*	94	*>311*	117	*>311*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	6	42	15	79	9	84
B: 10% to 40% COHb	14	199	25	*NA*	26	*NA*
C: 10% to 60% COHb	20	*NA*	39	*NA*	41	*NA*
D: 20% to 40% COHb	8	157	10	*NA*	17	*NA*
E: 20% to 60% COHb	14	*NA*	24	*NA*	32	*NA*
F: 40% to 60% COHb	6	*NA*	14	*NA*	15	*NA*
Predicted Outcome at test-specific run time	DEATH Expected	Incapacita-tion	DEATH Expected	Moderate to severe symptoms	DEATH Expected	Moderate to severe symptoms
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	7.5	234	33	*NA*	56	*NA*
400 ppm time +15 minutes	7-22	6-21?*	26-41	*NA*	48-63	*NA*
150 ppm time + 50 minutes	4-54	6-56	16-166	54-104	31-181	70-120
70 ppm time + 240 minutes	2-242	6-246	9-249	13-253	25-265	35-275
Peak % COHB @ 6 L/min RMV					92	15
Time to Peak % COHb @ 6 L/min RMV					210	300
Predicted Outcome at test-specific run time at 6L/min RMV					DEATH Expected	Low severity symptoms

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 8
Test I: Unmod GenX *(245 min. run time, 60 min. natural decay), Figs. 3a, 3b(i), 3b(ii), 3c(i), 3c(ii)*
Test Z: SO1-noncat (*281 min. run time, forced venting), Figs 4a, 4b, 4c*
House configuration 3: garage door closed, house door open, HVAC fan ON,

Overview, *Unmod GenX*

Test I is essentially similar to the test conditions of test B except, in test I, the HVAC fan was on, and the engine run time was longer (four load cycles).[19] In house configuration 3, Unmod GenX produced rapidly rising CO levels that were still climbing when the run time ended at just after 4 hours. At this time, the approximate CO peak levels were 18,600 ppm in the garage, 10,600 ppm in the FAM, and 9,750 ppm in the MBR. The corresponding COHb profiles show that death (~ 60% COHb) would be expected to occur early in the test, at approximately 36 minutes in the garage, 86 minutes in the FAM, and 108 minutes in the MBR, when corresponding CO levels had already reached about 3,930 ppm, 2,940, and 2,950, respectively. At 108 to 117 minutes, with the HVAC fan on, the MBR CO levels were essentially identical to BR2 and BR3 and were in the transition range between CO analyzers N3 and N2 low. In the living spaces, symptom onset is delayed by about 30 minutes in the FAM, and 50 minutes in the MBR, compared to the garage.

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance of perceptible adverse symptoms to their expected appearance, starts about 16 minutes after generator startup, and only lasts 6 minutes *(like test B, this matches the 6-minute interval between consecutive readings for the CO analyzer, i.e., near limit of resolution for time estimates).* **After 22 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 6 minutes (HETI-D).** The interval between incapacitation and probable death is also about 6 minutes (HETI-F). In test I, in the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to probable death (~60% COHb) is only 14 minutes (HETI-E).

In the living spaces, symptom onset and progression is delayed and lasts longer compared to the garage. In the FAM, the window of symptom perception (HETI-A) starts about 47 minutes after generator startup, and lasts about 15 minutes. **After 62 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 10 minutes (HETI-D),** and the interval between incapacitation and probable death is only about 14 minutes (HETI-F). In test I, in the FAM, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to probable death (~60% COHb) is about 24 minutes (HETI-E).

In the MBR, the window of symptom perception (HETI-A) starts about 67 minutes after generator startup and lasts up to 9 minutes. **After 76 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation**

[19] Natural decay (60 minutes) is inconsequential to test outcomes, as early death is predicted in all areas.

in about 25 minutes (HETI-D), and the interval between incapacitation and probable death is only about 17 minutes (HETI-F). In test I, in the MBR, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to probable death (~60% COHb) is about 32 minutes (HETI- E).

Comparative performance of SO1-noncat

When assessing the comparative performance of the SO1-noncat generator in house configuration 3, it should be noted that in test Z, the prototype operated for about 280 minutes, and CO data collected up to about 300 minutes was used to model COHb to reflect the impact of the delayed infiltration and rise of CO in the living spaces.[20] The prototype completed nearly five load cycles and ran over 30 minutes longer than Unmod GenX in comparative test I, which makes comparative assessment of the prototype's performance more reliable, compared to test pair B and N. The results show that even with the longer run times, the prototype's dramatically reduced CO emissions result in an obvious delay in symptom onset and progression in all spaces. The CO profiles reflect the cyclical load, with the effect being most obvious in the garage (see NIST report, Fig 10a). In the garage, the CO peaks increased slightly with each successive load cycle result, reaching an approximate peak level of about 640 ppm at 240 minutes. Peak CO levels of about 360 ppm in the FAM, and 340 ppm in the MBR, were measured slightly later, at 246 and 264 minutes, respectively. After running for 4.75 hours, the prototype's CO emissions resulted in relatively slow-rising COHb levels compared to Unmod GenX. When the test ended and forced venting was implemented, the peak 43% COHb level predicted at 296 minutes for garage occupants, had not reached fatal levels. Predicted levels reached about 30% COHb at 294 minutes in the FAM, and about 28% COHb at 300 minutes in the MBR (or just 15% COHb at 300 minutes at 6L/min RMV in the MBR). Staff did not estimate the COHb levels expected in each house area for a full tank of gas, but from the CO data patterns presented in the NIST report, it appears likely that COHb levels would continue to rise slowly as long as the engine continued operating.

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance of perceptible adverse symptoms to their expected appearance, starts about 42 minutes after generator startup and also lasts about 42 minutes *(comparative test I, Unmod GenX times are 16 and 6 minutes*). **After 84 minutes of engine operation, symptoms progress relatively slowly from expected perception to incapacitation in about 157 minutes (HETI-D)** *(comparative Test I, Unmod GenX time is just 8 minutes)*. The time from generator startup to incapacitation is about 240 minutes *(comparative test I, Unmod GenX times is just 30 minutes).* In test Z, although the COHb levels appear to still be rising, reaching incapacitating levels at 240 minutes, fatal CO exposure levels were not reached even after 280 minutes of prototype operation. In contrast, in corresponding test I, Unmod GenX, fatal outcome is likely by 36 minutes of test time, with only 14 minutes needed for the exposure to progress from obvious symptoms to probable death (HETI-E).

[20] The 2011 NIST interim report indicates the SO1-noncat generator ran out of fuel (it did not start with a full tank), and the test house was then forcefully vented.

In the FAM, the window of symptom perception (HETI-A) starts about 114 minutes after generator startup and lasts about 79 minutes *(comparative test I, Unmod GenX times are 47 and 15 minutes)*. **In test Z, in the FAM, symptoms do not progress to incapacitation during the 280 test time. The predicted COHb level reaches 20 percent at 193 minutes and peaks at 30 percent at 294 minutes when moderate (and likely worsening) symptoms are likely**. In contrast, in corresponding test I, Unmod GenX, the comparative time to reach 30% COHb is about 65 minutes, and fatal outcome is likely by 86 minutes of test time, with only 24 minutes needed for the exposure to progress from obvious symptoms to probable death (HETI-E).

In the MBR, the window of symptom perception (HETI-A) starts about 132 minutes after generator startup and lasts about 84 minutes before reaching 20% COHb *(comparative test I, Unmod GenX times are 67 and 9 minutes)*. **In test Z, in the MBR, symptoms do not progress to incapacitation during the 280-minute test time. The predicted COHb level peaks at 28 percent at 300 minutes and is indicative of moderate (and likely worsening) symptoms.** In contrast, in corresponding test I, Unmod GenX, the comparative time to reach 28% COHb is about 93 minutes, and fatal outcome is likely by 108 minutes of test time, with only 32 minutes needed for the exposure to progress from obvious symptoms to probable death (HETI-E).

The results of comparative test pair I and Z provide strong evidence that the prototype can significantly delay the rise is CO levels, and consequently delay CO poisoning symptom onset and progression throughout the house, including the garage.

CO alarms

Examination of the CO profiles indicate that in test I of Unmod GenX, a CO alarm would be expected to activate at about 33 to 41 minutes in the FAM, and at about 56 to 63 minutes in the MBR. Alarm activation could allow a short but adequate window of opportunity for hypothetical occupants in each respective area to leave the test house before being incapacitated by the fast-rising CO levels (39 min for FAM, 37 minutes for FAM). At the time of alarm activation in the MBR, the window for individuals in the FAM would be reduced to 16 minutes (59 percent decrease compared to MBR window). These estimates apply, provided individuals do not exit via the garage, where the CO level had reached 6.800 ppm and was rising. Any individual who entered the garage in an attempt to rescue someone, turn off the OEM generator, or to exit the home via the garage, is expected to be incapacitated within a few minutes by the sudden extreme hypoxia resulting from inhalation of the high CO concentration (HETI-D lasts about 4.25 minutes starting 4 minutes after garage entry; these time estimates do not consider, and would be reduced by, any preexisting COHb body burden and rising garage CO levels).

In test Z of SO1-noncat, a CO alarm would be expected to activate at about 104 minutes in the FAM, and at about 120 minutes in the MBR. Alarm activation could allow an adequate window of opportunity for hypothetical occupants in each respective area to leave the test house, even via the garage, before being incapacitated by the rising CO levels (estimated at >190 minutes for both FAM and MBR because the COHb level did not reach 40 percent during the test). In test Z, at the time of alarm activation in the MBR, the window for individuals in the FAM would still be close to 190 minutes.

Table 9. Paired Test Results: UnMod GenX Test D and SO1-Noncat Test AH

SUMMARY DATA FOR TESTS D AND AH						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	D	AH	D	AH	D	AH
Generator Unit	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC
Bay Door Position	closed	closed	closed	closed	closed	closed
House Door Position	closed	closed	closed	closed	closed	closed
HVAC fan status	OFF	OFF	OFF	OFF	OFF	OFF
Engine Run Time (min)	121	301	121	301	121	301
Decay (min) v Forced Venting	FV	D (45)	FV	D (45)	FV	D (45)
Test Duration	145	370	145	370	145	370
CO ppm at 60 min	11120	1060	690	80	80	60
CO ppm at 120 min	22950	2060	1660	180	610	170
CO ppm at 180 min	*NA*	2020	*NA*	320	*NA*	320
CO ppm at 240 min	*NA*	1940	*NA*	410	*NA*	400
CO ppm at 300 min	*NA*	1550	*NA*	470	*NA*	470
Peak CO ppm	23060	2060	1660	470	610	470
Time of Peak CO ppm	121	96	120	306	120	306
% COHb at 60 min	94	26	7	2	2	2
% COHb at 120 min	94	67	42	5	11	5
% COHb at 180 min	*NA*	77	*NA*	14	*NA*	13
% COHb at 240 min	*NA*	78	*NA*	23	*NA*	23
% COHb at 300 min	*NA*	74	*NA*	32	*NA*	32
Peak % COHB	94	78	50	37	17	35
Peak exceeded 70% COHb	yes	no	no	no	no	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	*37*	210	132	348	138	354
Time to 10% COHb - mins	15	30	67	160	120	160
Time to 20% COHb - mins	20	50	88	220	*>145*	222
Time to 30% COHb - mins	25	68	106	284	*>145*	288
Time to 40% COHb - mins	28	85	117	*>370*	*>145*	*>370*
Time to 50% COHb - mins	31	99	132	*>370*	*>145*	*>370*
Time to 60% COHb - mins	34	111	*>145*	*>370*	*>145*	*>370*
Time to 70% COHb - mins	37	126	*>145*	*>370*	*>145*	*>370*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	5	20	21	60	*NA*	62
B: 10% to 40% COHb	13	55	50	*NA*	*NA*	*NA*
C: 10% to 60% COHb	19	81	*NA*	*NA*	*NA*	*NA*
D: 20% to 40% COHb	8	35	29	*NA*	*NA*	*NA*
E: 20% to 60% COHb	14	61	*NA*	*NA*	*NA*	*NA*
F: 40% to 60% COHb	6	26	*NA*	*NA*	*NA*	*NA*
Predicted Outcome at test-specific run time	DEATH Expected	DEATH Expected	Death Possible	Moderate to severe symptoms	Low severity symptoms	Moderate to severe symptoms
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	7.5	10	53	*NA*	120	*NA*
400 ppm time +15 minutes	6-21	6-21	49-64	234-269	105-120	235-250
150 ppm time + 50 minutes	0-50	0-50	36-186	111-161	75-225	113-163
70 ppm time + 240 minutes	0-240	0-240	19-259	52-298	60-300	72-312
Peak % COHB @ 6 L/min RMV					7	21
Time to Peak % COHb @ 6 L/min RMV					144	360
Predicted Outcome at test-specific run time at 6L/min RMV					Low level symptoms if any	Moderate symptoms

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 9
Test D: Unmod GenX *(120 min. run time, forced venting), Figs. 5a, 5b, 5c*
Test AH: SO1-noncat (*300 min. run time, 45 min. decay time), Figs. 6a, 6b, 6c.*
House configuration 5: bay door closed, house door closed, HVAC fan off,

Overview, Unmod GenX

In test D, house configuration 5,[21] Unmod GenX produced rapidly rising CO levels that were still climbing when the run time ended at 120 minutes after nearly two load cycles. At this time (~186 to 192 minutes), the approximate CO peak levels were 23,000 ppm in the garage, 1,660 ppm in the FAM, and 610 ppm in the MBR. The corresponding COHb profiles show that death (~60% COHb) would be expected to result much earlier in the test, at approximately 34 to 37 minutes in the garage. However, although CO levels in this relatively short test were still rising in all areas when the test ended, the significant, progressive, staggered infiltration of CO into living spaces means that lethal exposure levels were not reached in the FAM or MBR within the 2-hour test time. With the HVAC off and the house door closed, CO distribution in the house was unequal, and the MBR had significantly lower CO levels than all other home areas, which is reflected in the correspondingly low estimated MBR peak level of 17% COHb compared to 50% COHb in the FAM during the 2-hour engine run time.

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance of perceptible adverse symptoms to their expected appearance, starts about 15 minutes after Unmod GenX startup, and is estimated to last only about 5 minutes *(which is <6 minute interval between consecutive readings for the CO analyzer, i.e., near limit of resolution for time estimates).* **After 21 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 8 minutes (HETI-D),** and the interval between incapacitation and probable death is only about 6 minutes (HETI-F). In test D, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to possible death (~60% COHb) is estimated at about 14 minutes.

In the FAM, the window of symptom perception (HETI-A) starts at 67 minutes, and lasts only 21 minutes. **After 88 minutes of engine operation, symptoms take just 29 minutes (HETI-D) to progress from expected perception to incapacitation;** the predicted COHb level peak at 50 percent for the short test time is equivalent to a possibly lethal exposure rather than a probable death. However, based on the rising CO and COHb profile patterns for test D, and results of similar tests of Unmod GenX, B and I, HS staff fully expects that 60% COHb would have been reached shortly in the FAM if the test had continued for just a little longer. In test D, for the FAM, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to possible death (~50% COHb) is estimated at about 35 minutes (HETI- E).

[21] Unmod GenX Test D differs from Test B, because in Test B, the house door was open; Test D differs from Test I, because in Test I, the house door was open and the HVAC was fan on.

The MBR, as noted, had the lowest CO level in the house, at just 610 ppm at 120 minutes, equivalent to a peak level of 17% COHb. Based on the clearly rising MBR CO and COHb profiles in test D, and results of similar Unmod GenX tests B, I, and J, with longer engine run times, HS staff fully expects that the COHb levels, although delayed compared to garage and FAM levels, would have continued to rise to higher "probable" or "expected" lethal" outcomes at longer test durations of a few more hours (at a minimum, the peak CO level of 610 ppm reached in 120 minutes, is equivalent to an equilibrium COHb level of ~50%). **In test D, in the MBR, a peak level of 17% COHb was reached, and symptoms do not progress beyond low-severity symptoms during the 2-hour test time.**

Comparative performance of SO1-noncat

When assessing the comparative performance of the SO1-noncat generator in house configuration 5, it should be noted that in test AH, the prototype operated for about 5 hours, followed by a 45-minute natural decay period. The prototype completed nearly five load cycles (but could not meet the applied load output) and ran more than 3 hours longer than Unmod GenX in comparative test D. The results show that even with the longer run times up to 5 hours, the prototype's dramatically reduced CO emissions result in an obvious delay in symptom onset and progression in all living spaces compared to Unmod GenX. In the garage, three cyclical CO peak levels each reached about 2,300 ppm during three consecutive load cycles (as shown in Figure 14a of NIST interim report for the N2 analyzer), while the N3 CO levels reached the maximum detection limit of 2,060.[22] The COHb levels climbed steadily during the 5-hour test, reaching 70% COHb at 126 minutes, and slowly rising to a peak of 78% COHb by 210 minutes *(COHb peaks cycle between 73% and 76% based on modeled N2 CO analyzer data)*. Peak CO levels of about 468 ppm in the FAM, and 469 ppm in the MBR, corresponding to just over 32% COHb in each area, were both measured at 306 minutes, immediately after the run time ended. Peak levels of 37% COHb and 35% COHb were measured at 348 and 354 minutes in these two areas, showing sufficient CO remained during the period of natural decay to elevate the COHb levels further for a short time after the generator engine had stopped. In test AH, although the house configuration was identical to test D with the HVAC fan off, unexpectedly and inexplicably, the CO house profiles appeared virtually identical in all house areas. The prototype CO profiles showed no suggestion of the staggered progression of CO infiltration throughout the house, normally expected with the HVAC fan off, or the significantly lower CO levels in the MBR, as is evident in the Unmod Gen X tests B and D, and SO1-cat prototype test N, where the HVAC fan was also off.

[22] Figure 14a, in the NIST interim report shows that in the garage, during the last 4 of 5 load cycles applied to the SO1-noncat prototype unit, the CO levels appeared to stabilize around 2,000 ppm CO; the N2 High range CO analyzer data shows CO levels cycling above and below the 2,000 ppm limit of the more sensitive N3 analyzer, which *"maxed out."* The respective garage COHb profiles in Fig 6a, Appendix 2, were modeled from N3 CO data because it was considered most accurate for predicting COHb formation during early COHb formation (it is specifically noted that despite "maxing out," earlier times to 60% COHb were predicted from N3 CO data than from N2 CO data).

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance of perceptible adverse symptoms to their expected appearance, starts about 30 minutes after SO1-noncat start up and is estimated to last about 20 minutes *(comparative test D Unmod GenX times are 15 and 5 minutes).* **After 50 minutes of engine operation, symptoms progress from expected perception to incapacitation in about 35 minutes (HETI-D)** *(comparative test D Unmod GenX HETI-D time is just 8 minutes)*. The time from generator start up to incapacitation is about 85 minutes *(comparative test D, Unmod GenX time is just 28 minutes).* In test AH, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to possible death (~60% COHb) is estimated at about 61 minutes (*comparative test D, Unmod GenX time is 14 minutes).*

In the FAM, the window of symptom perception (HETI-A) begins about 160 minutes after SO1-noncat engine start up and lasts about 60 minutes *(comparative test D, Unmod GenX times are 67 and 21 minutes*)*.* **In the FAM, obvious symptom appearance is expected at around 220 minutes, but HETI-D was not completed because symptoms do not progress to incapacitation during the 300 minutes of run time plus 45 minutes of natural decay** *(comparative test D, Unmod GenX HETI-D interval is 29 minutes*)**.** In test AH, the predicted COHb level peaks at 37 percent at 348 minutes and is indicative of moderate-to-severe symptoms, approaching incapacitation for this relatively long test time (5-hour run time plus 45-minute decay). In corresponding Unmod GenX test D, possible fatal outcome (50% COHb) is likely by 132 minutes of engine operation time, with only 44 minutes needed for the exposure to progress from obvious symptoms to "possible" death. When the engine was stopped at 121 minutes, CO levels had reached 1,657 ppm and were climbing steeply, and it appears likely that death would occur a short time later.

In the MBR, the window of symptom perception (HETI-A) starts about 160 minutes after generator start up and lasts about 62 minutes *(comparative test D Unmod GenX times are 67 and 9 minutes*)*.* Obvious symptoms are expected by 220 minutes but did not reach incapacitation, and a peak level of 35% COHb is predicted at 354 minutes. (At 6L/min RMV, the corresponding predicted peak level at this time is 21% COHb in sleeping/resting occupants). **The unexpected difference between D and AH regarding staggered versus coinciding house CO profile timing, coupled with the short 2-hour run time of test D, make reliable comparisons of projected window of opportunity to escape difficult for the MBR location.** However, it is noted that at the 120-minute time point SO1-noncat, test AH values (170 ppm CO and 5% COHb) were significantly lower than corresponding Unmod GenX test D values (611 ppm CO and 11% COHb).

The comparative test D and AH results provide evidence that the prototype can significantly delay the rise in CO levels, and consequently, CO poisoning symptom onset and severity over the nearly 6-hour test time (5-hour run time, 45-minute decay). It also allows individuals in the garage a longer window of time to recognize a problem and leave the area before being overcome by CO poisoning, where only an 8-minute reaction time exists with the Unmod GenX.

CO alarms

Examination of the CO profiles indicates that, in test D of Unmod GenX, a CO alarm would be expected to activate at about 53 to 64 minutes in the FAM, and at about 120 minutes in the MBR. Alarm activation could allow a short but adequate window of opportunity for hypothetical occupants in each respective area to exit the test house before being incapacitated by the fast-rising CO levels, provided they did not try to exit via the garage, where the CO level had already reached 23,000 ppm. Any individual who entered the garage in an attempt to rescue someone, turn off the OEM generator, or exit the home via the garage, is expected to be incapacitated within a minute or two by the sudden, extreme hypoxia resulting from inhalation of the high CO concentration (HETI-D is just 1 minute, starting 1.5 minutes after entry, without considering any preexisting COHb burden or rising garage CO ppm). In test D of Unmod Gen X, at the time of alarm activation in the MBR (120 minutes), occupants in the FAM would have already reached 42% COHb and likely might be unable to remove themselves from the area.

