NIST Technical Note 1834

Development of a Test Method to Determine Carbon Monoxide Emission Rates from Portable Generators

Steven J. Emmerich
Andrew K. Persily

http://dx.doi.org/10.6028/NIST.TN.1834

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

This publication is available free of charge from: http://dx.doi.org/10.6028/NIST.TN.1834

NIST Technical Note 1834

Development of a Test Method to Determine Carbon Monoxide Emission Rates from Portable Generators

Steven J. Emmerich
Andrew K. Persily
Energy and Environment Division
Engineering Laboratory

This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.TN.1834

August 2014

U.S. Department of Commerce
Penny Pritzker, Secretary

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

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

National Institute of Standards and Technology Technical Note 1834
Natl. Inst. Stand. Technol. Tech. Note 1834, 28 pages (August 2014)
CODEN: NTNOEF

This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.TN.1834

ABSTRACT
The U.S. Consumer Product Safety Commission (CPSC) staff is considering developing a performance standard to address the hazard of acute residential carbon monoxide (CO) exposures from portable gasoline engine-powered generators that result in death or serious and/or lasting adverse health effects in exposed individuals. As of April 23, 2013, the CPSC databases contain records of at least 739 deaths (in 552 incidents) from CO poisoning caused by consumer use of a generator in the period of 1999 through 2012. There were an additional 61 CO poisoning deaths (in 45 incidents) involving consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 800 CO poisoning deaths (in 597 incidents) involving generators for the same 14-year period. The vast majority of these deaths occur when consumers use a generator in an enclosed space. A small percentage occurs when the consumer uses the generator outdoors near an opening, such as an open window, which allows the exhaust to enter the building.

The CPSC is working to reduce the occurrence of future generator-related CO poisoning incidents, especially those associated with operating a generator in an enclosed space. To that end, the CPSC issued an *Advance Notice of Proposed Rulemaking; Request for Comments and Information* in 2006 describing its strategy to reduce generator engine CO emission rates. If the CPSC is to issue such a rule, it will need to include a test method for determining CO emission rates from portable generators while operating in an enclosed space. This report describes work performed to support the development of such a test method as well as the draft test method.

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

TABLE OF CONTENTS

1. INTRODUCTION

The U.S. Consumer Product Safety Commission (CPSC) and others are concerned about the hazard of acute residential carbon monoxide (CO) exposures from portable gasoline-powered generators, which can result in death or serious adverse health effects in exposed individuals. As of April 23, 2013, the CPSC databases contain records of at least 739 deaths (in 552 incidents) from CO poisoning caused by consumer use of a generator in the period of 1999 through 2012 (Hnatov 2013). There were an additional 61 CO poisoning deaths (in 45 incidents) involving consumer use of both a generator and at least one other CO-producing consumer appliance, for a total of 800 CO poisoning deaths (in 597 incidents) involving generators for the same 14-year period. The vast majority of these deaths occur when consumers use a generator in an enclosed space. A small percentage occurs when the consumer uses the generator outdoors near an opening, such as an open window, which allows the exhaust to enter the building. Avoiding the operation of such generators in or near homes would reduce indoor CO exposures significantly. The CPSC has regulations that require packaging and on-product warning labels for portable generators that state, in part, the use of a generator in an enclosed space can ‘kill you in minutes’, and never to use a generator inside a home or garage, even if doors and windows are open. This mandatory labeling for portable generators was established in 2007. However, consumers continue to operate generators in enclosed or partially enclosed spaces and near partially open doors and windows, and therefore fatalities continue to occur.

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

The issue of how CO emission rates relate to occupant exposure involves the interaction between generator operation, house characteristics, occupant activity, and weather conditions. In order to support life-safety based analyses of potential CO emission limits for generators, a computer simulation study was conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate (Persily et al. 2013). That simulation study employed the multizone airflow and contaminant transport model CONTAM (Walton and Dols 2005), which was applied to a collection of 87 dwellings that are representative of the U.S. housing stock. A total of almost one-hundred thousand individual 24-hour simulations were conducted that cover a range of house layouts and sizes, airtightness levels and weather conditions, as well as generator locations and CO source strengths. The locations include attached garages and basements, in the houses that have such spaces, and an interior room in all of the houses considered. The results of the simulations were summarized as frequency distributions of maximum carboxyhemoglobin levels in the occupied zones of the simulated homes.