In test AH of SO1-noncat, a CO alarm would be expected to activate at about 161 minutes in the FAM and at about 163 minutes in the MBR. At the time of an alarm activation in the MBR (at 163 minutes), occupants in both the MBR and FAM should still have ample time to leave the home before being incapacitated (>140 minutes), even if they chose to exit via the garage, where CO levels were about 2,000 ppm.

Table 10. Paired Test Results: UnMod GenX Test J and SO1-cat Test W

SUMMARY DATA FOR TESTS J AND W						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	J	W	J	W	J	W
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door Position	closed	closed	closed	closed	closed	closed
House Door Position	closed	closed	closed	closed	closed	closed
HVAC fan status	ON	ON	ON	ON	ON	ON
Engine Run Time (min)	140	361	140	361	140	361
Decay (min) v Forced Venting	FV	FV	FV	FV	FV	FV
Test Duration	168	378	168	378	168	378
CO ppm at 60 min	10450	480	440	45	190	25
CO ppm at 120 min	19440	650	1670	75	935	50
CO ppm at 180 min	*NA*	640	*NA*	95	*NA*	75
CO ppm at 240 min	*NA*	770	*NA*	130	*NA*	100
CO ppm at 300 min	*NA*	790	*NA*	135	*NA*	115
Peak CO ppm	21350	960	1808	145	1250	125
Time of Peak CO ppm	139	204	126	348	138	360
% COHb at 60 min	94	18	8	2	3	1
% COHb at 120 min	94	30	40	4	20	3
% COHb at 180 min	*NA*	42	*NA*	6	*NA*	4
% COHb at 240 min	*NA*	53	*NA*	9	*NA*	7
% COHb at 300 min	*NA*	54	*NA*	12	*NA*	9
Peak % COHB	94	55	62	14	40	12
Peak exceeded 70% COHb	no	no	no	no	no	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	55	312	150	366	156	372
Time to 10% COHb - mins	17	30	67	258	97	324
Time to 20% COHb - mins	22	66	91	*>378*	121	*>378*
Time to 30% COHb - mins	26	120	106	*>378*	138	*>378*
Time to 40% COHb - mins	29	162	120	*>378*	156	*>378*
Time to 50% COHb - mins	32	218	132	*>378*	*>168*	*>378*
Time to 60% COHb - mins	35	*>378*	149	*>378*	*>168*	*>378*
Time to 70% COHb - mins	38	*>378*	*>168*	*>378*	*>168*	*>378*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	6	36	24	*NA*	24	*NA*
B: 10% to 40% COHb	13	132	53	*NA*	59	*NA*
C: 10% to 60% COHb	19	*NA*	82	*NA*	*NA*	*NA*
D: 20% to 40% COHb	7	96	29	*NA*	35	*NA*
E: 20% to 60% COHb	13	*NA*	58	*NA*	*NA*	*NA*
F: 40% to 60% COHb	6	*NA*	29	*NA*	*NA*	*NA*
Predicted Outcome at test-specific run time	DEATH Expected	DEATH Possible	DEATH Probable	Low severity symptoms	Incapacita-tion	Low severity symptoms
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	8.5	11	70	*NA*	98	*NA*
400 ppm time +15 minutes	7.2-22.5	6-21	52-67	*NA*	85-100	*NA*
150 ppm time + 50 minutes	3.5-53.5	6-56	18-68	*NA*	55-105	*NA*
70 ppm time + 240 minutes	3-*243*	6-246	13-*253*	162-*402*	35-275	162-*402*
Peak % COHB @ 6 L/min RMV					17	6
Time to Peak % COHb @ 6 L/min RMV					156	372
Predicted Outcome at test-specific run time at 6L/min RMV					Low severity symptoms	Low level symptoms if any

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 10
Test J: Unmod GenX *(140 min. run time, reversed load cycle, forced venting), Figs. 7a, 7b, 7c)*
Test W: SO1-cat (*360 min. run time, forced venting), Figs. 8a, 8b, 8c)*
House configuration 4: garage door closed, house door closed, HVAC fan ON

Overview, *Unmod GenX*

In test J, house configuration 4 Unmod GenX produced rapidly rising CO levels that were still climbing when the run time ended at 140 minutes during the third load cycle, which was reversed.[23] At this time, the approximate CO peak levels reached 21,300 ppm in the garage, 1,800 ppm in the FAM, and 1,250 ppm in the MBR. The corresponding COHb profiles show that death (~60% COHb) would be expected to result at approximately 35 minutes in the garage and at about 149 minutes in the FAM. However, although CO levels in this relatively short test were still rising in all areas when the test ended, the significant, progressive, staggered infiltration of CO into living spaces means that lethal exposure levels were not reached in the MBR within the 140-minute run time. Although the HVAC fan was reported to be on and the house door closed, for unclear reasons, CO distribution in the house was unequal, and the MBR (and other bedrooms) had significantly slower rise and reduced peak levels of CO levels compared to the FAM (and kitchen) (see NIST Fig. 11b). This is reflected in the correspondingly low estimated MBR peak level of 40% COHb at 150 minutes compared to 62% COHb in the FAM at this time.

In the garage, the window of symptom perception (HETI-A), from earliest possible appearance to expected appearance of perceptible adverse symptoms, starts about 17 minutes after Unmod GenX start up and is estimated to last only about 6 minutes *(which matches the 6-minute interval between consecutive readings for the CO analyzer, i.e., near limit of resolution for time estimates).* **After just over 22 minutes of engine operation, symptoms rapidly progress from expected perception to incapacitation in about 7 minutes (HETI-D)**, and the interval between incapacitation and probable death is only about 6 minutes (HETI-F). In test J, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to possible death (~60% COHb) is estimated at about 13 minutes. No impact of reversed load cycle on COHb levels was apparent.

In the FAM, the window of symptom perception (HETI-A), starts at about 67 minutes, and lasts only 24 minutes. **After 91 minutes of engine operation, symptoms take just 29 minutes (HETI-D) to progress from expected perception to incapacitation;** and the interval between incapacitation and probable death is only about 29 minutes (HETI-F). In test J, for the FAM, the total time taken for CO poisoning to progress from manifestation of obvious symptoms (~20% COHb) to probable death (~60% COHb) is estimated at about 58 minutes (HETI-E).

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[23] Test J differs from Test D because the load cycle is reversed and the HVAC fan is on, rather than off; the NIST interim report (Figure 11a) informs that Test J was terminated at 140 minutes when the significantly reduced oxygen level (~16%) severely compromised Unmod GenX's engine performance.

In the MBR, the window of symptom perception (HETI-A), starts at about 97 minutes, and lasts only 24 minutes. **After 121 minutes of engine operation, symptoms take just 35 minutes (HETI-D) to progress from expected perception to incapacitation**. Based on the clearly rising CO and COHb profiles and results of similar (though not identical) Unmod GenX tests B, and I, HS staff expects the COHb levels would have continued to rise to higher "probable" or "expected" lethal" if the run time had not been terminated and/or possibly if allowed to decay naturally. (The peak CO level of 1,250 ppm at 138 minutes, at a minimum, is equivalent to an equilibrium COHb level above 60%). In test J, in the MBR, a peak level of 40% COHb attained during the test time is indicative of incapacitation after a 140-minute engine run time.

Comparative performance of SO1-cat

When assessing the comparative performance of the SO1-cat generator in house configuration 4, it should be noted that in test W, the prototype operated for about 360 minutes, completing six load cycles. The results show that even with the longer run times of up to 6 hours, the prototype's dramatically reduced CO emissions result in an obvious delay in symptom onset and slowed progression in all living spaces compared to Unmod GenX test J. In the garage, cyclical CO peak levels in test W stayed below 960 ppm during the 6 consecutive load cycles (peak of 960 ppm at 204 minutes during the fourth cycle). The garage COHb levels climbed relatively slowly during the 6-hour test, reaching 53% COHb at 4 hours, and rising by only 2 percent more, to a peak of 55% COHb at 312 minutes, coinciding with the sixth load cycle (a sustained 960 ppm level will equilibrate just under 60% COHb). Peak CO levels of about 146 ppm at 348 minutes in the FAM, and 125 ppm at 360 minutes in the MBR, eventually resulted in corresponding delayed COHb peaks of about 14% COHb at about 366 minutes, and 12% COHb at about 372 minutes, in each respective area, just after the engine was turned off. This shows that, despite forced venting, sufficient CO remained to elevate further the relatively low COHb levels predicted in the living spaces for a short time.

In the garage, in test W, the window of symptom perception (HETI-A) starts about 30 minutes after SO1-cat start up and is estimated to last about 36 minutes *(comparative test J, Unmod GenX times are 17 and 6 minutes).* **After 66 minutes of engine operation, symptoms progress from expected perception to incapacitation in about 96 minutes (HETI-D) *(comparative test J, Unmod GenX time is just 7 minutes)*.** The total time from generator start up to incapacitation is about 162 minutes *(comparative test J, Unmod GenX corresponding time is just 29 minutes).* In test W, for the garage, the predicted COHb levels approached, but did not quite reach, the probable death level (60% COHb) during the 6-hour run time. The total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) to *possible* death *(~50% COHb*) is estimated at about 152 minutes for SO1-cat *(comparative test J, Unmod GenX time takes just about 10 minutes to rise from 20% to 50% COHb, and only 13 minutes to go from 20% to 60% COHb reaching probable death (HETI-E).*

In the FAM, the window of symptom perception (HETI-A) starts about 258 minutes after generator start up (*comparative test J, Unmod GenX time is 67 minutes*).

In test W, in the FAM, the projected 14% COHb peak level did not reach the level of obvious symptom recognition within the SO1-cat engine's 360 minute run time. *In corresponding test J, Unmod GenX, probable fatal outcome is predicted by 149 minutes***.**

In the MBR, symptom perception (HETI-A) may start at about 324 minutes after SO1-cat generator start up (*comparative test J, Unmod GenX time is 97 minutes*), but **the projected 12% COHb peak level did not reach the level of obvious symptom recognition during the engine's the 360 minute run time.** In corresponding test J, Unmod GenX, HETI-D, the more realistic window of perception reaction and escape, began 2 hours after engine start up and lasted just 35 minutes before probable incapacitation was predicted at about 156 minutes; the CO levels were still rising when the engine was stopped at 140 minutes.

The results of comparative tests J and W provide strong evidence that, compared to Unmod GenX, the prototype equipped with a catalyst muffler can delay the rise in CO levels very significantly, which consequently delays CO poisoning symptom onset, and limits severity for at least 6 hours. Importantly, only low-severity symptoms presenting minimal concern of lethal outcome to healthy adults were indicated in the living spaces in this 6-hour test. The prototype's 96-minute HETI-D also allows even individuals in the garage a greater chance of recognizing a problem and leaving the area before being overcome by CO poisoning, whereas limited opportunity exists with Unmod GenX (where the garage HETI D is just 7 minutes).

CO alarms

Examination of the CO profiles indicates that in test J of Unmod GenX, a CO alarm would be expected to activate at about 67 to 70 minutes in the FAM, and at about 98 to 100 minutes in the MBR. Alarm activation could allow a short but adequate window of opportunity for hypothetical occupants in each respective area to exit the test house before being incapacitated by the fast-rising CO levels, provided that they do not exit via the garage. At the time of MBR alarm activation, the garage CO level had already reached 18,500 ppm, and was still rising. At this level, anyone who entered the garage is expected to be incapacitated within 3 minutes by the sudden extreme hypoxia resulting from inhalation of the high CO concentration (HETI-D is just 1.5 minutes, starting 1.5 minutes after entry, not considering any preexisting COHb body burden or rising garage CO ppm). In test J, at the time of an alarm activation in the MBR (~98 minutes), occupants in the FAM would have nearly reached 26% COHb, reducing the window to escape before incapacitation to just about 22 minutes.

In contrast, in test W of SO1-cat, CO levels in the FAM and MBR did not reach the activation criteria required for an alarm during the 6-hour plus test, although it is projected that alarm activation would have occurred at about by 400 minutes in these areas, assuming CO levels remained at least above 70 ppm. With slowly rising garage CO levels below 800 ppm at 300 minutes, occupants of FAM and MBR should still be able to escape via the garage at the time of MBR CO alarm activation.

Table 11. Paired Test Results: UnMod GenX Test K and SO1-noncat Test V

SUMMARY DATA FOR TESTS K AND V						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	K	V	K	V	K	V
Generator Unit	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC
Bay Door Position	24"	24"	24"	24"	24"	24"
House Door Position	2"	2"	2"	2"	2"	2"
HVAC fan status	OFF	OFF	OFF	OFF	OFF	OFF
Engine Run Time (min)	130	140	130	140	130	140
Decay (min) v Forced Venting	FV	FV	FV	FV	FV	FV
Test Duration	152	164	152	164	152	164
CO ppm at 60 min	680	50	225	65	195	70
CO ppm at 120 min	615	45	305	55	285	55
CO ppm at 180 min	NA	NA	NA	NA	NA	NA
CO ppm at 240 min	NA	NA	NA	NA	NA	NA
CO ppm at 300 min	NA	NA	NA	NA	NA	NA
Peak CO ppm	685	430	321	135	300	90
Time of Peak CO ppm	61	12 spike	126	12	132	24
% COHb at 60 min	19	6	5	4	4	3
% COHb at 120 min	32	7	14	5	12	5
% COHb at 180 min	NA	NA	NA	NA	NA	NA
% COHb at 240 min	NA	NA	NA	NA	NA	NA
% COHb at 300 min	NA	NA	NA	NA	NA	NA
Peak % COHB	34	7	17	6	16	5
Peak exceeded 70% COHb	no	no	no	no	no	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	132	142	144	154	150	160
Time to 10% COHb - mins	35	NA	93	NA	103	NA
Time to 20% COHb - mins	64	NA	NA	NA	NA	NA
Time to 30% COHb - mins	112	NA	NA	NA	NA	NA
Time to 40% COHb - mins	NA	NA	NA	NA	NA	NA
Time to 50% COHb - mins	NA	NA	NA	NA	NA	NA
Time to 60% COHb - mins	NA	NA	NA	NA	NA	NA
Time to 70% COHb - mins	NA	NA	NA	NA	NA	NA
Health Effects Time Intervals						
A: 10% to 20% COHb	29	NA	NA	NA	NA	NA
B: 10% to 40% COHb	NA	NA	NA	NA	NA	NA
C: 10% to 60% COHb	NA	NA	NA	NA	NA	NA
D: 20% to 40% COHb	NA	NA	NA	NA	NA	NA
E: 20% to 60% COHb	NA	NA	NA	NA	NA	NA
F: 40% to 60% COHb	NA	NA	NA	NA	NA	NA
Predicted Outcome at test-specific run time	Moderate to severe symptoms	No symptoms likely	Low severity symptoms	No symptoms likely	Low severity symptoms	No symptoms likely
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	46	NA	NA	NA	NA	NA
400 ppm time +15 minutes	11-26	NA	NA	NA	NA	NA
150 ppm time + 50 minutes	3-53	NA	41-91	NA	49-99	NA
70 ppm time + 240 minutes	3-243	NA	15-255	12-NR	22-262	24-NR
Peak % COHB @ 6 L/min RMV					8	3
Time to Peak % COHb @ 6 L/min RMV					150	160
Predicted Outcome at test-specific run time at 6L/min RMV					Low level symptoms if any	No symptoms likely

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 11
Test K: Unmod GenX *(130 min. run time, reversed load cycle, forced venting), Figs. 9a, 9b, 9c*
Test V: SO1-noncat (*140 min. run time, reversed load cycle, forced venting), Figs. 10a, 10b, 10c*
House configuration 7: bay door open, house door open, HVAC fan off

Overview, *Unmod GenX*

In test K, house configuration 7, Unmod GenX with the garage bay door open, the CO profiles in the garage and living spaces were completely different to other Unmod GenX tests (B, I, D, and J) where the bay door was closed. In this test, the open bay door allowed significant ventilation that greatly reduced the accumulation of CO in the garage and its infiltration into the test house living spaces. In the 130-minute test, Unmod GenX completed two reversed load cycles (*applied high to low in test K)* and started a third. The emissions pattern in the garage gives some indication of cyclic CO production with cyclical peak CO levels evident at the end of the two consecutive load cycles. The garage peak CO levels subsequently dropped near-immediately as the next cycle started and the applied load transitioned from lowest to largest. In the garage, with the bay door open, CO peak levels stayed below 700 ppm during the two consecutive load cycles (reaching 685 ppm CO at 61 minutes and 654 at 114 minutes). Predicted COHb levels for the garage climbed relatively slowly and steadily, reaching 34% COHb at 130 minutes, just after the third load cycle started and the generator was turned off. Peak CO levels of about 321 ppm at 126 minutes in the FAM, and 301 ppm at 132 minute in the MBR, are predicted to result in corresponding delayed COHb peaks of about 17% COHb and 16% COHb at about 144 and 150 minutes, in each area respectively. (This indicates that even with forced mechanical venting of the house, sufficient CO remained in the areas to elevate the COHb levels further for a brief period beyond the engine run time).

In the garage, the window of symptom perception (HETI-A) starts about 35 minutes after Unmod GenX start up and is estimated to last about 29 minutes. **In test K, in the garage, expected symptom perception at 20% COHb was predicted at about 64 minutes after engine start up, but the COHb peak level did not exceed 34% at the end of the short, 130-minute engine run time. Examination of the CO and COHb profiles suggests worsening symptoms would be expected with longer run times, and, although the upper limit of symptom severity is not clear, it appears likely that the 40% COHb threshold for incapacitation would be reached shortly (meaning HETI-D would last at least 66 minutes)**. In test K, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb) *to moderate to severe* symptoms (~*30%* COHb) is estimated at about 48 minutes**.**

In the FAM, the window of symptom perception (HETI-A) starts about 93 minutes after generator start up. **However**, **in test K, in the FAM, for the limited 130-minute generator run time, the projected 17% COHb peak level at 144 minutes did not reach the level of obvious symptom recognition.**

In the MBR, the window of symptom perception (HETI-A) starts about 103 minutes after generator start up. **However**, **in test K, in the MBR, for the limited 130-minute generator run time, the projected 16% COHb peak level at 150 minutes did not reach the level of obvious symptom recognition.**

Comparative performance of SO1-noncat

When assessing the comparative performance of the SO1-noncat generator in house configuration 7, it should be noted that in test V, the prototype operated for about 140 minutes, just over two load cycles. In test V, with the garage bay door open, SO1-noncat CO profiles in the garage and living spaces were completely different to other SO1 tests (N, Z, AH, and W) where the bay door was closed. In the 140-minute test, SO1-noncat completed two load cycles and started a third. However, there is barely any reflection of the load cycle in the garage CO profile because the prototype's reduced CO emissions caused only a short-lived CO spike of about 430 ppm at 12 minutes after start up, then stayed below 100 ppm for rest of the 140-minute run time.[24] Corresponding predicted COHb levels in the garage were extremely low and did not rise above an estimated 7% COHb for the entire 140-minute run time. In the living spaces, CO levels were even lower, with early spikes of 135 ppm at 12 minutes in the FAM, and 90 ppm at 24 minutes in the MBR, which steadily declined to about 50 ppm in both areas over the test duration. The corresponding COHb profiles do not show any evidence of the CO spike but show minimal, very slowly rising levels that had only reached peaks of about 6% COHb at about 54 in the FAM, and 5% COHb at 160 minutes in the MBR, *i.e.*, shortly after the engine was turned off.

In test V, in the garage, FAM, and MBR, predicted COHb levels for the entire 140-prototype engine run time did not even reach the 10% COHb level at which possible appearance of perceptible adverse symptoms might occur. In comparison, in corresponding test K Unmod GenX with a slightly shorter run time of 130 minutes, peak COHb predictions of 17% COHb in the FAM and 16% COHb in the MBR approached the 20% COHb level, where obvious perceptible symptoms would be expected.

The results of comparative test pairs K and V (when also compared to closed bay door test pair D and AH) show that the bay door position is a major influence on the severity of adverse health effects expected when a generator is operated in a garage. Furthermore, tests K and V provide promising evidence that, even with the bay door open when CO levels from the Unmod GenX are relatively low, the SO1-noncat prototype further reduces the rise is CO levels, to levels that essentially negate the onset and progression of CO poisoning symptoms in living spaces during a 140 minute run time.

[24] The NIST interim report indicates a short data recording gap at about 60 minutes due to a software error: HS staff notes this affects 66 to 72 minutes of the CO data used for COHb modeling and coincides with application of the highest load at the beginning of the second load cycle. Although a large CO spike cannot be ruled out entirely during this data gap, staff notes only a small transient CO rise was seen for the corresponding times at the onset of the third load cycle, and aside from a short-lived CO spike during engine start up, the prototype's performance appeared consistent over each load cycle.

CO alarms

Examination of the CO profiles indicates that in test K, Unmod GenX, a CO alarm would be expected to activate at about 91 minutes in the FAM, and at about 99 minutes in the MBR. It is not clear how much higher the slowly rising CO levels in the living spaces would be at extended run times (they had reached peak levels of 321 ppm and 301 in each area, after a 130 minute run time), but alarm activation should allow an adequate window of opportunity for hypothetical occupants in each respective area to exit the test house slightly before they reach 10% COHb, and well before they would reach the 30% COHb threshold for moderate to severe symptoms. At the time of MBR CO alarm activation, garage CO levels appeared to be cycling between about 375 and 700 ppm and occupants should still be able to exit via the garage without serious risk of being overcome.

In test W of SO1-cat, CO levels in the FAM and MBR did not even reach meet the CO alarm activation criteria, consistent with the fact that predicted levels remained below 10% COHb.

Table 12. Paired Test Results: UnMod GenX Test G and SO1-cat Test U

SUMMARY DATA FOR TESTS G AND U						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	G	U	G	U	G	U
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door Position	24"	24"	24"	24"	24"	24"
House Door Position	2"	2"	2"	2"	2"	2"
HVAC fan status	ON	ON	ON	ON	ON	ON
Engine Run Time (min)	126	123	126	123	126	123
Decay (min) v Forced Venting	FV	D (30)	FV	D (30)	FV	D (30)
Test Duration	153	159	153	159	153	159
CO ppm at 60 min	305	30	160	30	125	30
CO ppm at 120 min	410	25	225	20	190	20
CO ppm at 180 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
CO ppm at 240 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
CO ppm at 300 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Peak CO ppm	1110	260	225	90	190	35
Time of Peak CO ppm	84	12 spike	120	12 spike	120	42
% COHb at 60 min	19	4	6	3	3	2
% COHb at 120 min	35	4	12	3	8	2
% COHb at 180 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
% COHb at 240 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
% COHb at 300 min	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Peak % COHB	35	4	14	3	10	3
Peak exceeded 70% COHb	no	no	no	no	no	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	128	66	144	108	144	144
Time to 10% COHb - mins	25	*>159*	102	*>159*	138	*>159*
Time to 20% COHb - mins	68	*>159*	*>153*	*>159*	*>153*	*>159*
Time to 30% COHb - mins	86	*>159*	*>153*	*>159*	*>153*	*>159*
Time to 40% COHb - mins	*>153*	*>159*	*>153*	*>159*	*>153*	*>159*
Time to 50% COHb - mins	*>153*	*>159*	*>153*	*>159*	*>153*	*>159*
Time to 60% COHb - mins	*>153*	*>159*	*>153*	*>159*	*>153*	*>159*
Time to 70% COHb - mins	*>153*	*>159*	*>153*	*>159*	*>153*	*>159*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	43	*NA*	*NA*	*NA*	*NA*	*NA*
B: 10% to 40% COHb	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
C: 10% to 60% COHb	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
D: 20% to 40% COHb	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
E: 20% to 60% COHb	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
F: 40% to 60% COHb	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Predicted Outcome at test-specific run time	Moderate to severe symptoms	No symptoms likely	Low severity symptoms	No symptoms likely	Low level symptoms, if any	No symptoms likely
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	15.5	*NA*	*NA*	*NA*	*NA*	*NA*
400 ppm time +15 minutes	10-25	*NA*	*NA*	*NA*	*NA*	*NA*
150 ppm time + 50 minutes	4.5-55	*NA*	30-80	*NA*	82-132	*NA*
70 ppm time + 240 minutes	3-243	*NA*	8-248	*NA*	31-271	*NA*
Peak % COHB @ 6 L/min RMV					5	2
Time to Peak % COHb @ 6 L/min RMV					150	156
Predicted Outcome at test-specific run time at 6L/min RMV					Low level symptoms, if any	No symptoms likely

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 12
Test G: Unmod GenX *(126 min. run time, forced venting), Figs. 11a, 11b, 11c*
Test U: SO1-cat (123 *min. run time, 30 min. decay time), Figs. 12a, 12b, 12c*
House configuration 6: bay door open, house door open, HVAC fan on,

Overview, *Unmod GenX*

Test G of Unmod GenX, in which the bay door and house door were open, is similar to UnmodGen X test K, except that the HVAC fan was on, and an increasing load cycle was applied, rather than the decreasing load cycle used in test K. Like test K, the CO profiles for the garage and house areas and corresponding predicted COHb profiles in test G, are substantially different to profiles in other Unmod GenX tests, in which the garage bay door was closed (B, I, D, and J). During the 126-minute run time of test G, Unmod GenX completed two load cycles before the run time was ended. To some extent, the load cycle is reflected in the garage CO profiles,[25] and to decreasing extents in the FAM, then MBR CO profiles. In the garage, with the bay door open, CO peak levels reached about 1,100 ppm at 84 minutes during the second consecutive load cycle. Predicted COHb levels for the garage also reflect the load cycle-related CO emission pattern, and climbed relatively slowly and steadily in two waves, reaching 33% COHb at 90 minutes during the second load cycle, and then slowly rising to a peak of 35% COHb at 128 minutes, just after the generator was turned off. Peak CO levels of about 220 ppm at 120 minutes in the FAM, and 190 ppm at 120 minutes in the MBR, are predicted to result in corresponding, delayed peaks of about 14% COHb and 10% COHb in each respective area; both living space CO peaks occurred at 144 minutes, reflecting even distribution by HVAC fan. (This indicates that even with forced mechanical venting of the house, sufficient CO remained in the house areas to elevate the COHb levels further for a brief period beyond the 126-minute engine run time).

In the garage, the window of symptom perception (HETI-A) starts about 25 minutes after Unmod GenX start up and is estimated to last about 43 minutes. **In test G, in the garage, expected perception of obvious symptoms at 20% COHb was predicted at about 68 minutes after engine start up, but the COHb peak level did not exceed 35% by the end of the short 126-minute run time. Examination of the CO and COHb profiles suggests worsening symptoms would be expected with longer run times, and, although the upper limit of symptom severity is not clear, it appears likely that the 40% COHb threshold for incapacitation would be reached shortly (meaning HETI-D would last more than 58 minutes)**. In test G, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (~20% COHb) *to early moderate to severe* symptoms (~*30%* COHb) is estimated at 18 minutes.

In the FAM, possibly perceptible symptoms might appear, starting at about 102 minutes after generator start up. **However**, **in the FAM, for the limited 126-minute**

[25] The NIST report Table 2 indicates that no low-range, high-sensitivity CO analyzer was present in the garage for any Unmod GenX test, except Test K. Consequently, garage CO levels below 1,000 ppm measured by the higher range N1 analyzer, are considered less reliable than similar data reported for the prototype's garage CO data, which were measured by more sensitive N3 or TE CO analyzers.

run time of test G, the projected 14% COHb peak level at 144 minutes is below the level of obvious symptom recognition (~20% COHb).

In the MBR, the onset of possibly perceptible symptoms at the 10% COHb peak level was not predicted until 138 minutes after generator start up, and at that time, Unmod GenX had been turned off for about 13 minutes**.**

Comparative performance of SO1-cat

Prototype test U, in which the bay door and house door were open, is similar to test V, except the HVAC fan was on, the load cycle was not reversed, and the SO1 unit was equipped with the cat muffler. This is reflected in their similarly shaped CO profiles and corresponding predicted COHb profiles for the garage and house areas, which are substantially different to profiles in other SO1 tests, in which the garage bay door was closed (N, Z, AH, and W). During the 123-minute run time, SO1-cat unit completed two load cycles before being switched off. There is barely any reflection of the load cycle in the resulting CO profiles for the garage and house. Aside from an early, short-lived CO spike when the generator was turned on (peaks of 258 ppm at 12 minutes, 92 ppm at 12 minutes, and 37 ppm at 42 minutes, in garage, FAM, and MBR, respectively), the CO levels dropped below 30 ppm until the run time ended. The corresponding COHb profiles in the garage, FAM, and MBR, show minimal impact of the CO spike and essentially remained around 4% COHb in the garage and 3% COHb in both the FAM and MBR during this 123-minute engine run time plus 30 minutes of natural decay.

For the entire test U duration (123-minute run time, plus the 30 minutes of natural decay), predicted COHb levels in the garage did not reach 5% COHb, regarded as a level where healthy individuals would be asymptomatic. In comparison, in corresponding test G, Unmod GenX, with a comparable 126-minute engine run time, 35% COHb was reached, indicative of moderate to severe symptoms.

For the entire test U duration, predicted COHb levels in the FAM and MBR did not exceed 3% COHb, regarded as a level where most individuals would be asymptomatic. In comparison, in corresponding test G, Unmod GenX, the predicted COHb levels were rising when the test ended and predicted peak levels of 14% and 10% COHb in the FAM and MBR, respectively, are indicative of the onset of possible symptom perception.

Like test pair K and V, the comparative tests G and U show that the bay door position is a major influence on the severity of adverse health effects expected when a generator is operated in a garage. Furthermore, they provide evidence that, even when CO levels from the Unmod GenX are low, SO1-cat further reduces CO accumulation to levels that essentially negate the onset and progression of CO poisoning symptoms in living spaces, at least for a 123-minute run time.

CO alarms

Examination of the CO profiles indicates that in test G, Unmod GenX, a CO alarm might be expected to activate at about 80 minutes in the FAM and 132 minutes in the MBR. Alarm activation should allow an adequate window of opportunity for hypothetical occupants in each respective area to exit the test house slightly before they reach 10% COHb. In test G, the garage CO levels appeared to be cycling between about 400 and 1,100 ppm during the first 120 minutes of the test, but with forced venting, they were falling below 400 ppm at the projected time of CO alarm activation in the MBR. Even if the garage level had been 1,000 ppm CO at 132 minutes, during this test duration, house occupants of both the FAM and the MBR would be expected to be able to exit via the garage without being incapacitated.

In test U, SO1-cat, FAM and MBR CO levels did not reach the CO alarm activation criteria, and predicted COHb levels remained below 4% COHb in living spaces and below 5% COHb in the garage.

Table 13. Paired Test Results: UnMod GenX Test F and SO1-cat Test T

SUMMARY DATA FOR TESTS F AND T						
	GARAGE		FAMILY ROOM		MASTER BEDROOM	
Test ID	F	T	F	T	F	T
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door Position	24"	24"	24"	24"	24"	24"
House Door Position	closed	closed	closed	closed	closed	closed
HVAC fan status	OFF	OFF	OFF	OFF	OFF	OFF
Engine Run Time (min)	250	182	250	182	250	182
Decay (min) v Forced Venting	D (60)	FV	D (60)	FV	D (60)	FV
Test Duration	318	205	318	205	318	205
CO ppm at 60 min	410	25	70	4	20	4
CO ppm at 120 min	915	25	120	2	60	2
CO ppm at 180 min	1040	25	180	1	105	1
CO ppm at 240 min	1115	*NA*	200	*NA*	130	*NA*
CO ppm at 300 min	415	*NA*	160	*NA*	145	*NA*
Peak CO ppm	1355	330	210	55	145	10
Time of Peak CO ppm	204	6 spike	252	30 spike	288	24
% COHb at 60 min	20	4	2	ND-v low	1	ND-v low
% COHb at 120 min	40	4	6	ND-v low	2	ND-v low
% COHb at 180 min	59	4	11	ND-v low	5	ND-v low
% COHb at 240 min	65	*NA*	15	ND-v low	8	ND-v low
% COHb at 300 min	52	*NA*	18	ND-v low	12	ND-v low
Peak % COHB	65	4	18	NM-v low	12	NM-v low
Peak exceeded 70% COHb	no	no	no	no	no	no
Time to Peak % COHb if <70% COHb *or to 70% COHb*	251	30	312	NM-v low	312	NM-v low
Time to 10% COHb - mins	25	*>205*	174	*>205*	270	*>205*
Time to 20% COHb - mins	61	*>205*	*>318*	*>205*	*>318*	*>205*
Time to 30% COHb - mins	80	*>205*	*>318*	*>205*	*>318*	*>205*
Time to 40% COHb - mins	121	*>205*	*>318*	*>205*	*>318*	*>205*
Time to 50% COHb - mins	143	*>205*	*>318*	*>205*	*>318*	*>205*
Time to 60% COHb - mins	189	*>205*	*>318*	*>205*	*>318*	*>205*
Time to 70% COHb - mins	NA	*>205*	*>318*	*>205*	*>318*	*>205*
Health Effects Time Intervals *mins*						
A: 10% to 20% COHb	36	*NA*	*NA*	*NA*	*NA*	*NA*
B: 10% to 40% COHb	96	*NA*	*NA*	*NA*	*NA*	*NA*
C: 10% to 60% COHb	164	*NA*	*NA*	*NA*	*NA*	*NA*
D: 20% to 40% COHb	60	*NA*	*NA*	*NA*	*NA*	*NA*
E: 20% to 60% COHb	128	*NA*	*NA*	*NA*	*NA*	*NA*
F: 40% to 60% COHb	68	*NA*	*NA*	*NA*	*NA*	*NA*
Predicted Outcome at test-specific run time	DEATH Probable	No symptoms likely	Low severity symptoms	No symptoms likely	Low level symptoms, if any	No symptoms likely
CO alarm times (first alarm point reached is highlighted)						
600 ppm instant alarm	15	*NA*	*NA*	*NA*	*NA*	*NA*
400 ppm time +15 minutes	10-25	*NA*	*NA*	*NA*	*NA*	*NA*
150 ppm time + 50 minutes	4-54	*NA*	141-191	*NA*	*NA*	*NA*
70 ppm time + 240 minutes	3-240	*NA*	60-300	*NA*	132-*372*	*NA*
Peak % COHB @ 6 L/min RMV					6	<3 NM
Time to Peak % COHb @ 6 L/min RMV					318	<3 NM
Predicted Outcome at test-specific run time at 6L/min RMV					Low level symptoms, if any	No symptoms likely

Note: Times to specific % COHb values and calculated HETI can differ by 1 minute due to rounding.

Test Results Analysis and Discussion: Summary Table 13
Test F: Unmod GenX *(250 min. run time, 60 min. decay time), Figs. 13a, 13b, 13c*
Test T: SO1-cat (182 *min. run time[26], forced venting), Figs. 14a, 14b, 14c*
House configuration 2: bay door open, house door closed, HVAC fan off

Overview, Unmod GenX

As with Unmod GenX tests K and G, in which the bay door was open, in test F,[27] the CO profile and corresponding predicted COHb profiles for the garage and house areas are substantially different to corresponding profiles in other Unmod GenX tests where the garage bay door was closed (tests B, I, D, J). During the 250-minute run time, Unmod GenX completed four load cycles before the engine run time was ended and 60 minutes of natural decay was allowed. In the garage, with the bay door open, the load cycle influence was apparent as CO levels rose slightly higher with each successive cycle, peaking at about 1,350 ppm[28] at 204 minutes during the fourth consecutive load cycle. Predicted COHb levels for the garage also reflect the load cycle-related CO emission pattern, and climbed relatively slowly and steadily, reaching a peak of 65% COHb just around 248 minutes, right before Unmod GenX was turned off. Figure 6a in the NIST report clearly shows the staggered infiltration of CO through the different living spaces of the test house when circulated by natural air currents rather than the HVAC fan; it also shows how the FAM and MBR represent the upper and lower limits infiltration into the multiple living spaces. Peak CO levels of about 210 ppm at 252 minutes in the FAM, and 146 ppm at 288 minutes in the MBR, are predicted to result in corresponding delayed peaks of about 18% COHb and 12% COHb in each area, at a coincident test time of 312 minutes. (This indicates that with staggered infiltration and a 60-minute natural decay period, in this Unmod GenX test, sufficient CO remained in the house/garage system to elevate further the quite low COHb levels in living space occupants for about an hour after the engine was stopped at 250 minutes).

In the garage, the window of symptom perception (HETI-A) starts about 25 minutes after Unmod GenX start up, and is estimated to last about 36 minutes. **At about 61 minutes after engine start up, symptoms progressed to the 20% COHb level of expected perception, then took another 60 minutes to reach projected incapacitation at 40% COHb (HETI-D).** The interval between incapacitation and probable death is about 68 minutes (HETI-F). In test F, for the garage, the total time taken for CO poisoning to progress from manifestation of obvious, though nonspecific, symptoms (at ~20% COHb), to probable death (~60% COHb) is estimated at 128 minutes (HETI-E).

In the FAM, the onset of possibly perceptible symptoms starts about 174 minutes after generator start up. **However**, **in the FAM, after Unmod GenX's 250-minute run time, plus 60 minute decay time, the projected 18% COHb peak level at 312**

[26] The NIST interim report informs Test T ended prematurely at 3 hours when a circuit breaker tripped.
[27] Test F (bay door open), is similar to: (1) Test K, except the house door was closed and the load cycle increased, and (2) Test G, in which the house door was open and the HVAC fan on.
[28] Measured with the low-sensitivity N1 CO analyzer.

minutes did not quite reach the level of obvious symptom recognition (~20% COHb).

In the MBR, the onset of possibly perceptible symptoms (10% COHb) starts about 270 minutes after generator start up. **However**, **in the MBR, after Unmod GenX's 250-minuterun time, plus 60 minute decay time, the projected 12% COHb peak level at 312 minutes did not reach the level of obvious symptom recognition.**

Comparative performance of SO1-cat

As with SO1 tests V and U, in which the bay door was open, in test T the CO profiles for the garage and house areas, and corresponding predicted COHb profiles, are substantially different to corresponding profiles in other SO1 tests where the garage bay door was closed (tests N, Z, AH, W). During the 182-minute run time, SO1-cat completed three load cycles before the run time was ended prematurely when a circuit breaker tripped. There is little, if any, reflection of the load cycle in the resulting minimal CO profiles for the garage, FAM, and MBR. Aside from an early, short-lived CO spike when the generator was turned on (peaks of 332 ppm at 6 minutes in the garage, 53 ppm at 30 minutes in the FAM, and 10 ppm at 24 minutes in the MBR), CO accumulation was not evident, and the CO levels decreased at different rates to between 16 to 26 ppm in the garage, and to negligible levels (below 5 ppm) in the FAM and MBR. These CO levels were so low that only the garage COHb profile was modeled to assess the impact of the initial CO spike. A very slight, insignificant effect of the early CO peak on the COHb profile was only noticeable by greatly magnifying the % COHb scale (this showed a corresponding short-lived peak was barely evident at just over 4% COHb, then COHb levels continued declining slowly and steadily to under 4% COHb by the end of the 182-minute run time).

For the entire 182-minute run time of test T, predicted COHb levels in all three areas did not reach 5% COHb, which is regarded as a level where healthy individuals would be asymptomatic. In comparison, in corresponding test F, Unmod GenX, where run time was 250 minutes, a lethal level of 60% COHb was predicted at 189 minutes for the garage, with peaks of 18% COHb and 12% COHb predicted in the FAM and MBR (at 312 minutes) by the end of the test.

As with test pairs K and V, and G and U, the comparative paired tests F and T show that the bay door position is a major influence on the severity of adverse health effects expected when a generator is operated in a garage. Furthermore, they provide evidence that, even when a closed house door reduces the rate of CO entry into living spaces, the SO1-cat unit can further reduce CO to levels that essentially negate the onset and progression of CO poisoning symptoms in living spaces, at least as indicated by a 180 minute SO1-cat run time.

CO alarms

Examination of the CO profiles indicates that in test F, Unmod GenX, a CO alarm might be expected to activate at about 190 minutes in the FAM, but the alarm criteria was not met in the MBR during this test but was projected at about 372 minutes.

Assuming garage levels did not rise significantly above 1,200 to 1,400 ppm, where they last appeared to be cycling between 200 to 260 minutes, MBR occupants should be able to exit safely at 372 minutes, even via the garage. At the relatively slow rate of rise of CO in the living spaces (compared to closed bay door tests with Unmod GenX, particularly B and I), CO alarm activation in the FAM at 190 minutes should allow an adequate window of escape for hypothetical occupants in all living space locations to exit the test house slightly before they reach 10% COHb, even If they were to exit via the garage, where CO levels at that time appeared to be cycling slightly erratically between 1,200 to 1,400 ppm.

In test T, SO1-cat, FAM and MBR CO levels did not reach the CO alarm activation criteria; in fact, CO levels < 5ppm CO are close to background, so they are not considered a specific health concern.

8. **Comparisons Among and Between All Tests**

To facilitate comparison of specific data across all tests, key data from all paired test summaries are grouped together in the following figures and tables in this section.

Figures 15a, 15b, and 15c, summarize all 14 test findings related to the relative onset, rate of progression, and severity of the CO poisoning risk presented in the garage, FAM, and MBR areas of the NIST test house, by operation of OEM Unmod GenX and prototype SO1 generator units in the attached garage. Here, the CO poisoning risk is shown in terms of timing of predicted COHb levels, as modeled from empirical CO data measured in the NIST test house under the various house configurations applicable to each test. The COHb time profiles for each test have been translated into bars where the total height of the bar indicates each specific test time.[29] Each bar is subdivided into color-coded bands (as described below) which, when read from the time of generator start up at the base of the bar, indicate if, or when, predicted COHb levels reached 10%, 20%, 40%, and 60% COHb thresholds (as indicated by the interface between respective bands) during each specific test duration. For bands separated by interfaces at each end, the height of the band indicates the amount of time that the COHb levels are expected to remain in specific COHb ranges before entering the next higher range (*i.e.,* the duration of specific "Health Effects Time Intervals [HETI]") as further detailed below:

- the lowest green band represents the time spent below 10% COHb, which is the time considered "safe" in terms of not being likely to cause perceptible symptoms in healthy adults, *i.e*., the safe window;

- the blue band represents the time interval between 10% and <20% COHb (HETI-A), which is the time range from when possible symptom perception might begin, to the time that obvious adverse health symptoms are expected to occur and be perceived, *i.e.,* the window of possible symptom perception up to the recognition of obvious symptoms;

- the purple band represents the time interval between 20% to <40% COHb (HETI-D), which is the time range from when obvious relatively mild symptoms (headache, fatigue) are expected to worsen progressively, through nausea, vomiting, mental confusion, up to the point of incapacitation. This **CRITICAL TIME INTERVAL** translates into the "window of opportunity for occupants to react to obvious developing symptoms and escape the hazardous CO environment," which could be viewed as the most realistic estimate of available egress time;

[29] engine run time plus "useful data" collected in each test beyond the time of engine shut off, which includes any natural decay allowed, and based on HS staff's judgment, some variable period of additional data collected during delayed spread of CO into living spaces, as influenced by the house configuration used in each test (the longest delays in CO infiltration were observed in the MBR, especially in tests where the HVAC fan was off so air was circulated by natural currents and pathways in the test house).

- the pink band represents the time interval between 40% to <60% COHb (HETI-F), which is the time range when severe incapacitating symptoms progress to the point where self-rescue is not possible and will probably progress to lethal exposures without rescue by outside parties;

- the red band represents the time above 60% COHb, where exposure is considered most likely to result in death without rapid rescue by outside parties; and

- the tan band represents the time spent in an incomplete "COHb HETI range" below the likely lethal level of 60% COHb and above the next highest COHb band below, as is applicable to the particular test. (Note: in tests where levels did not exceed 10% COHb, the entire bar is simply colored green to represent CO exposures considered safe.)