The CPSC is working to reduce the occurrence of future generator-related CO poisoning incidents, especially those associated with operating a generator in an enclosed space. To that end, the CPSC issued an *Advance Notice of Proposed Rulemaking; Request for Comments and Information* in 2006 describing its strategy to reduce generator engine CO emission rates. If the CPSC is to issue such a rule, it will need to include a test method for determining CO emission rates from portable generators operating in an enclosed space. Such a test method needs to consider the fact that when portable generators are operated in an enclosed space with inadequate combustion air supply, the combustion process can be affected, resulting in increased CO generation. This report describes work performed to support the development of such a test method, as well as other information needed to support the development of a *Notice of Proposed Rulemaking.* The report is organized around three main tasks of this effort:

- a literature review of technical publications and standards to identify material that would be useful in developing a test method for measuring CO emissions from portable generators,
- the development of a draft test method to perform generator emission rate tests in a chamber at reduced oxygen level,
- and an estimate of the fraction of CO that is emitted by a generator outdoors and may enter a house.

The draft test method itself is included in Appendix B of this report.

2. LITERATURE REVIEW

As an initial step in this effort, a literature review of technical publications and standards was performed to identify material that would be useful in developing a test method for measuring CO emissions from portable generators. This review was conducted with the support of NIST Research Library staff, as well as through the authors' familiarity with the subject matter. This section discusses information that was identified which is relevant to the determination of CO emission rates from portable generators operating in an enclosed space. This review was used to identify relevant test procedures, equipment specifications, and test conditions (such as test enclosure volume, air temperature, pressure, and relative humidity) that will likely be needed by the CPSC in the development of a proposed rule. The documents identified in the literature are listed in Appendix A of this report.

2.1 Literature

Other than recent work conducted by NIST for CPSC (Emmerich et al. 2013 and Persily et al. 2013), no other research efforts were identified that were directly relevant to the development of test methods for CO emissions from portable generators. However, three studies of interest are discussed here. The first is a study of emissions from kerosene space heaters (Carteret et al. 2012). Of note is the chamber volume used, 8 m^3, and the air change rates employed, about 3 h^{-1} to 25 h^{-1}. As discussed later in this report, the question of chamber volume and air change are important to the development of a test method for portable generators. Priest et al. (2000) reported on a study of emissions from lawnmowers in an 8 m^3 shed. While this paper does not discuss the control or measurement of air change rates, the authors report measured CO emission rates in g/h. The third study involved emissions tests of a number of combustion devices (a kerosene lamp, an oil lamp, a kerosene space heater, a portable gas range, and four unscented candles) in a room, including CO emissions (Fan, C.-W. and J. Zhang 2001). The protocol used in that study and the results obtained are of interest though not directly relevant to testing portable generators.

Several other studies were identified in the literature review that were far less relevant to the current effort for a number of reasons. For example, some reported CO concentrations but not emission rates, did not report air change rates, measured emissions on a dynamometer but not in a chamber, or focused on combustion devices other than generators or small engines. Others were extremely outdated or focused on unrelated issues such as concentration measurement methods and effects of fuel blends.

2.2 Existing standards

The review also examined existing standards relevant to the determination of CO emissions from portable generators. Four such standards were identified. The U.S. Environmental Protection Agency (EPA) has test procedures for measuring emissions from engines (40 CFR part 1065), which are focused on emissions to ambient air. In these procedures, the engines are installed on a dynamometer with combustion air supplied at ambient oxygen levels. Therefore the test results do not apply to indoor operation with reduced oxygen. Also, engine operation and emissions are different when the engine is installed in a generator and a load is imposed. The State of California also has an engine emissions test method for lawn and garden equipment engines (CA 1995), but these tests are also conducted on a dynamometer at ambient oxygen.

The American National Standards Institute (ANSI) standard for portable gas camp heaters (ANSI Z21.63-2000) is also of interest. These tests are conducted in a 2.8 m^3 chamber with air change rates of about 1 h^{-1}. The test does not yield a CO emission rate however; instead it limits the measured CO concentration in the chamber to 114 mg/m^3. ANSI Z21.11.2-2013 applies to gas-fired room heaters and covers a range of performance issues including shutdown devices, pilot operation and pressure regulation. It does contain a limit on CO in a room with no ventilation, but not an emission rate limit.

The Portable Generator Manufacturers' Association (PGMA) has a standard for testing portable generators (G200). This standard covers a range of performance issues, including electrical output, but does not include CO emission rates. However, the testing that is done as part of this standard is conducted with a constant supply of ambient air.

2.3 Summary

While the literature review identified some interesting material in the context of developing a test method for measuring CO emissions from portable generators, it did not yield anything of direct relevance. The standards reviewed are of interest primarily in terms of format and their approaches to quality control.

3. DRAFT TEST METHOD

This section discusses the draft test method to perform generator CO emission rate tests in a chamber at reduced oxygen levels. The draft test method is included in Appendix B of this report. The test method was developed based on the experience gained from past CPSC and NIST testing of portable generators (as described in Brown 2006 and 2008 and Emmerich et al. 2013) in indoor environments ranging from a 10 m^3 chamber to a 90 m^3 test house garage. These tests demonstrated that the CO emissions from portable generators can increase dramatically as O_2 levels decrease from ambient conditions to as low as 17 %. Therefore a critical element of the test procedure is the necessity of achieving reduced O_2 levels low enough and for a sufficient length of time to determine the CO emissions under such conditions. Beyond this critical feature, the draft test method provides flexibility in terms of chamber type and size, ventilation rate, and measurement equipment within limitations of achieving reasonable measurement accuracy.

3.1 Discussion of Test Method

The draft test method in Appendix B consists of a main body, which describes the required equipment and test procedures to be followed to perform generator emission rate tests in a chamber at a reduced oxygen level, and an appendix with guidance on selecting the chamber size and ventilation rate. It is important to note that carbon monoxide is a poisonous gas and that appropriate safety measures need to be taken, but this test procedure does not cover the safety measures.

The main body of the draft test method includes four main sections: Equipment, Experimental Set-up Verification, Test Procedure and Calculation Procedures. The equipment section contains requirements for the test chamber, chamber ventilation fan and measurement of ventilation rate, gas concentration analyzers, air temperature and humidity sensors, electric load bank and power measurement, and generator fuel and lubricants.

The chamber size and ventilation rate are not specified to allow flexibility, but they must be chosen so as to achieve the reduced O_2 levels specified in Section C of the test procedures. The appropriate chamber size and ventilation rate will depend on the generator being tested and the load setting for a given test. The test method appendix provides guidance on selecting an initial chamber size and ventilation rate based on the O_2 consumption rate of the generator at the load setting. However, since the O_2 consumption may not be known in advance, a methodology is included that may be used to estimate that value based only on the load setting. This estimation methodology is derived from the results of previous testing by NIST and CPSC. If the initial test does not yield the required O_2 levels in Section C, an O_2 consumption rate may be calculated from the initial test to determine an appropriate adjustment to the ventilation rate or chamber size.

The experimental set-up verification section addresses verifying proper performance of test equipment including calibration, determination of chamber volume, and verification of gas concentration uniformity in the test chamber. Mixing in the test chamber is expected to be driven by the generator engine heat and exhaust, as such, it is considered sufficient to evaluate it once for each chamber volume, ventilation rate and generator loading combination. Supplemental mixing fans may be used if necessary to meet the uniformity requirements.

The test procedure section includes 9 steps which should be performed for each of two load settings for each generator being tested. The required load settings are 100 % and 50 % of the generator's rated continuous output at ambient oxygen and standard temperature and pressure conditions. Steps 1 through 5 describe setting up equipment, setting test conditions and warming up the generator prior to starting the generator for the emission test itself (Step 6). Step 7 describes the requirements for the reduced O_2 level to be reached for a test to be considered valid. The O_2 level must decrease below 18.5 % but cannot decrease below 17.5 % in less than 30 minutes. If the O_2 level does not decrease sufficiently or decreases too quickly, the test should be repeated with a different ventilation rate or chamber volume. An exception is provided for partial load tests at generator load settings below 1 kW. Steps 8 and 9 contain additional requirements for repeating tests due to either generator or instrumentation malfunction. If the test endpoint is not reached due to generator stalling or dropping the load, the test can be restarted no more than four times. There is no limit on test restarts due to instrumentation failure.