CO poisoning symptom onset and progression is indicated by transition from the lower green band, through blue, purple, and pink bands, up to lethal exposure levels indicated by a red band. The height of each colored band represents the relative rate of symptom progression, with shorter, tightly grouped bands indicative of rapid symptom progression (as in Fig 15a, with Unmod GenX tests B, I, D, and J). In particular, the height of the purple band (HETI-D) is considered critical because it indicates the likely window of opportunity to escape. Put simply, when viewing these bars, "green is good" and "pink and red are very bad."

Comparing the same bar (test letter ID) between Figures 15a, 15b, and 15c provides for each specific test, an indication of the rate at which the CO hazard builds up in the generator location (garage) and then spreads into the different living areas of the test home (as represented by the FAM and MBR) during the test-specific duration.

Comparisons between test bars B, I, D, J, K, G, and F provide information on how the different house configurations used in each test influence the CO poisoning risk presented by OEM Unmod GenX in the GAR, FAM, and MBR locations.

Comparisons between tests N, Z, AH, W, V, U, and T, provide information on how the different house configurations used in each test influence the CO poisoning risk presented by the prototype SO1 generator in each area. Specific attention is drawn to the fact that in tests N, W, U, and T the SO1 unit was equipped with the cat muffler. This is important because subsequent independent testing determined the cat muffler was needed for the prototype to meet the EPA's Phase 2 and 3 HC+NOx emissions standards (Buyer, 2012).

Comparisons between the pairs of adjacent bars (test pairs B and N; I and Z; D and AH; J and W; K and V; G and U; and F and T) show how the CO poisoning risk presented by Unmod GenX and SO1 generators compares under identical test house configurations, at least for the respective duration of each test. For the paired tests, it is clear that the SO1 unit greatly delayed and increased the relative times of HETI-A between 10 to <20% COHb, and where applicable, the critical duration of HETI-D or the time spent in the 20 to <40% COHb range.

Comparisons (i) of tests N and Z with each other, and with test I or B; (ii) of tests AH and W with each other and with tests D or J; and (iii) of tests V and U with each other and between K and G, provide some understanding of the superior performance of the SO1 unit in achieving reduced CO emissions when equipped with the catalyst muffler, compared to the SO1 unit equipped with a non-cat muffler, and to UnmodGenX under identical garage and house door configurations.

Tables 14 and 15 provide summary data of key data for all 14 tests, including predicted times to reach levels of 10%, 20%, 40% and 60% COHb for occupants in garage, FAM, and MBR test house locations, assuming 15 L/min RMV (light to moderate activity level) and estimated times of mandatory CO alarm activation,

Although the test durations varied, the OEM Unmod X and prototype SO1 generators did run for at least 2 hours in all 14 tests; therefore, it is appropriate to compare predicted COHb levels at 1- and 2-hour engine run times. These data are shown graphically in Figures 16a and 16b and are included to illustrate how the SO1 prototype reduces the CO poisoning risk in the garage, FAM, and MBR during the early hours of engine operation.

Figure 17 shows the maximum COHb levels predicted for each test in the garage, FAM, and MBR during the entire test duration; and although the figures should be interpreted cautiously with respect to engine run times, attention is drawn to the fact that in tests Z, AH, and W, the SO1 engine operated for more than 4.5 hours to 6 hours and greatly exceeded their matched pair Unmod GenX run times (tests I, D, and J, respectively).

Figures 18a and 18b show the maximum CO levels measured in the garage, FAM, MBR, and also BR3, during each test; and, in order to provide greater detail of the various peak CO levels reached inside the living spaces, Figure 18b shows the same CO peak data as 18a, minus the garage data. This figure shows that: (i) in Unmod GenX tests B and D, significantly lower peak CO levels were measured in the MBR, compared to other living spaces (HVAC fan off); and (ii) in some tests, although the lowest peak CO levels were recorded in BR2 or BR3, these levels were not very different from the corresponding CO levels in the MBR (which supports HS staff's decision, when modeling COHb levels for all tests, to treat the MBR CO data as representative of the lowest CO levels in the living space).

Collectively, the grouped test data figures and tables provide summary information, with some immediate visual insight, on the effectiveness of the prototype SO1 unit in delaying the onset, slowing the progression, and in some cases, reducing the severity of CO poisoning across multiple test scenarios for specific test durations, as compared to the unmodified Unmod GenX. However, it is **important** that the data be viewed carefully with full awareness of limits, particularly with respect to different specific engine run times used in each test, and with regard to whether the test data accounted for any period of natural decay of CO levels in the test house that is expected to occur normally in the absence of mechanical forced venting.

It is clear from the data analysis and figures that, relative to the unmodified unit, the reduced CO emissions of the SO1 prototype dramatically delayed formation of COHb, and so significantly delayed the onset and rate of progression of CO poisoning symptoms for hypothetical occupants in all areas of the NIST test home, in all seven paired tests. It is particularly noteworthy that in 6 of 7 seven SO1 prototype tests, even after 2 hours of operation, predicted COHb levels for the FAM and MBR living spaces did not reach the 10% COHb threshold indicative of symptom onset—only in test Z, where the SO1 unit was not equipped with the cat muffler, were higher living space levels (11% COHb) predicted by 2 hours. In comparison, for Unmod GenX at 2 hours, incapacitation or death was predicted in the FAM and MBR for the Unmod Gen tests B and I (closed bay door, open house door), and incapacitation was predicted in the FAM; symptomatic levels between 10% to 19% COHb were predicted in the MBR in tests D and J (closed bay door, closed open door). **Most importantly, the SO1 unit can increase HETI-D, the critical window of time in which consumers might be expected to become aware of adverse symptoms and be able to react before being incapacitated by rising CO levels**. It is recognized that this does not guarantee safety, which, even with slowed progression of symptoms, will be dependent on the behavioral responses taken by individuals.

By significantly reducing the engine's CO emissions, the SO1 prototype, particularly if equipped with a catalyst in the muffler, definitely increases the exposure time needed to cause COHb levels to rise to incapacitating levels in even the most extreme circumstances inside the garage. In the garage, for all Unmod GenX tests (B, I, D and J) with the bay door closed, the estimated time to reach 10% COHb ranges between 15 to 20 minutes. The estimated time to progress from 10% to 20% COHb takes only 5 to 6 minutes, **from 20% to 40% COHb takes only 7 to 8 minutes**, and from 40% to 60% COHb takes only 6 to 7 minutes. This means the time from obvious symptom recognition to death (20% to 60% COHb) takes only 13 to 14 minutes and an exposed individual would likely be unconscious for the last 6 to 7 of these minutes. In the garage, regardless of the house door position, the closed bay door results of tests B, I, D, and J, of Unmod GenX, show remarkably consistent, ***very short times*** taken for symptom onset and progression to incapacitation and death with just a 7 to 8 minute useful reaction time (HETI-D). These projected COHb data explain why generators have killed so many consumers who were in the same enclosed or partially enclosed location as the generator, or who for any reason, entered the generator location during the time an Unmod GenX type generator was operating or in the immediate hours after it stopped running[30]. The data indicate how little time these victims might have had to perceive, recognize, and react to the rapidly developing CO hazard.

[30] HS staff's preliminary unpublished CFK-based modeling suggests that at 15L/min RMV, an individual entering an area having a 20,000 ppm CO level would reach 20% COHb in less than 80 seconds, and reach 40% COHb approximately 165 seconds after entry (85 seconds later), not including any pre-existing COHb body burden.

The staff's findings are in line with NIOSH's (1996) findings regarding small gasoline-powered engines and tools, that "*CO can overcome exposed persons without warning. Often there is little time before they experience symptoms that inhibit their ability to seek safety".* In the corresponding SO1 tests (N, Z, AH, W), despite generator engine run times between 138 to 360 minutes, levels above 40% COHb were projected in the garage for only one test (AH) where the SO1 unit did not have the cat muffler and where it ran for 5 hours. This shows how much extra time the SO1 generator, particularly if equipped with the catalyst muffler, can add to the window of opportunity to escape the developing hazardous CO environment in the garage. The potential life-safety benefits of the prototype's reduced CO emission rate applies to individuals already inside this location and individuals who, for any reason, enter the garage during operation of the generator engine or in the hours after it stops.

In the house living spaces, the beneficial impact of the SO1prototype in increasing the potential escape time, compared to Unmod GenX, is, to some extent, also influenced further by the house configuration (bay door position, house door position, HVAC fan status) and the presence of the catalyst muffler; but in all cases, it is extended by even longer times, compared to the increased HETI-D "escape window" projected for the garage location.

In the open bay door test scenarios, by 2 hours of engine run time, the Unmod GenX CO poisoning hazard in all areas was greatly reduced, compared to closed-bay door scenarios, indicating the strong influence of the bay door position on the CO hazard, but the levels were still obviously rising at the end of these relatively short tests (2 hours only for tests K and G) and were expected to climb further for extended run times. In contrast, the SO1 prototype, particularly when equipped with the catalyst muffler, was able to reduce further the hazard in the garage, and in some tests (test U, 2 hours), the reduced CO emissions greatly extend the window of opportunity for individuals in all home locations (even the generator location). Furthermore, in some scenarios, it appears these benefits might be maintained for longer run times. (Extended engine run times will be assessed by modeling studies.)

9. Conclusions

Modeling and analyzing COHb levels for seven comparative paired tests of the Unmod GenX generator and the SO1 generator, based on empirical CO profiles measured in the NIST test house under different house scenarios, provide some consistent, specific measures of engine performance in terms of impact on CO poisoning health effects. Collectively, they provide strong evidence that the reduced CO emissions of the SO1 prototype, particularly when equipped with a catalyst muffler, can significantly reduce the rate of CO accumulation in the garage and its infiltration into the home. Consequently, this translates to delayed onset and progression of CO poisoning symptoms and extends the window of opportunity for occupants in all areas to perceive, recognize, and react to the developing CO hazard before being incapacitated, as defined by a useful reaction time window based on the health effects time interval between 20 and 40% COHb (HETI-D). Staff notes that extending this reaction time interval **does not guarantee safety**, which is also dependent on the behavioral responses taken by individuals in response to cues they receive about the CO hazard (onset of adverse symptoms and/or activation of a CO alarm).

However, assuming that at least some occupants may react appropriately, the test results suggest that the level of reduced CO emissions achieved by the SO1 prototype, especially when fitted with the catalyst muffler, has significant potential for translating into reduced consumer CO deaths and injuries compared to current generator designs used in residential settings. Given that 551 of the 755 known generator-related CO poisoning deaths occurred in fixed residential structures, even a 10 percent appropriate response rate would represent a significant number of lives saved. Furthermore, to some degree, the reduced emissions benefits likely would extend to CO poisoning deaths involving use of generators in smaller, fixed detached structures, like garages and sheds.[31]

HS staff recognizes that portable generators provide great utility in situations where power is unavailable. It does not appear appropriate to require generator manufacturers to meet CO emission performance requirements equivalent to those that have been developed for combustion appliances that are designed to be used in indoor settings (*e.g.*, furnaces, water heaters, ranges). Rather, as previously noted, if a consumer unwittingly, or in trying to comply with manufacturers' instructions, operates a generator in an unsafe residential location, staff's aim is to reduce CO emissions to levels that would give the occupants an improved chance of survival, by allowing increased time to recognize and react to a developing CO hazard (by recognition of early CO poisoning symptoms and/or activation of a residential CO alarm) and by providing them with a longer window of opportunity to escape before incapacitating, life-threatening CO levels develop. The performance of the SO1 prototype in these tests shows potential for being able to do this.

10. Caveat

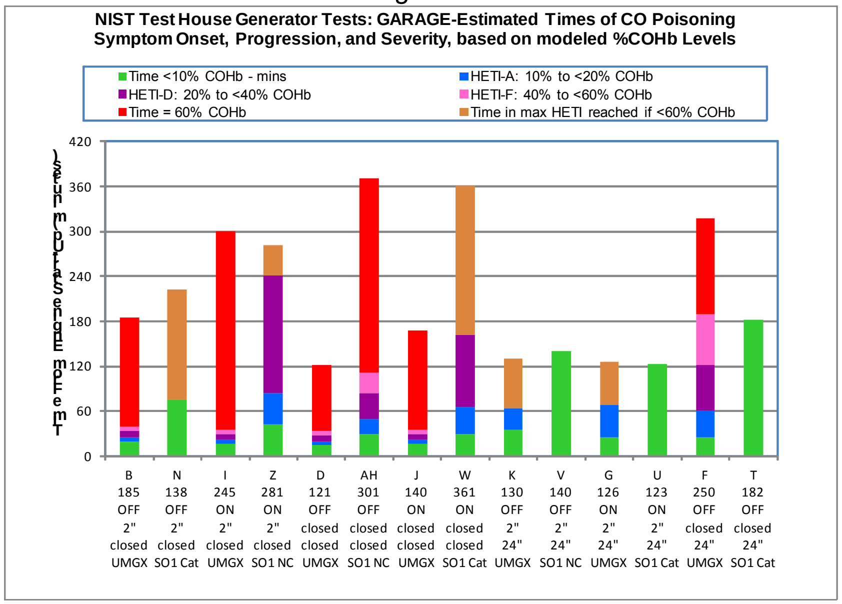
Staff cautions that the modeled COHb data presented in this report apply specifically to the NIST test house settings, generator units tested, and prevailing weather conditions during testing. Obviously, the size of a home, its specific layout, and rates of air exchange with the outdoor environment significantly impact the development of a potential indoor CO hazard. Larger homes and higher air exchange rates generally tend to reduce the hazard, and smaller homes and lower air exchange rates exacerbate the hazard. Although some current findings in this analysis may well hold true for other house designs and/or generator engines, this should not be automatically assumed to be the case. Future theoretical IAQ modeling studies are planned to assess impact of reduced CO emissions levels across a broad range of home structures.

HS staff further cautions that it should be clearly recognized that use of any model to predict COHb levels will give **approximate** estimates, the reliability of which will be dependent upon how closely the input values represent the population

[31] Although CO accumulates faster as volume decreases, smaller detached structures, like sheds and garages, typically have higher air exchange rates than living spaces of home structures.

characteristics and environmental exposure conditions. In addition to house specifics, the modeling and interpretations of health impact applied here are based on healthy adult males, who represent the majority of fatalities involving or associated with portable generators. It is recognized that certain subpopulations including those with cardiovascular disease, anemia, compromised lung function, and normal individuals such as children, and pregnant women and developing fetuses, under specific circumstances, are more susceptible to CO poisoning (Burton, 1996).

Fig. 15a



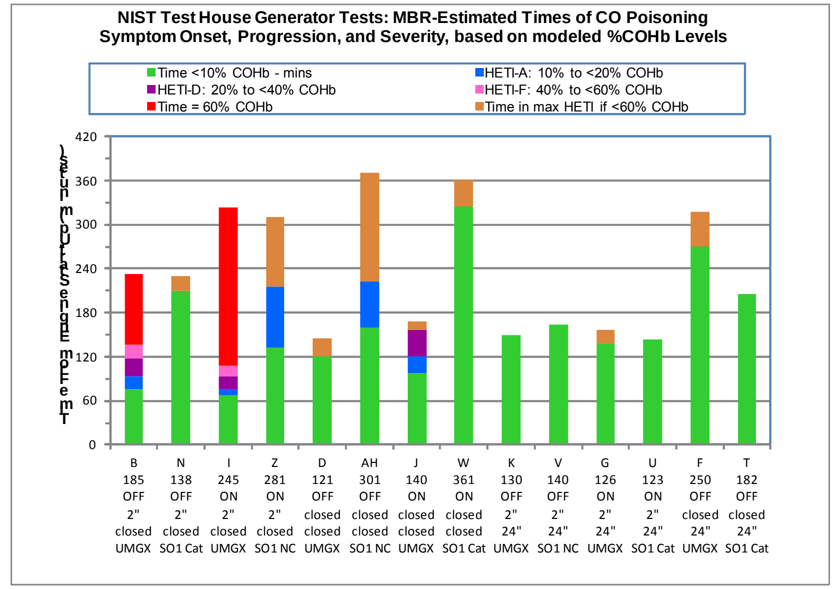


Fig. 15b

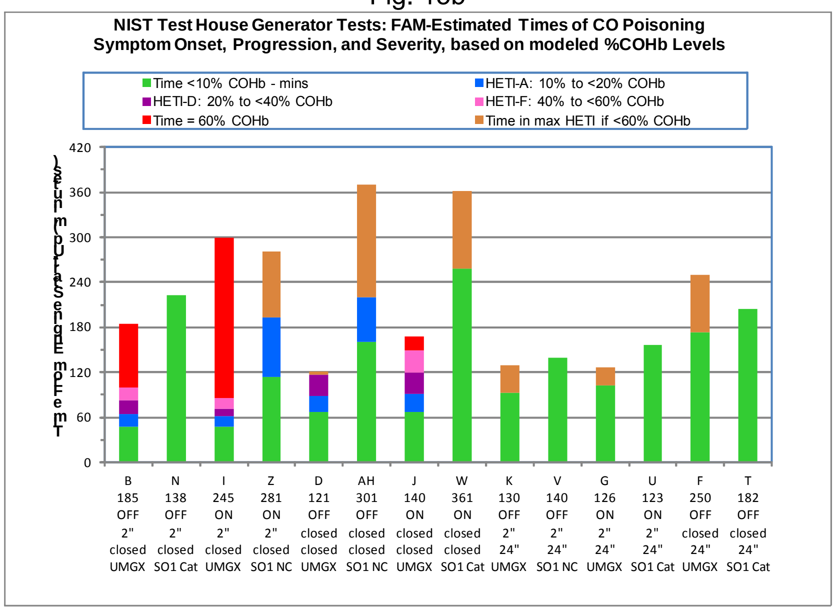


Fig. 15c

Table 14

NIST Generator Tests: Times to 10%, 20%, 40%, and 60% COHb and Duration of the Realistic Window of Opportunity to Escape (HETI-D, 20% to 40% COHb) for Individuals in Specific NIST Test House Locations.														
Test ID	B	N	I	Z	D	AH	J	W	K	V	G	U	F	T
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC	Unmod GenX	SO1 Cat	Unmod GenX	SO1 NC	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door	closed	closed	closed	closed	closed	closed	closed	closed	24"	24"	24"	24"	24"	24"
House Door	2"	2"	2"	2"	closed	closed	closed	closed	2"	2"	2"	2"	closed	closed
HVAC fan	off	off	ON	ON	off	off	ON	ON	off	off	ON	ON	off	off
Engine Run Time (minutes)	185	138	245	281	121	301	140	361	130	140	126	123	250	182
Decay (min) v Forced Venting	FV	D (45)	D (60)	FV	FV	D (45)	FV	FV	FV	FV	FV	D (30)	D (60)	FV
Test Duration	210	210	373	311	145	370	168	378	152	164	153	159	318	205
GARAGE - earliest CO alarm times	14	56	8	21	8	10	9	11	26	NR	5	NR	15	NR
Time to 10% COHb - mins	20	76	16	42	15	30	17	30	35	ERT	25	ERT	25	ERT
Time to 20% COHb - mins	26	ERT	22	84	20	50	22	66	64	ERT	68	ERT	61	ERT
Time to 40% COHb - mins	34	ERT	30	241	28	85	29	162	ERT	ERT	ERT	ERT	121	ERT
Time to 60% COHb - mins	40	ERT	36	ERT	34	111	35	ERT	ERT	ERT	ERT	ERT	189	ERT
HETI-D- minutes from 20% to 40% COHb	8	ERT	8	157	8	35	7	96	ERT	ERT	ERT	ERT	60	ERT
FAM - Earliest CO alarm times	44	312	33	104	53	161	67	402	31	NR	80	NR	191	NR
Time to 10% COHb - mins	47	ERT	47	114	67	160	67	258	93	ERT	102	ERT	174	ERT
Time to 20% COHb - mins	64	ERT	62	193	88	220	91	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 40% COHb - mins	83	ERT	72	ERT	117	ERT	120	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 60% COHb - mins	99	ERT	86	ERT	ERT	ERT	149	ERT	ERT	ERT	ERT	ERT	ERT	ERT
HETI-D- minutes from 20% to 40% COHb	19	ERT	10	ERT	29	ERT	29	ERT	ERT	ERT	ERT	ERT	ERT	ERT
MBR - Earliest CO alarm times	69	312	56	120	120	163	98	402	99	NR	132	NR	372	NR
Time to 10% COHb	76	210	67	132	120	160	97	324	103	ERT	138	ERT	270	ERT
Time to 20% COHb	93	ERT	76	216	ERT	222	121	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 40% COHb	118	ERT	93	ERT	ERT	ERT	156	ERT	ERT	ERT	ERT	ERT	ERT	ERT
Time to 60% COHb	136	ERT	108	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT	ERT
HETI-D- minutes from 20% to 40% COHb	25	ERT	17	ERT	ERT	ERT	35	ERT	ERT	ERT	ERT	ERT	ERT	ERT

NR: CO alarm activation criterion was not reached ERT: exceeded engine run tme - specific %COHb level was not reached during the duration of the test

Table 15: Projected Health Outcomes for Seven Paired Tests of the Unmod GenX Generator and “Reduced CO Emissions” SO1 Prototype Generator Based on Modeled COHb Levels for Test-Specific Engine Operation Times

Test ID	B	N	I	Z	D	AH	J	W	K	V	G	U	F	T
Generator Unit	Unmod GenX	SO1 Cat	Unmod GenX	SO1 NC	Unmod GenX	SO1 NC	Unmod GenX	SO1 Cat	Unmod GenX	SO1 NC	Unmod GenX	SO1 Cat	Unmod GenX	SO1 Cat
Bay Door Position	closed	closed	closed	closed	closed	closed	closed	closed	24"	24"	24"	24"	24"	24"
House Door Position	2"	2"	2"	2"	closed	closed	closed	closed	2"	2"	2"	2"	closed	closed
HVAC fan status	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF
Engine Run Time (min)	185	138	245	281	121	301	140	361	130	140	126	123	250	182
Decay (min) v Forced Venting	FV	D (45)	D (60)	FV	FV	D (45)	FV	FV	FV	FV	FV	D (30)	D (60)	FV
Test Duration	210	210	373	311	145	370	168	378	152	164	153	159	318	205
GARAGE: Predicted Outcome at test-specific run time based on 15L/min RMV	DEATH Expected	Low severity symptoms	DEATH Expected	Incapaci-tation	DEATH Expected	DEATH Expected	DEATH Expected	DEATH Possible	Moderate to severe symptoms	No symptoms likely	Moderate to severe symptoms	No symptoms likely	DEATH Probable	No symptoms likely
FAM: Predicted Outcome at test-specific run time based on 15L/min RMV	DEATH Expected	Low level symptoms if any	DEATH Expected	Moderate to severe symptoms	Death Possible	Moderate to severe symptoms	DEATH Probable	Low severity symptoms	Low severity symptoms	No symptoms likely	Low severity symptoms	No symptoms likely	Low severity symptoms	No symptoms likely
MBR: Predicted Outcome at test-specific run time based on 15L/min RMV	DEATH Expected	Low level symptoms if any	DEATH Expected	Moderate to severe symptoms	Low severity symptoms	Moderate to severe symptoms	Incapacit ation	Low severity symptoms	Low severity symptoms	No symptoms likely	Low level symptoms if any	No symptoms likely	Low level symptoms if any	No symptoms likely
MBR: Predicted Outcome at test-specific run time based on 6L/min RMV	DEATH Probable	Low level symptoms if any	DEATH Expected	Low severity symptoms	Low level symptoms if any	Moderate symptoms	Low severity symptoms	Low level symptoms if any	Low level symptoms if any	No symptoms likely	Low level symptoms if any	No symptoms likely	Low level symptoms if any	No symptoms likely

Fig. 16a

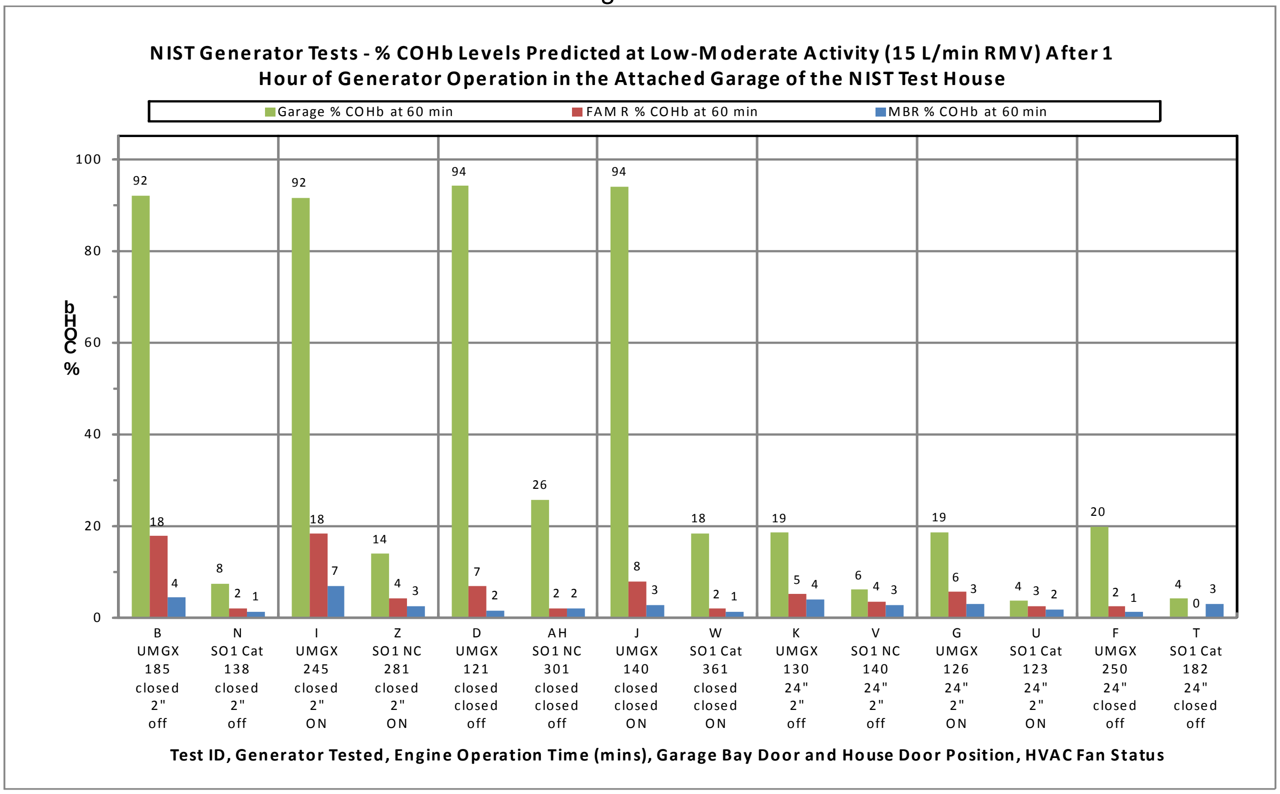


Fig. 16b

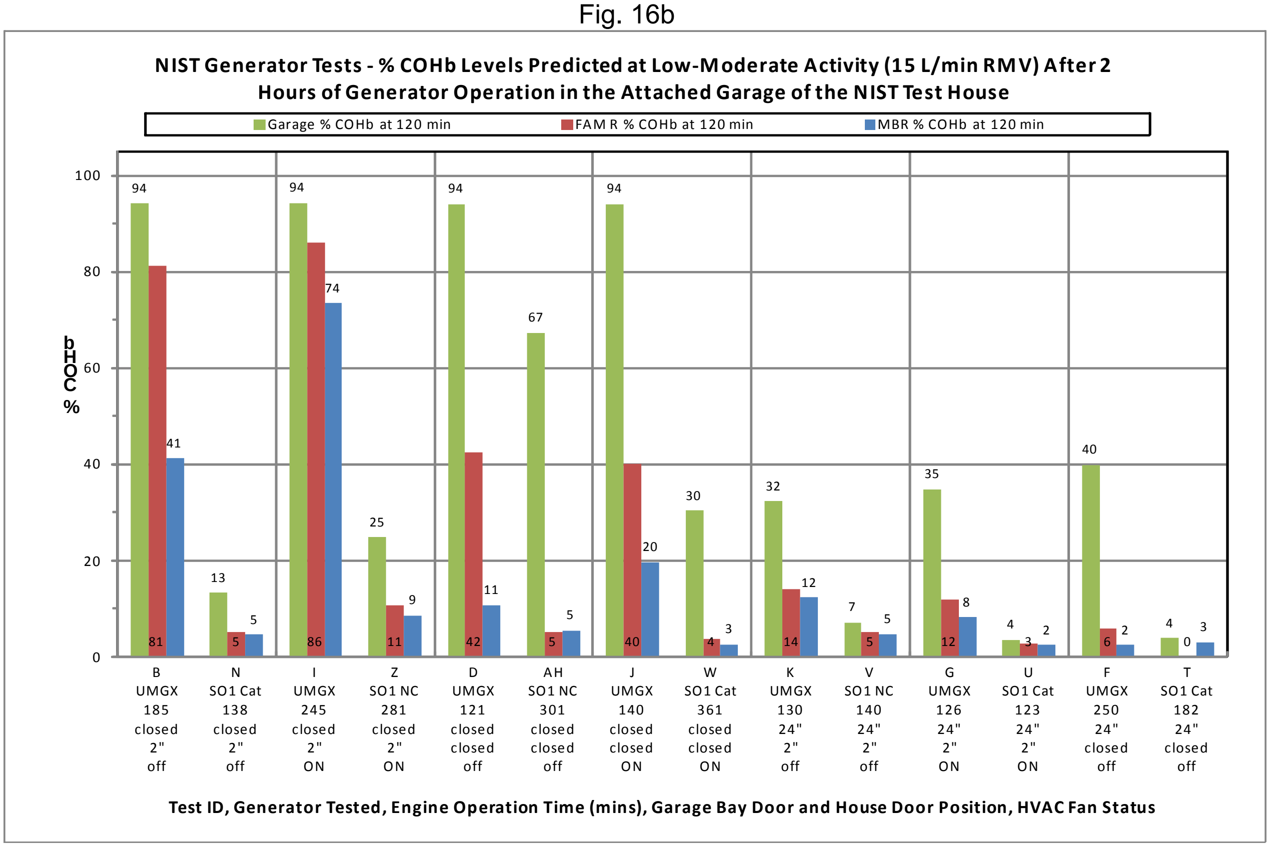


Fig. 17

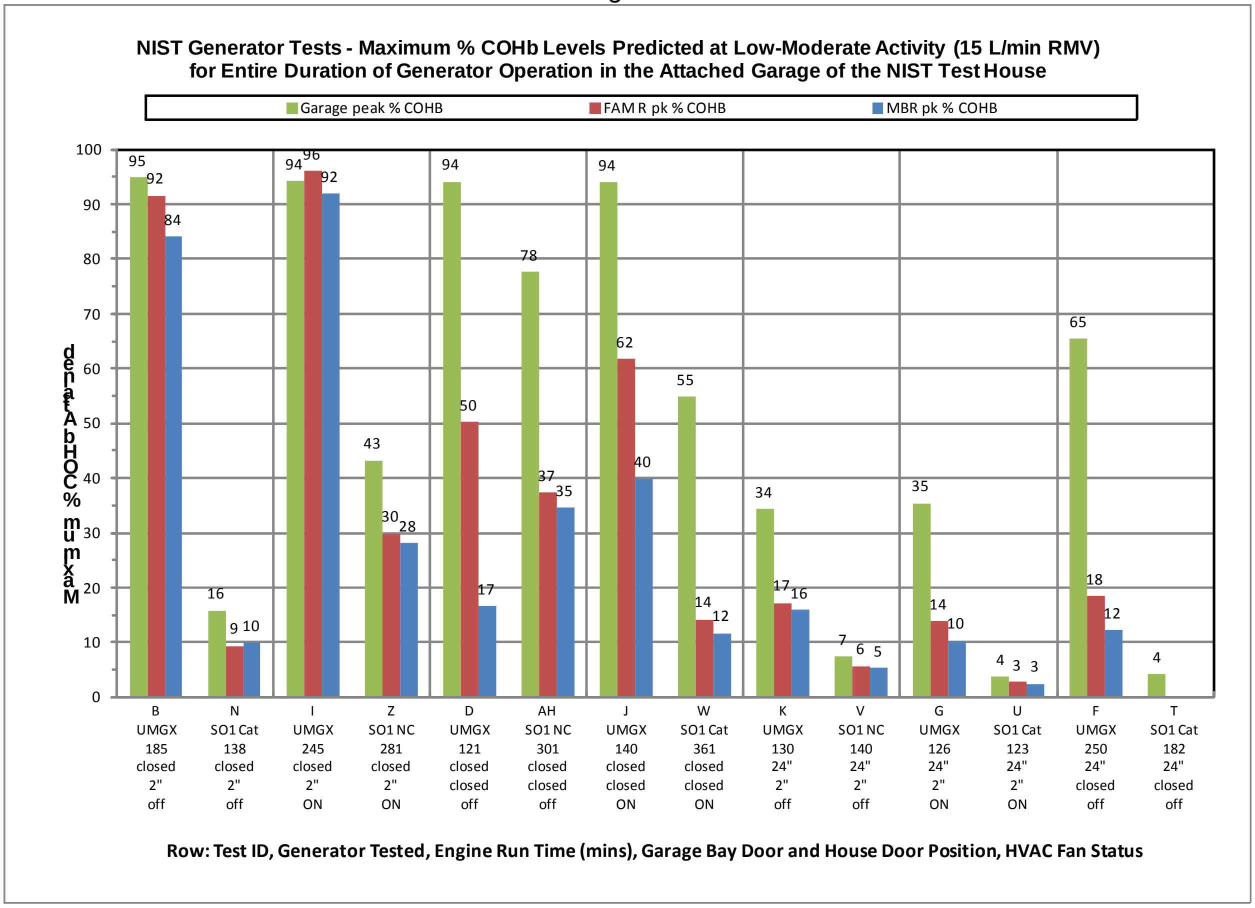

NIST Generator Tests - Maximum % COHb Levels Predicted at Low-Moderate Activity (15 L/min RMV) for Entire Duration of Generator Operation in the Attached Garage of the NIST Test House
Garage peak % COHB
FAM R pk % COHB
MBR pk % COHB
Maximum % COHb Attained
B UMGX 185 closed 2" off
N SO1 Cat 138 closed 2" off
I UMGX 245 closed 2" ON
Z SO1 NC 281 closed 2" ON
D UMGX 121 closed closed off
AH SO1 NC 301 closed closed off
J UMGX 140 closed closed ON
W SO1 Cat 361 closed closed ON
K UMGX 130 24" 2" off
V SO1 NC 140 24" 2" off
G UMGX 126 24" 2" ON
U SO1 Cat 123 24" 2" ON
F UMGX 250 24" closed off
T SO1 Cat 182 24" closed off
Row: Test ID, Generator Tested, Engine Run Time (mins), Garage Bay Door and House Door Position, HVAC Fan Status

Fig. 18a

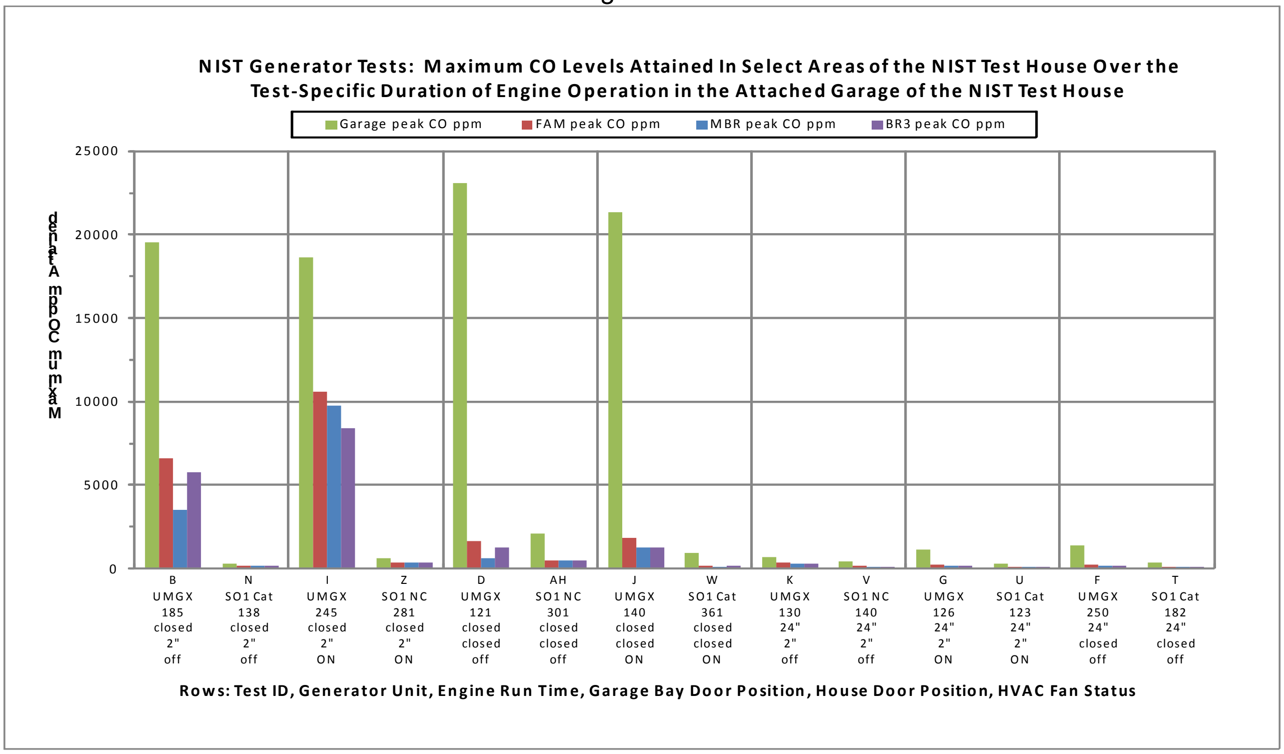
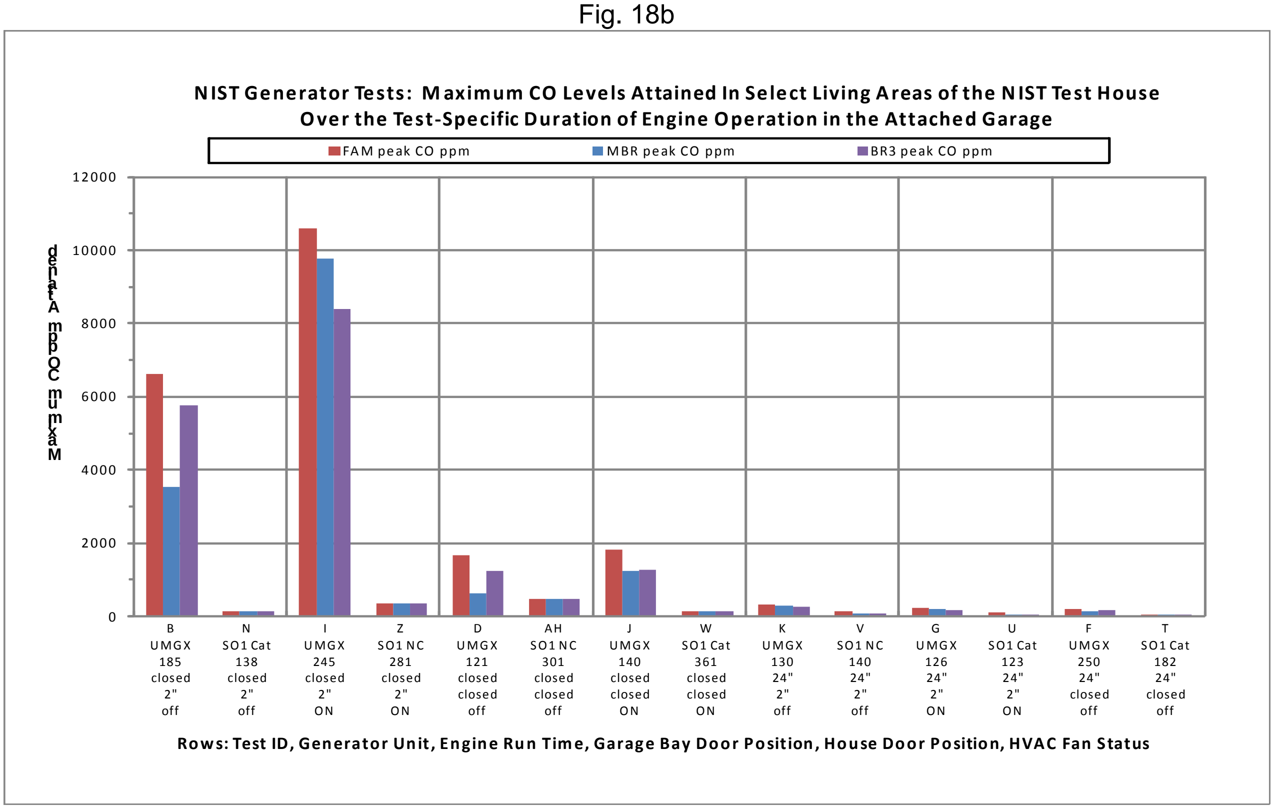


Fig. 18b



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Appendix 1. Relationships Between CO level (ppm), Duration of Exposure, and Exposed Individual's Activity Level on Predicted Carboxyhemoglobin (% COHb) Levels					
Activity Level	**CO level**	**% COHb* at Different Duration Exposures and at Equilibrium**			
(RMVs)	**(ppm)**	**1 hour**	**4 hours**	**8 hours**	**Equilibrium**
Resting/sleep (6 L/min)	**100**	2.6	6.0	9.1	14.5
	200	4.0	11.0	17.0	25.3
	300	5.5	15.8	24.3	33.7
	400	7.0	20.6	30.9	40.3
	500	8.4	25.2	36.9	45.7
	750	12.1	35.9	49.3	55.8
	1,000	15.7	45.5	58.3	62.7
	1,500	22.9	60.7	69.7	71.6
Low (10 L/min)	**100**	3.6	8.6	11.9	14.4
	200	6.2	16.2	21.9	25.2
	300	8.8	23.2	30.3	33.6
	400	11.3	29.7	37.4	40.2
	500	13.9	35.6	43.4	45.7
	750	20.1	48.0	54.5	55.8
	1,000	26.3	57.3	62.0	62.7
	1,500	38.1	69.2	71.4	71.6
Low- Moderate (15 L/min)	**100**	4.8	10.8	13.4	14.3
	200	8.6	20.1	24.1	25.2
	300	12.4	28.2	32.6	33.5
	400	16.1	35.3	39.5	40.2
	500	19.8	41.4	45.2	45.7
	750	28.5	51.5	53.6	53.8
	1,000	37.1	61.1	62.6	62.7
	1,500	51.9	71.1	71.6	71.6
Moderate (20 L/min)	**100**	5.8	12.1	13.9	14.3
	200	10.8	22.3	24.8	25.2
	300	15.6	30.7	33.2	33.5
	400	20.2	37.8	40.0	40.2
	500	24.8	43.7	45.5	45.7
	750	35.5	54.7	55.7	55.7
	1,000	45.0	62.2	62.7	62.7
	1,500	60.2	71.5	71.6	71.6
High (30 L/min)	**100**	7.61	13.4	14.2	14.3
	200	14.3	24.2	25.1	25.2
	300	20.6	32.7	33.5	33.5
	400	26.6	39.6	40.2	40.2
	500	32.2	45.2	45.6	45.6
	750	44.5	55.6	55.7	55.7
	1,000	54.2	62.6	62.7	62.7
	1,500	67.3	71.6	71.6	71.6

* % COHb estimated by Health Sciences using a customized computer model of the nonlinear form of the *Coburn Forster Kane (CFK) equation (*with *Peterson and Stewart* modifications) and the following input parameters: 70 kg male; blood volume = 5,500ml; baseline % COHb = 1.2% (urban nonsmoker); Haldane constant = 218; barometric pressure = 760 torr (sea level) and specified respiratory minute volumes (RMVs).