The calculation procedures section includes the equation used to calculate the CO emission rate for the test. The equation is based on a single zone mass balance equation. A sample calculation is included to demonstrate the application of the equation.

4. ESTIMATE OF CO ENTRY FROM OPERATION OF GENERATOR OUTDOORS

This section describes an analysis performed to estimate the potential fraction of CO emitted by a generator operated outdoors that may enter a house. An estimate of this fraction may be needed to evaluate an acceptable continuous operation CO emission rate for a generator which is designed with a shut-off mechanism to prevent indoor operation, but which may still be operated outdoors but near enough to a house such that CO entry is of potential concern. Since 2001, 16 portable generator related CO poisoning deaths occurred in cases where generators were operated outside the home (which does not include deaths that occurred when the generator was outside other structures, such as a boat, trailer, or temporary shelter) – usually near an open window or vent (Hnatov 2013). Additionally, the U.S. Centers for Disease Control has estimated that up to half of non-fatal CO poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within seven feet of the home (CDC 2006).

Wang and Emmerich (2010) and Wang et al. (2013) presented a study of the entry of CO from a generator exhaust into a one-story house and two-story house, respectively, by numerical simulation. A matrix of simulation scenarios was use to consider multiple factors contributing to the CO entry, e.g., generator location, exhaust temperature, exhaust speed, exhaust direction, window opening size, wind, temperature, house dimensions, and generator distance from the house. The transient indoor CO profiles were modeled using the CONTAM indoor air quality model (Walton and Dols 2005) integrated with computational fluid dynamics (CFD) models, CFD0 (Wang 2007) and FDS (McGrattan et al. 2010). These CFD models were used to predict outdoor CO dispersion near the house.

While those studies predicted CO concentrations indoors resulting from outdoor operation of a generator for a wide variety of scenarios, they did not directly examine the question of the fraction of the CO emitted outdoors that entered the houses. The approach used here is to examine the worst case from the previous modeled scenarios (i.e., the case that resulted in the highest indoor CO concentration of the cases simulated but not the worst case that is possible in actual usage), and then to perform CONTAM simulations to determine an indoor CO source that results in approximately equal indoor CO concentrations.

As seen in Figure 1 below (Figure 8 of Wang et al. 2010), the highest peak indoor CO concentration occurred for Case 1, which corresponds to the generator being located 1.8 m upwind from a two-story house, exhaust pointing toward the house, and a wind speed of 1 m/s. All cases considered indoor and outdoor temperatures constant at 20.9 °C, a single window with a 0.31 m^2 opening and the generator operating for 8 hours with a CO generation rate of 1000 g/h. Case 1 resulted in a peak CO concentration in the kitchen (the room with the open window) of about 9200 mg/m^3 after 8 hours. A CONTAM simulation with a generator operating in the kitchen with a constant CO emission rate of 350 g/h (under otherwise similar ambient conditions) resulted in a peak CO concentration of about 9100 mg/m3 after 8 hours, thus indicating that approximately 35 % of the CO emitted by the outdoor generator entered the house for this case.

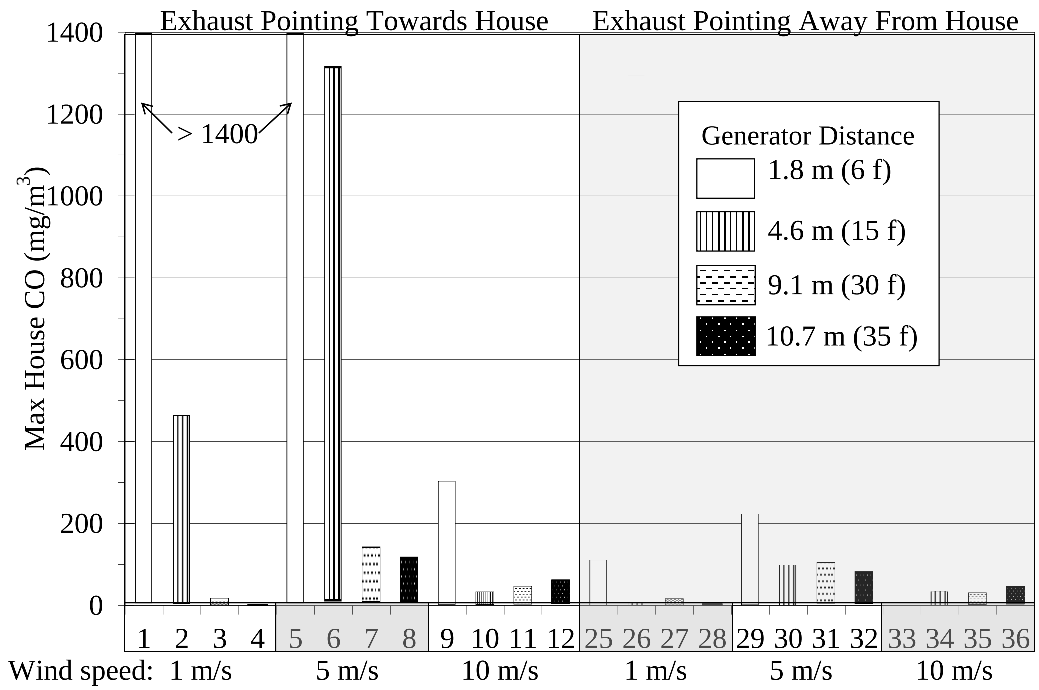

Figure 1. Maximum indoor CO in the house when the generator operated upwind of the house for 8 hours under zero indoor and outdoor temperature difference (Figure 8 of Wang et al. 2010). Notes: Numbers below bars are case numbers. Case 1 concentration reached 9200 mg/m^3.

5. SUMMARY

The CPSC is working to reduce the occurrence of future generator-related CO poisoning incidents, especially those associated with operating a generator in an enclosed space. To that end, the CPSC issued an *Advance Notice of Proposed Rulemaking; Request for Comments and Information* in 2006 describing its strategy to reduce generator engine CO emission rates. If the CPSC is to issue such a rule, it will need to include a test method for determining CO emission rates from portable generators operating in an enclosed space. This report described work intended to support the development of such a test method as well as other information needed to support the development of a *Notice of Proposed Rulemaking.*

6. ACKNOWLEDGEMENTS

This work was funded by the U.S. Consumer Product Safety Commission under interagency agreement No. CPSC-I-13-0012. The authors wish to express their appreciation for the support of Janet Buyer, Susan Bathalon, and Matt Brookman in conducting this effort. Stacy Bruss of the NIST Library assisted in conducting the literature search.

7. REFERENCES

ANSI. 2000. Z21.63-2000 Portable Type Gas Camp Heaters. ANSI.

ANSI. 2013. Z21.11.2-2013 Gas-fired room heaters, volume II, unvented room heaters. ANSI.

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

Brown CJ. 2008. *Engine-Driven Tools, Phase 2 Test Report: Portable Generator Equipped with a Safety Shutoff Device*, U.S. Consumer Product Safety Commission.

CA. 1995. California Exhaust Emission Standards and Test Procedures for 1995 and Later Utility and Lawn and Garden Equipment Engines. State of California Air Resources Board.

Carteret, M., Pauwels, JF and B Hanoune. 2012. "Emission factors of gaseous pollutants from recent kerosene space heaters and fuels available in France in 2010." Indoor Air 22(4): 299-308.

CDC. 2006. Carbon monoxide poisonings after two major hurricanes - Alabama and Texas, August - October 2005. Morbidity and Mortality Weekly Report (MMWR), United States Centers for Disease Control and Prevention: 4.

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

EPA. 2012. 40 CFR Part 1065 Engine Testing Procedures. U.S. EPA.

Fan, C-W and J Zhang. 2001. "Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures." Atmospheric Environment 35(7): 1281-1290.