Fig.1b(i), Test B: FAM

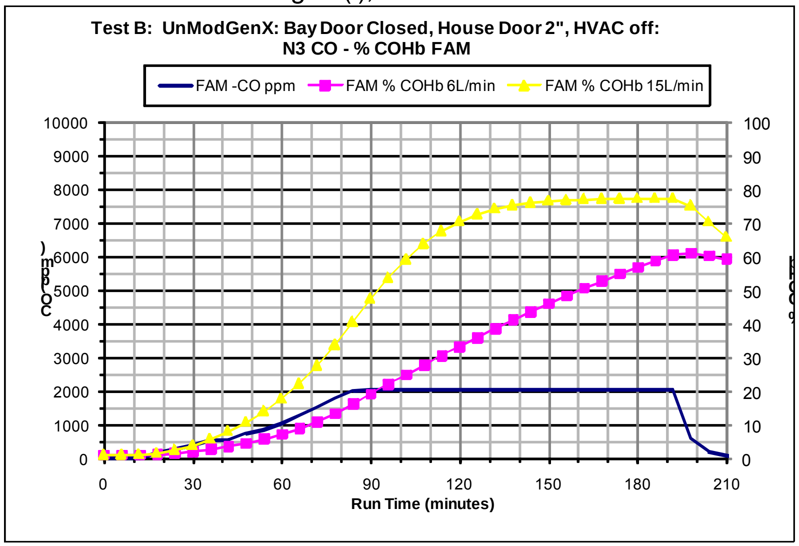


Fig. 2b, Test N: FAM

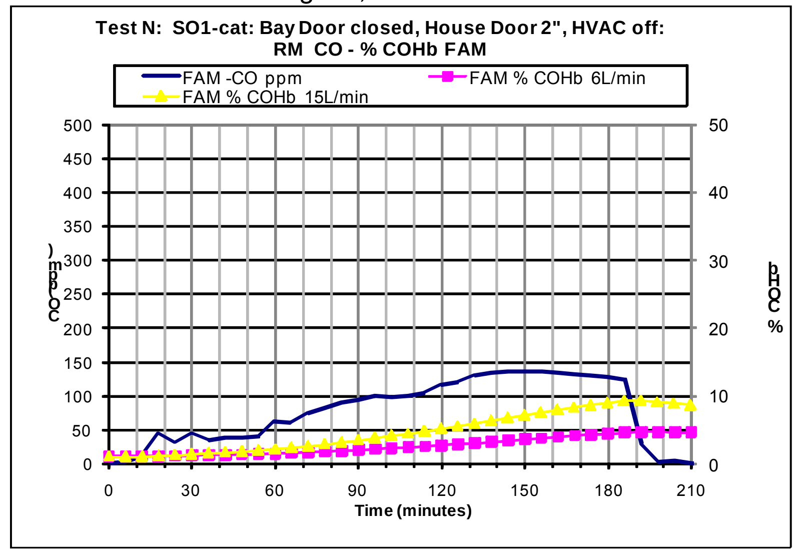


Fig.2a, Test N: Garage

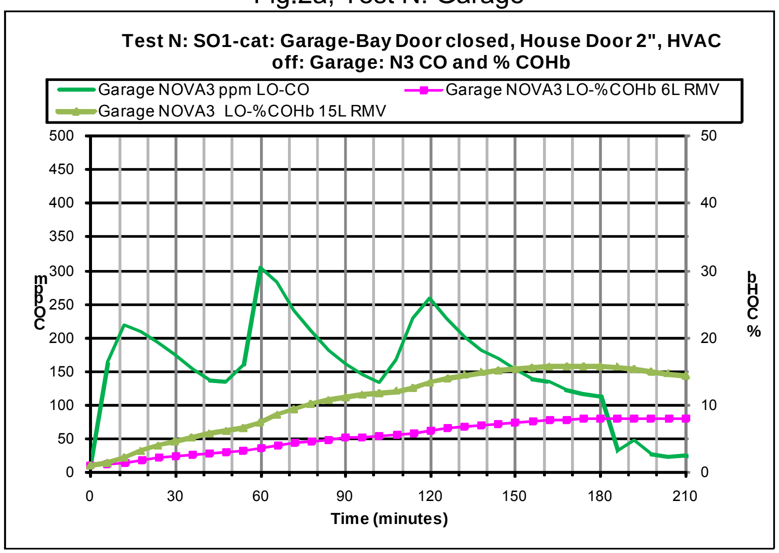


Fig. 1b(ii) Test B: FAM

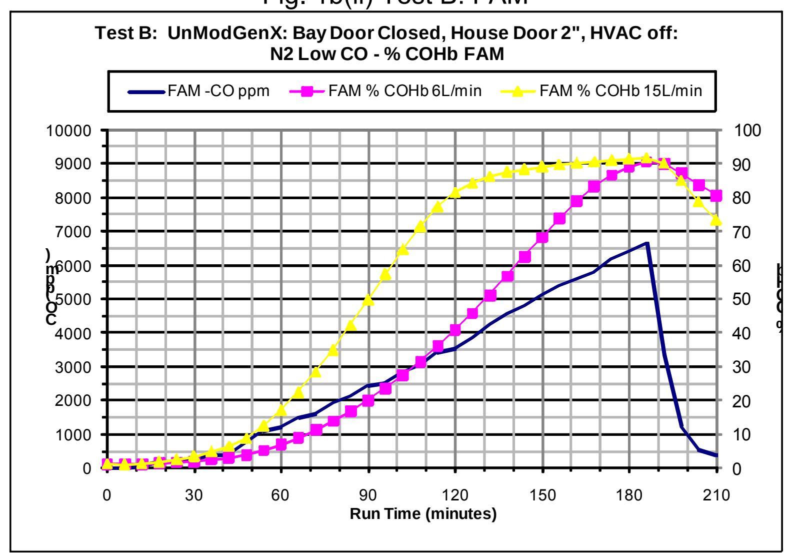


Fig.1c(i) Test B: MBR

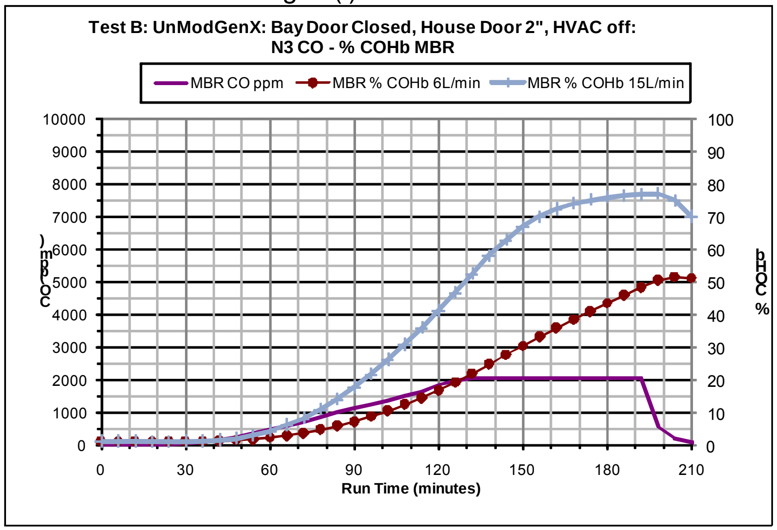


Fig. 2c, Test N: MBR

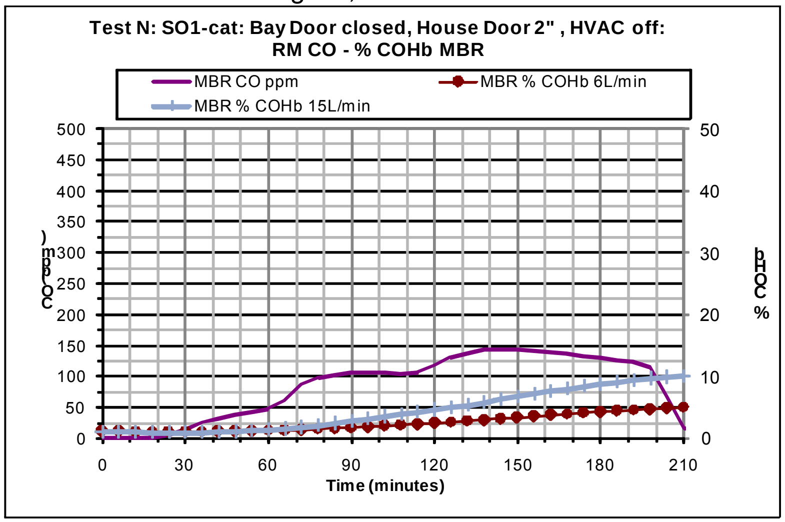


Fig. 1c(ii), Test B: MBR

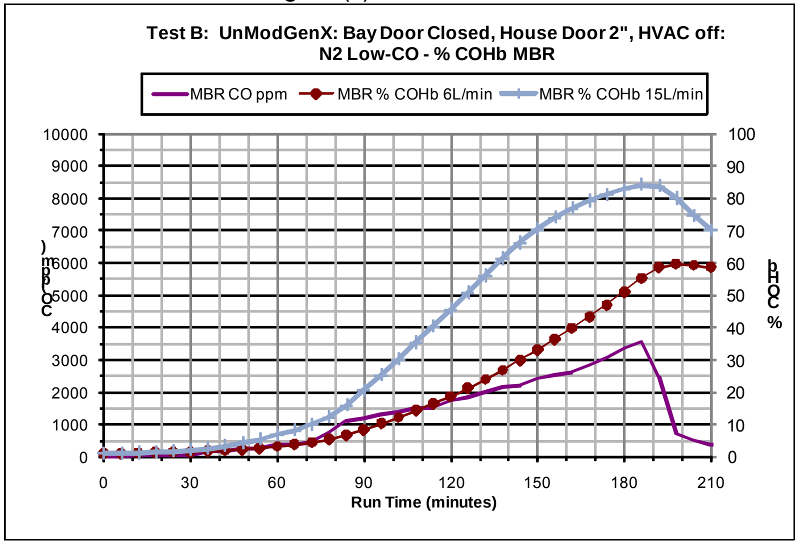


Fig. 3a, Test I: Garage

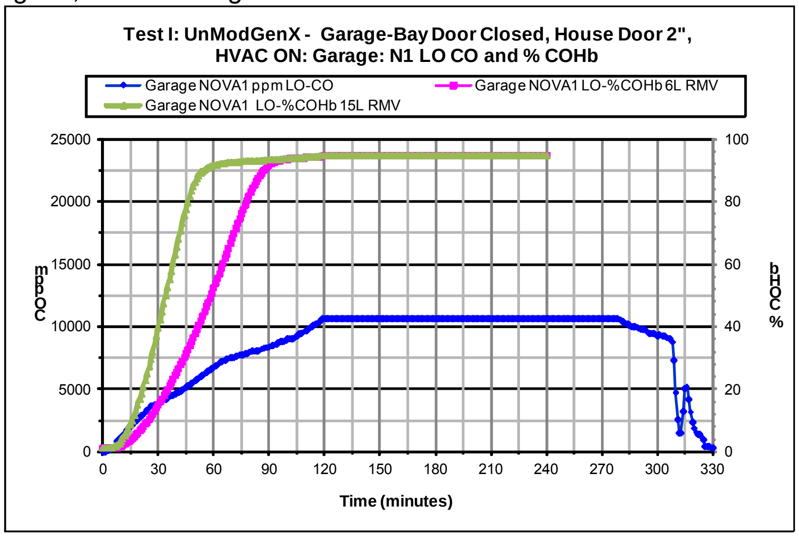


Fig. 3b(i) Test I: FAM

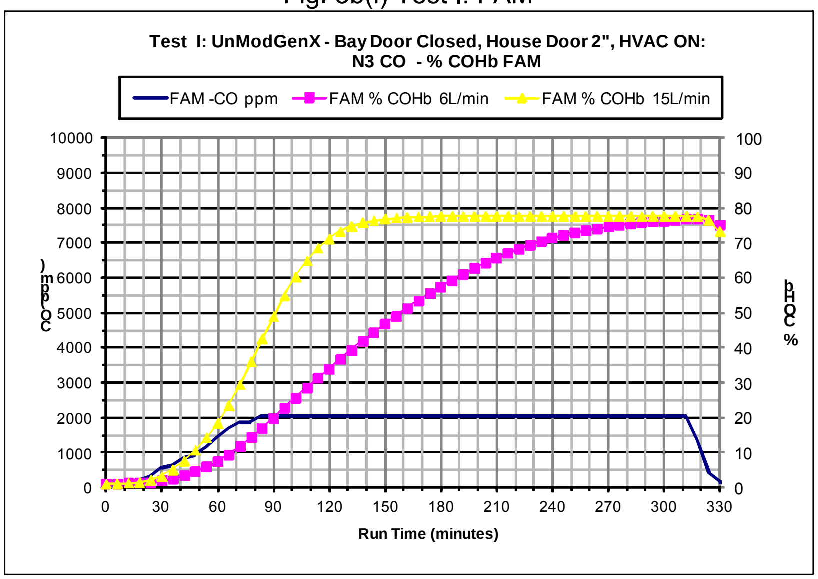


Fig. 4a, Test Z: Garage

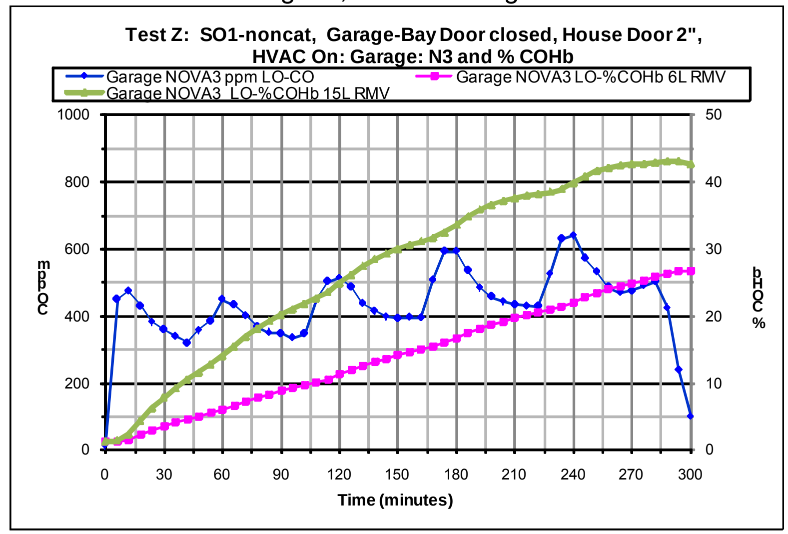


Fig. 4b, Test Z: FAM

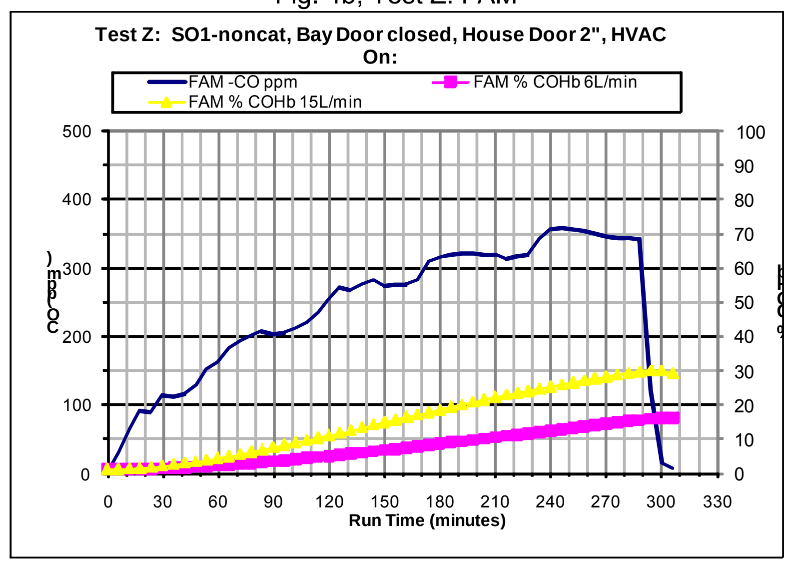


Fig. 3b(ii), Test I: FAM

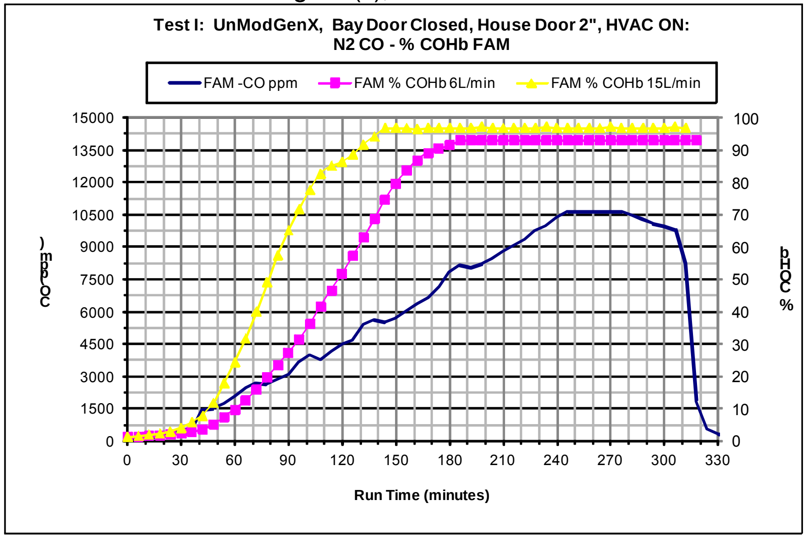


Fig. 3c(ii), Test I: MBR

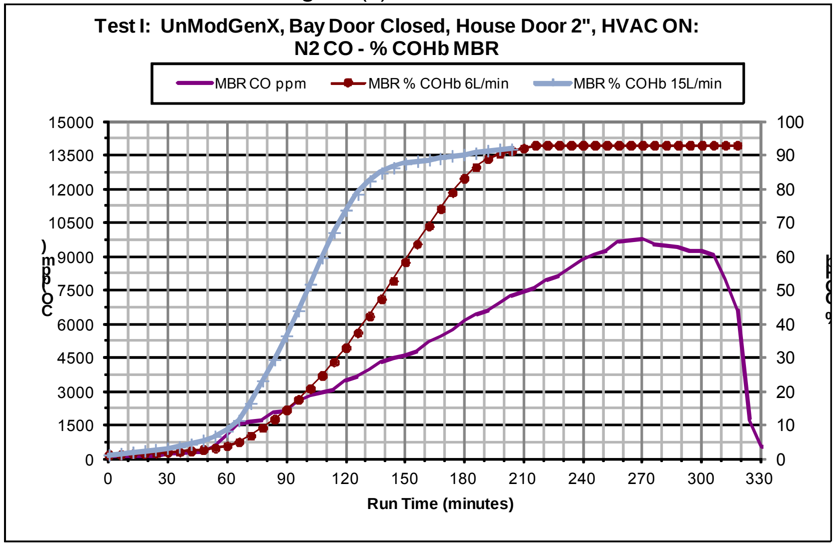


Fig 3c(i), Test I: MBR

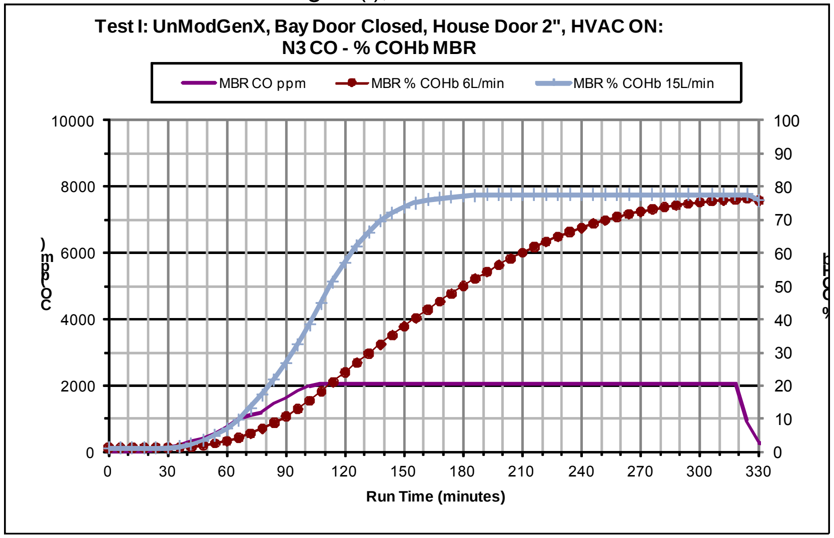


Fig. 4c, Test Z: MBR

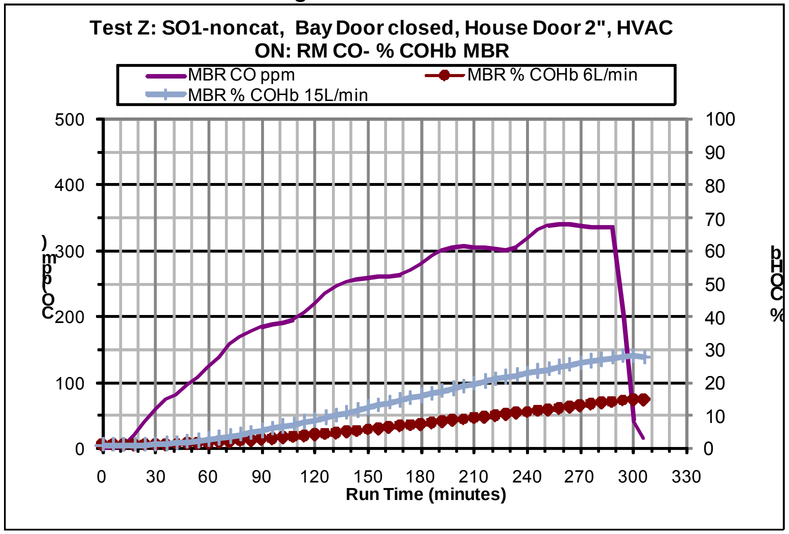


FIg. 5a, Test D: Garage

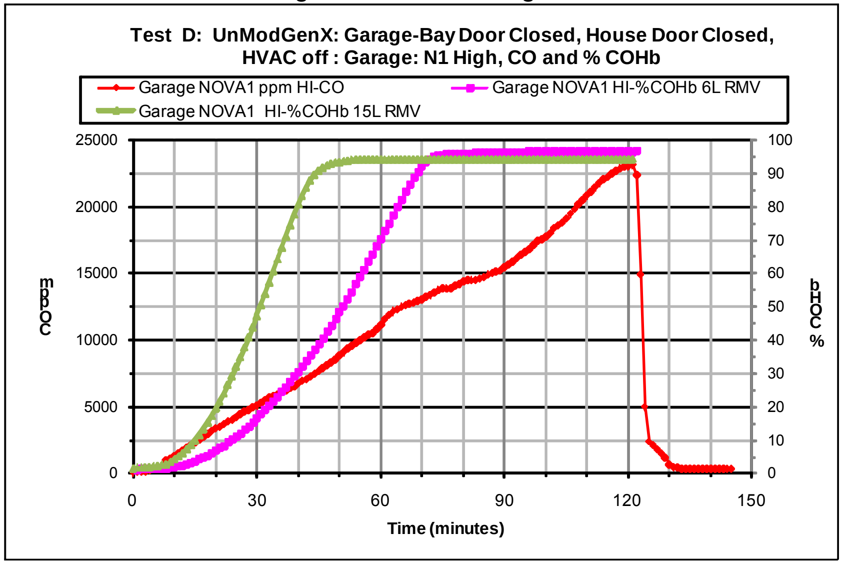


Fig. 6a, Test AH: Garage

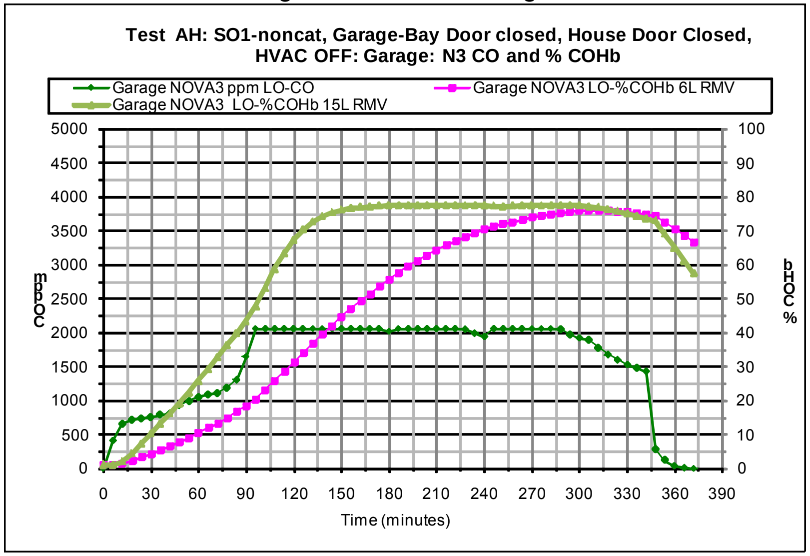


Fig. 5b, Test D FAM

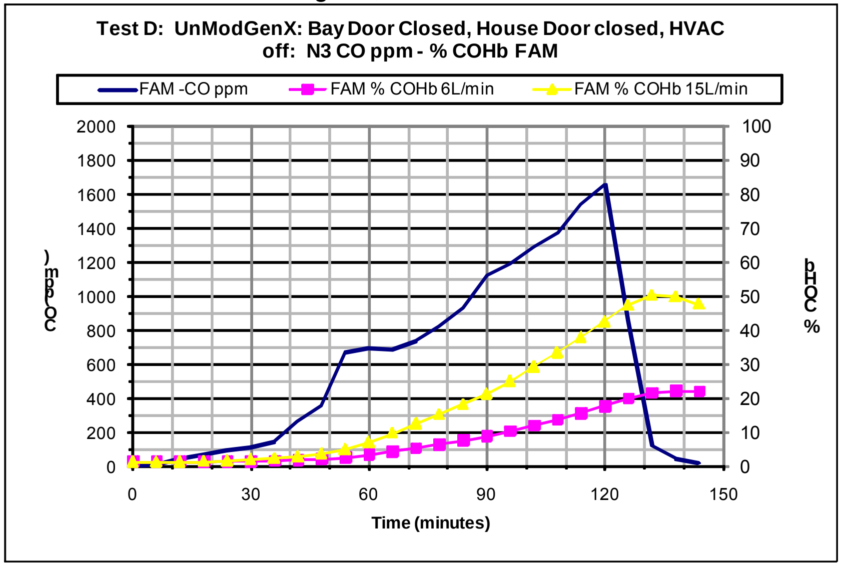


Fig. 6b, Test AH: FAM

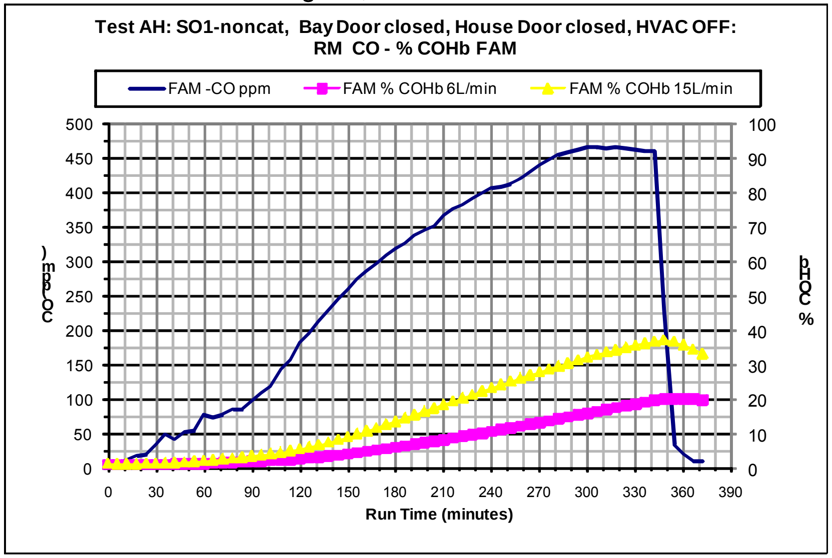


Fig. 5c, Test D: MBR

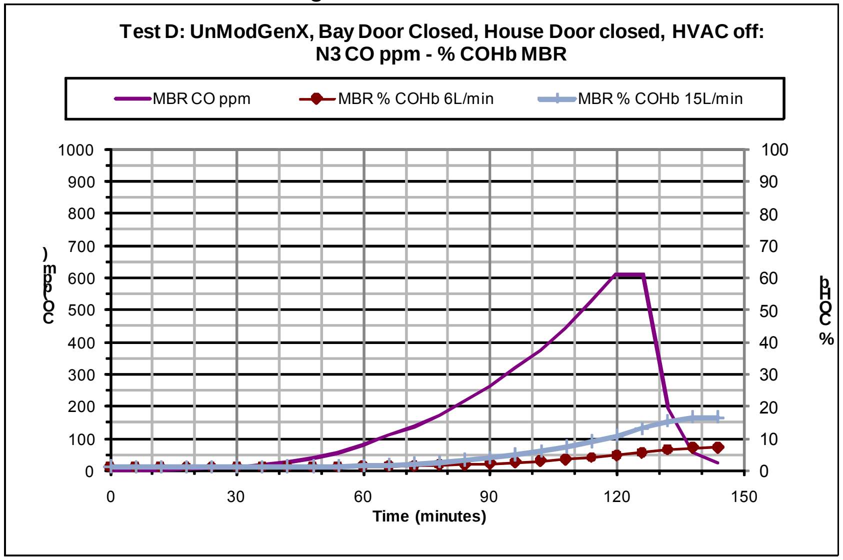


Fig. 6c, Test AH: MBR

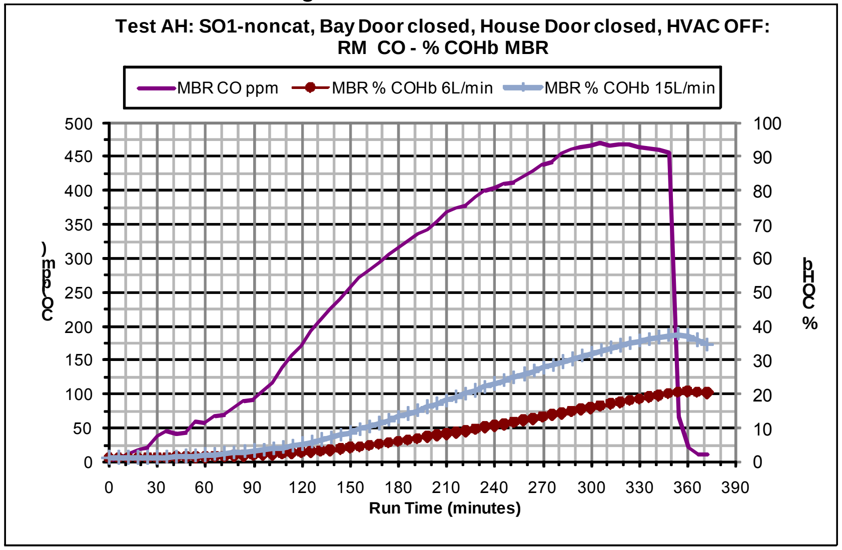


Fig. 7a, Test J: Garage

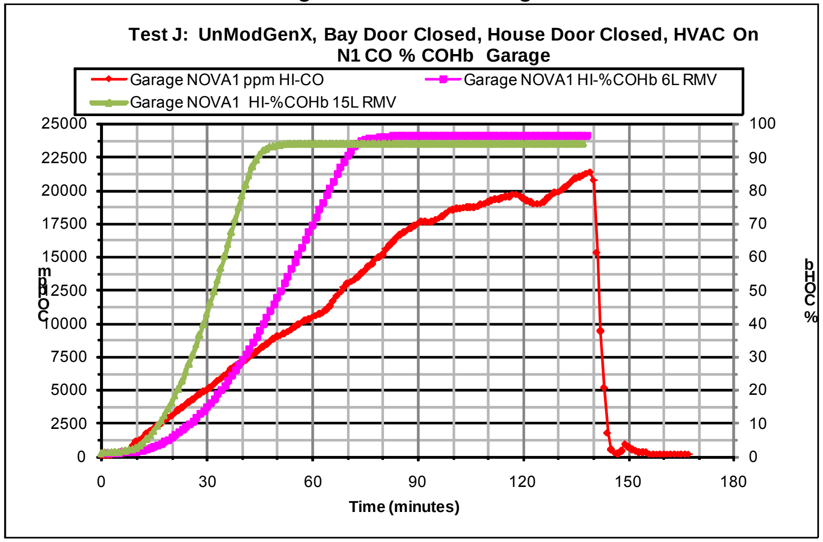


Fig. 8a, Test W: Garage

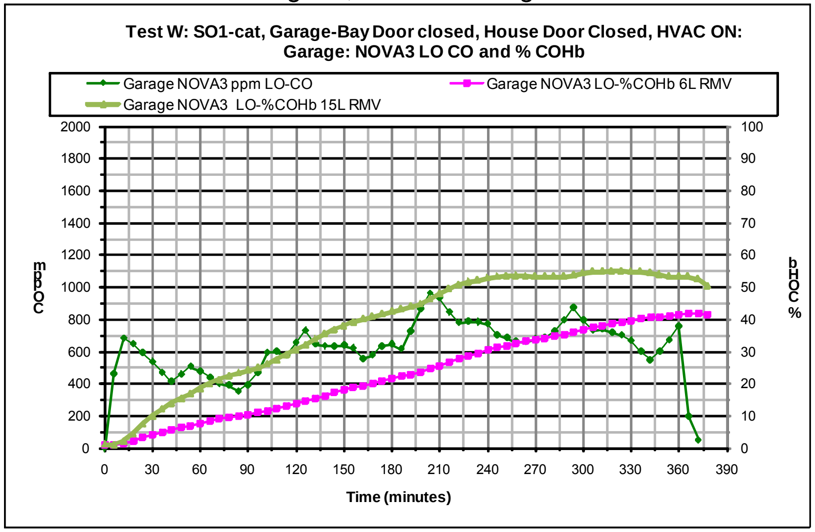


Fig. 7b, Test J FAM

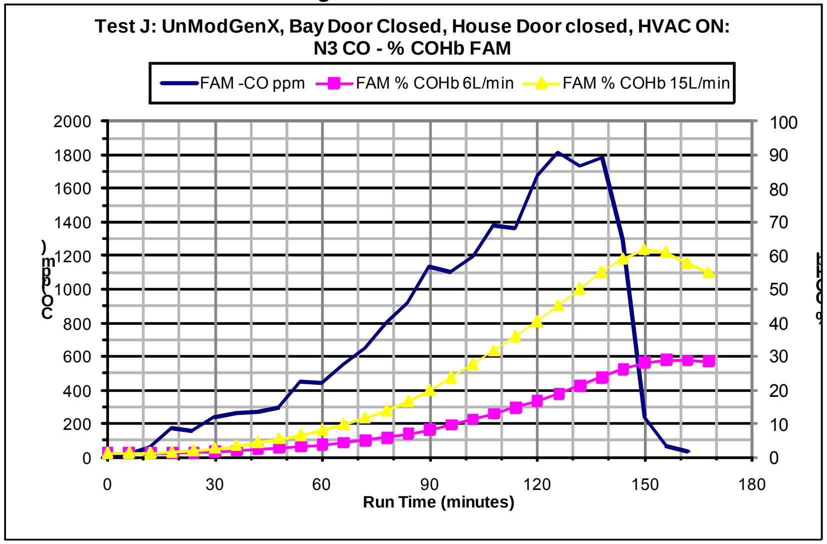


Fig. 8b, Test W: FAM

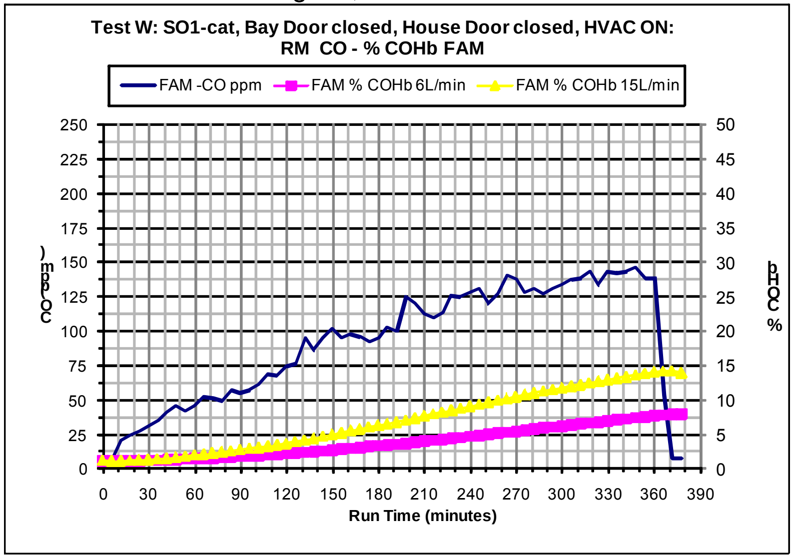


FIg. 7c, Test J: MBR

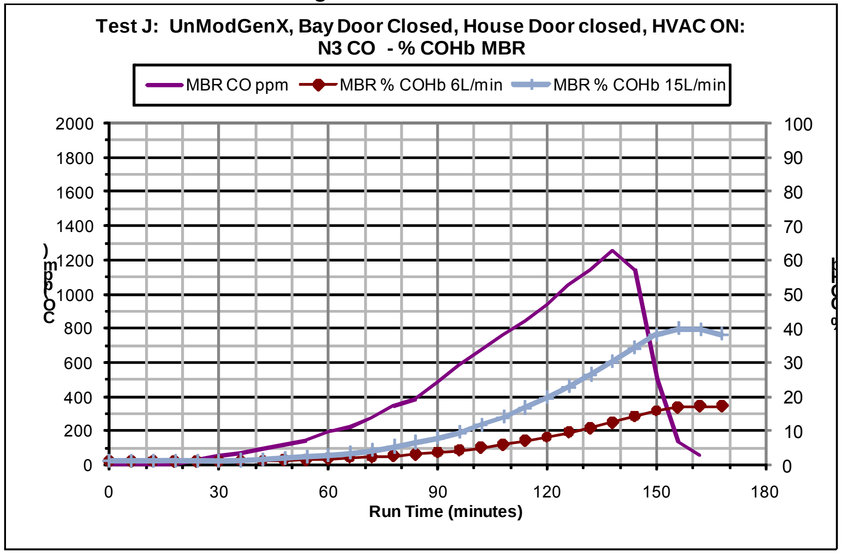


Fig. 8c, Test W: MBR

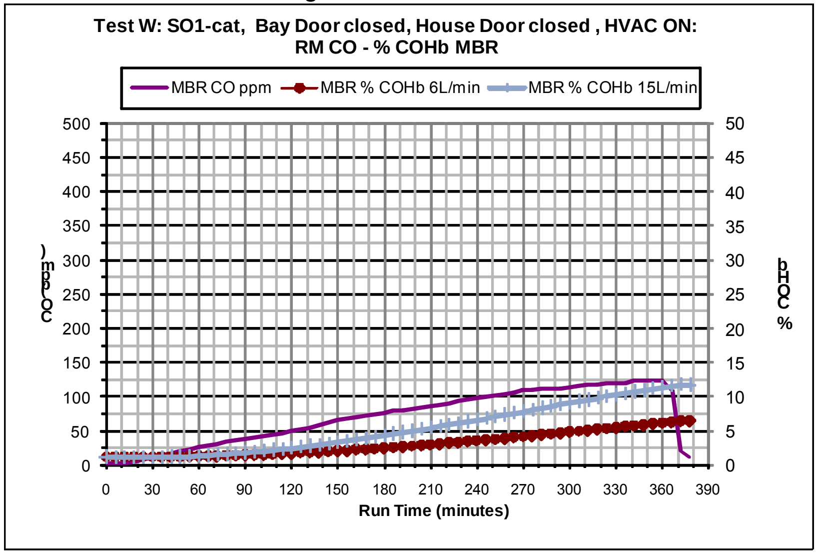


Fig. 9a, Test K: Garage

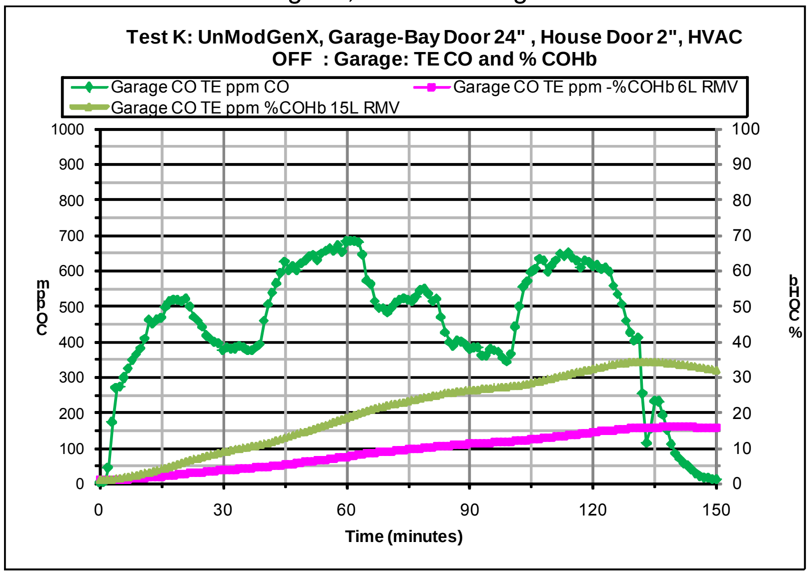


Fig. 10a, Test V: Garage

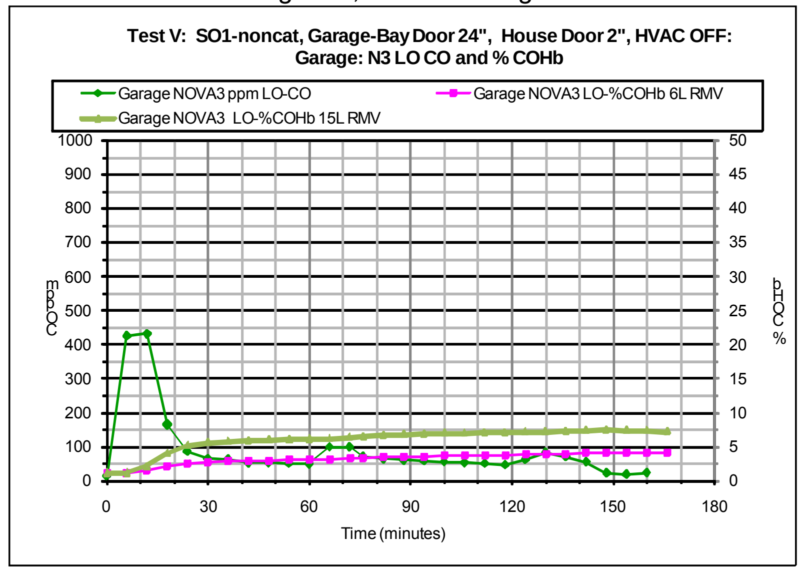


Fig. 9b, Test K FAM

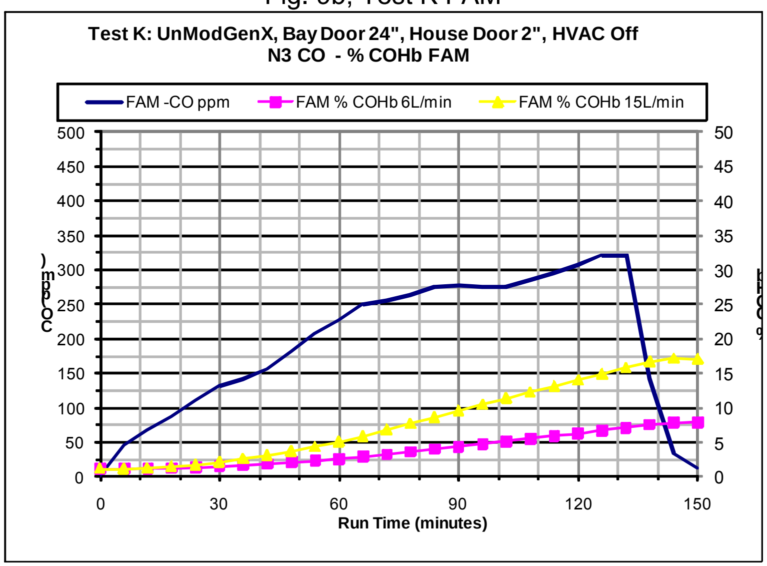


Fig. 10b, Test V: FAM

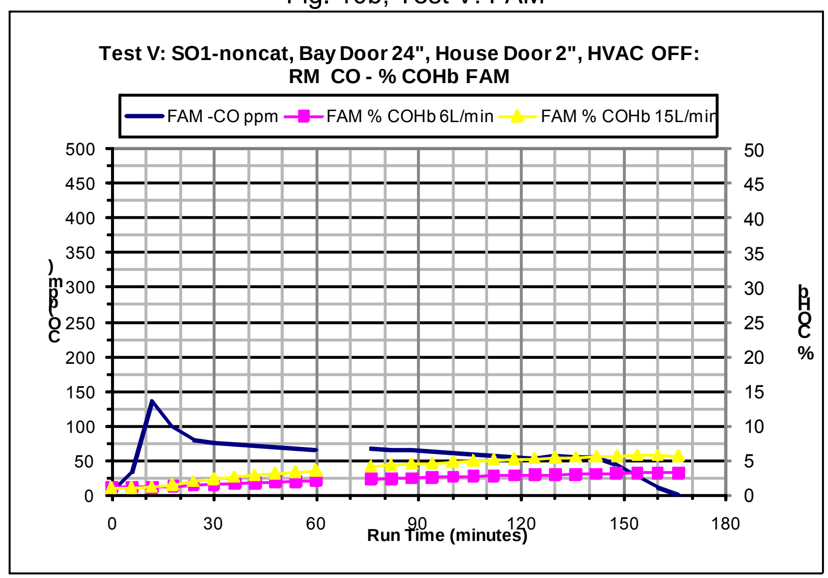


FIg. 9c, Test K: MBR

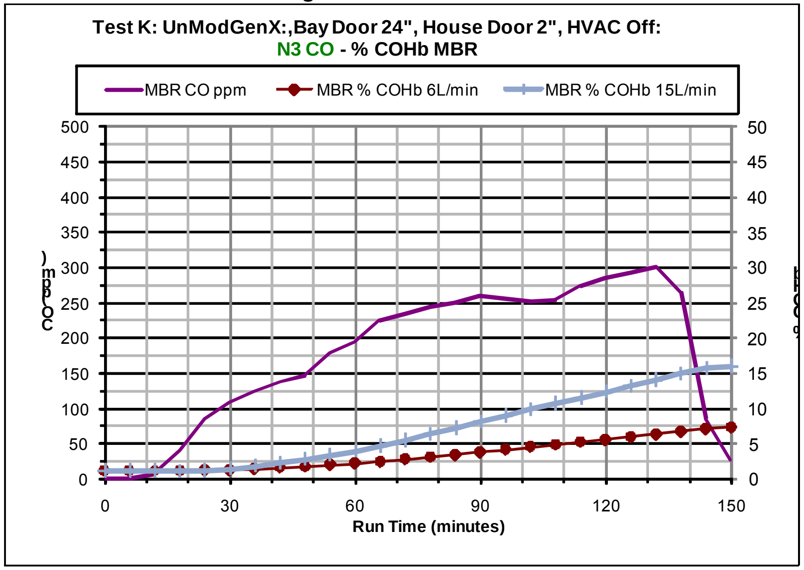


Fig. 10c, Test V: MBR

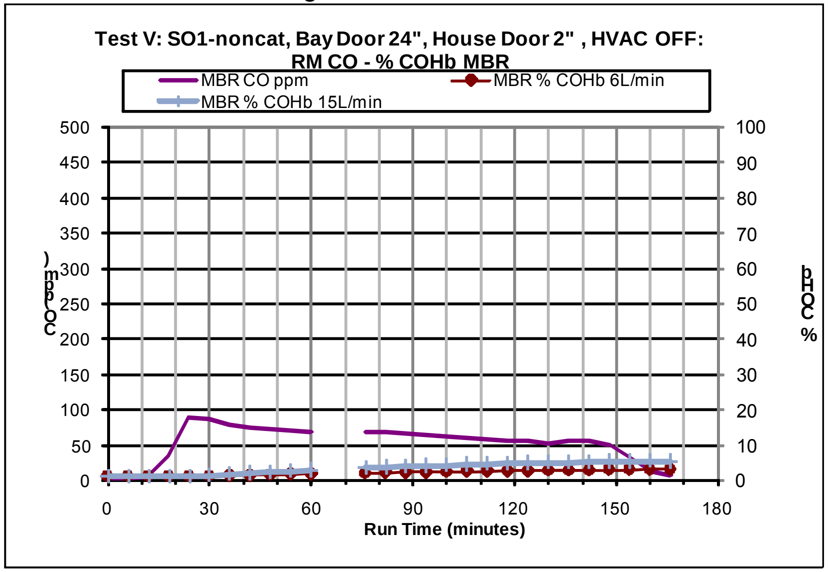


Fig. 11a, Test G: Garage

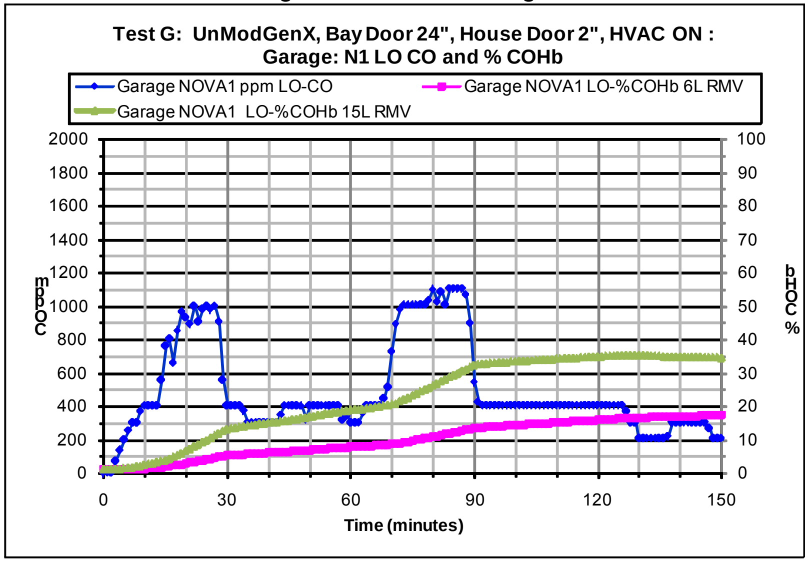


Fig. 12a, Test U: Garage

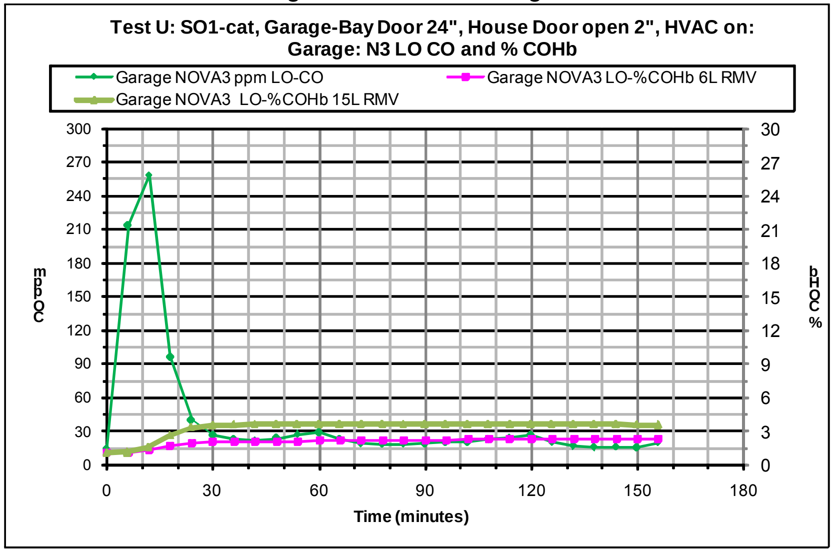
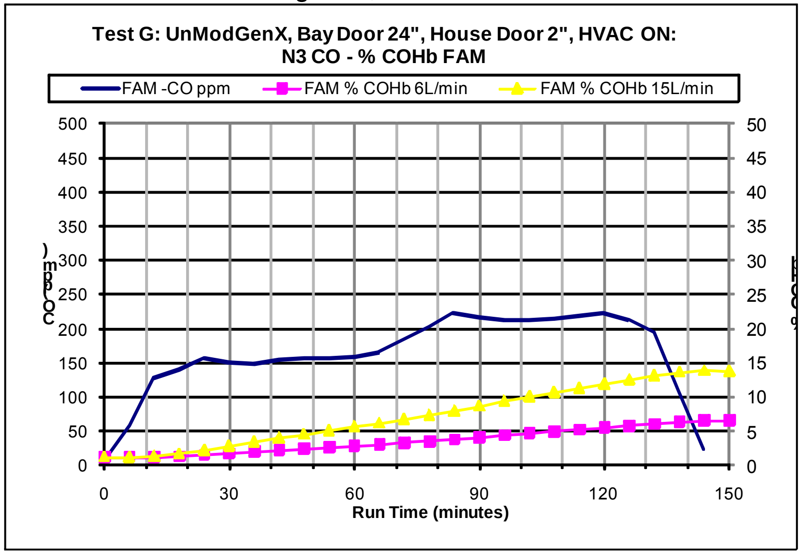


Fig. 11b, Test G FAM



Fig, 12b, Test U, FAM

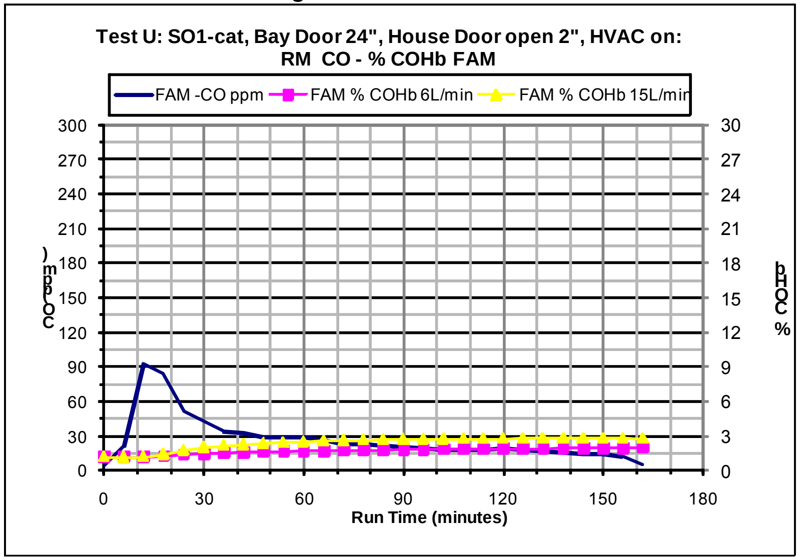


Fig. 12b, Test G: MBR:

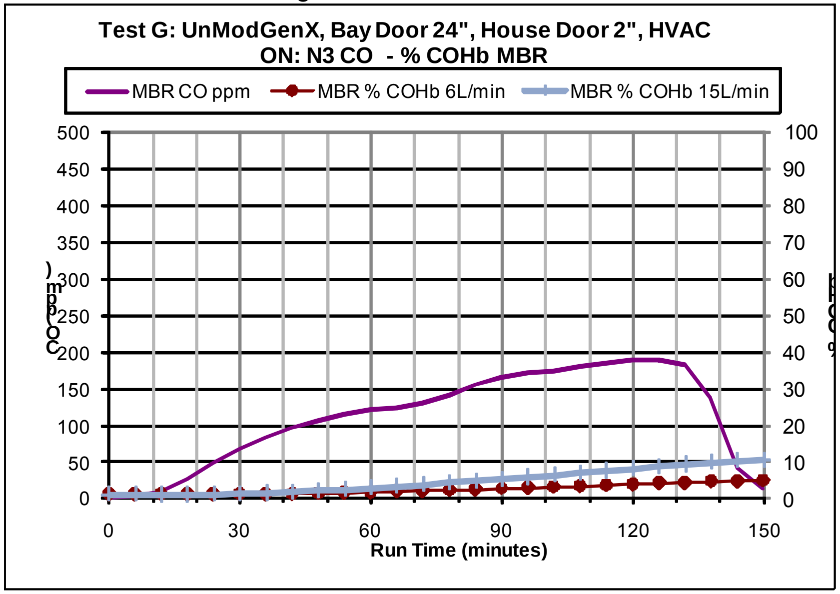


Fig. 12c, Test U: MBR

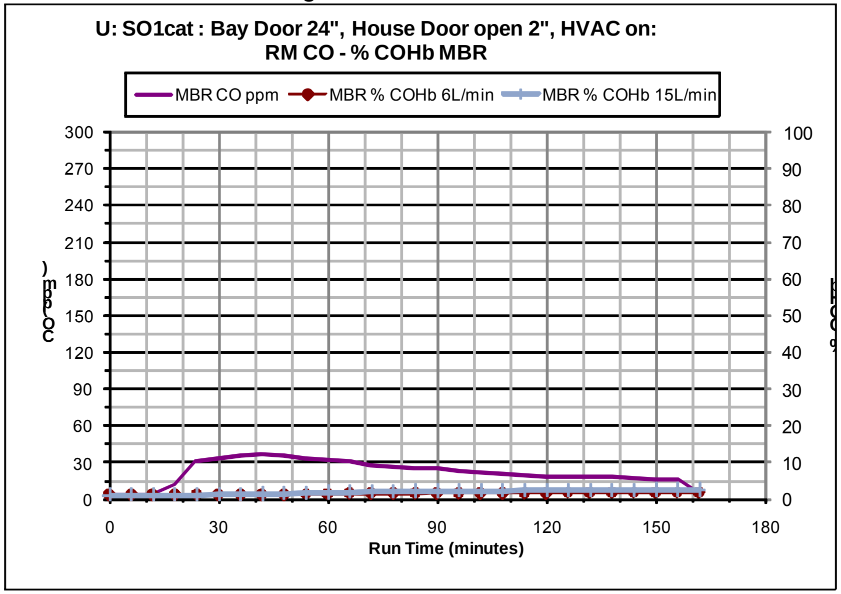


Fig. 13a, Test F: Garage

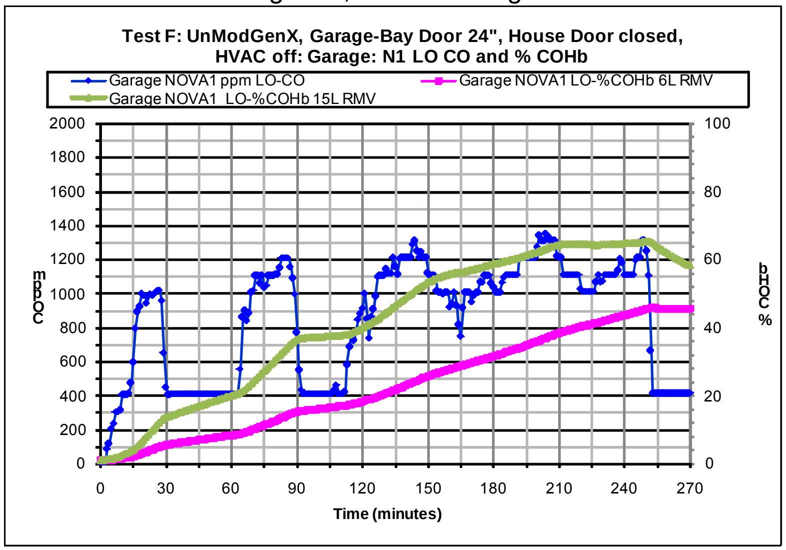


Fig. 14a, Test T: Garage

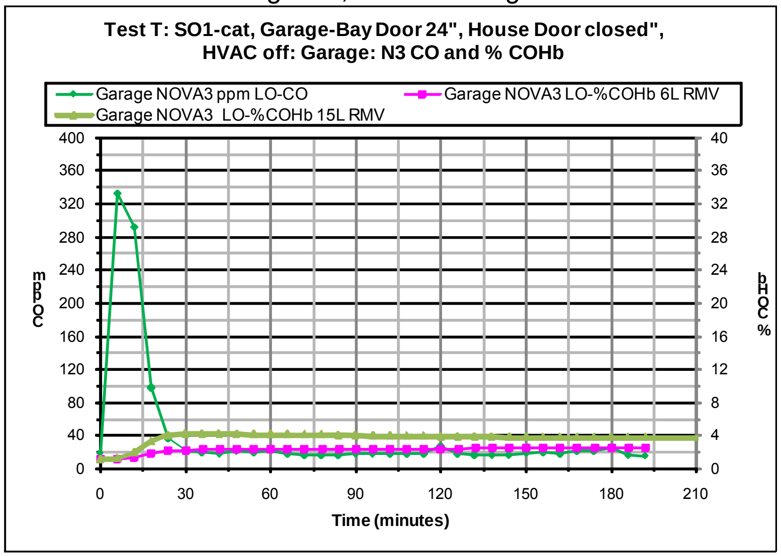


Fig. 13b, Test F FAM

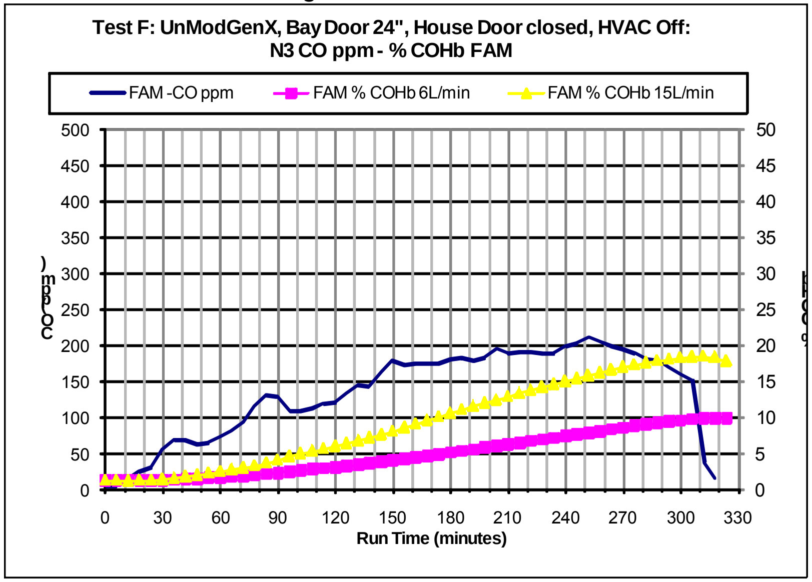


Fig. 14b, Test T: FAM

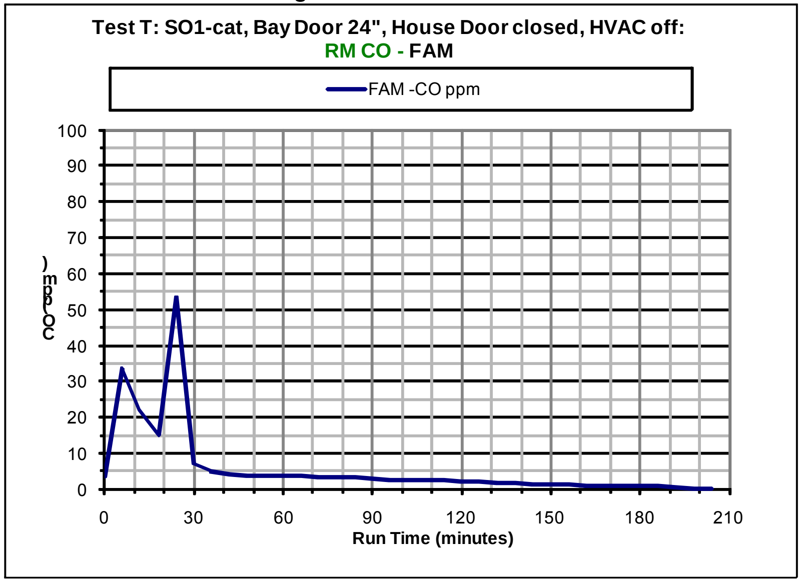


FIg. 13c, Test F: MBR

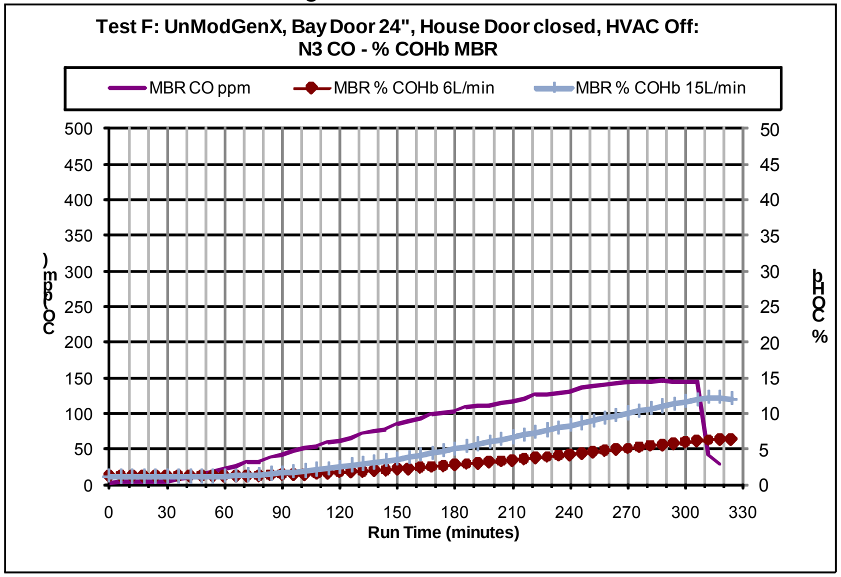


Fig. 14c, Test T: MBR