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

McGrattan K, McDermott R, Hostikka S, and J. Floyd. 2010. *Fire Dynamics Simulator (Version 5) User's Guide*. National Institute of Standards and Technology.

Persily, AK, Wang, Y, Polidoro, B and SJ Emmerich. 2013. *Residential Carbon Monoxide Exposure due to Indoor Generator Operation: Effects of Source Location and Emission Rate*. NIST Technical Note 1782.

Priest, MW, Williams, DJ and HA Bridgman. 2000. "Emissions from in-use lawn-mowers in Australia." Atmospheric Environment 34(4): 657-664.

PGMA. 2013. G200, Standard for Testing and Validating Performance of Portable Generators. Portable Generator Manufacturers' Association.

Walton, GN and WS Dols. 2005. CONTAMW 2.4 User Guide and Program Documentation. NISTIR 7251. Gaithersburg, MD, USA, National Institute of Standards and Technology: 286.

Wang, L. 2007. Coupling of multizone and CFD programs for building airflow and contaminant transport simulations. Mechanical Engineering. Purdue University. PhD: 271.

Wang, L and SJ Emmerich. 2009. *Modeling the effects of outdoor gasoline powered generator use on indoor carbon monoxide exposures*. NIST Technical Note 1637.

Wang, L, Emmerich, SJ, and R Powell, R. 2010. *Modeling the effects of outdoor gasoline powered generator use on indoor carbon monoxide exposures – Phase II.* NIST Technical Note 1666.

Wang, L and SJ Emmerich. 2010. Modeling the effects of outdoor gasoline powered generator use on indoor carbon monoxide exposures. Building Simulation, Vol 3(1).

Wang, L, Emmerich, SJ, and C-C Lin. 2013. Study of the Impact of Operation Distance of Outdoor Portable Generators under Different Weather Conditions. Indoor and Built Environment.

APPENDIX A: Literature Review Bibliography

This appendix contains a bibliography of the results of the literature search described in Section 2 in the form of the references for the publications considered as well as the abstract of each.

Bresenham, D. and J. Reisel (1999). The Effect of High Ethanol Blends on Emissions from Small Utility Engines. Warrendale, PA, SAE International.
Emissions of total hydrocarbons, carbon monoxide, nitrogen oxides, and combined hydrocarbons and nitrogen oxides from small utility engines were used to judge the effect of ethanol addition (zero to 50 %vol) to a hydrocarbon fuel with factory air- fuel ratio carburetor settings. In this study, emissions from two 4-stroke 9.3 kW (12.5 hp) side-valve engines and one 4-stroke 9.3 kW (12.5 hp) overhead valve engine were assessed to support conclusions. Emissions differences due to the differing valve orientations were addressed as a secondary objective. A series of RBOB plus ethanol (EtOH) fuel blends were used in this parametric study. RBOB is the base fuel in which oxygenates are blended to produce reformulated gasoline (RFG) for use in Clean Air Act Amendments-designated Ozone Non-attainment Areas. RBOB+EtOH fuel blend (an oxygenated fuel) emissions were compared to RBOB (a nonoxygenated fuel) emissions to assess the effect of ethanol addition on emissions. The RBOB+10%EtOH fuel blend is similar to one of the fuel blends currently used in Ozone Non- attainment Areas (a slightly higher oxygen content) while the higher ethanol fuel blends in this study provide insight into the behavior of air emission as the ethanol concentration is increased beyond current levels of oxygenate addition mandates. The fuel blends ranged from RBOB+0%EtOH to RBOB+50%EtOH.The emissions were measured by a 5-gas analyzer which measures total hydrocarbons, carbon monoxide, nitrogen oxides, oxygen, and carbon dioxide. EPA small engine test procedures were followed. The fuel flow method option was chosen as is the practice of small engine manufacturers. A method to deduce the air-fuel ratio from the fuel characteristics (carbon fraction and hydrogen fraction) and emissions was introduced by R. S. Spindt for conventional (nonoxygenated) fuels in 1965. This study uses a modified Spindt Method to accommodate highly oxygenated fuels developed in a related study for use with this engine and fuel set. The Spindt method technique allows estimation of the actual (operating) air-fuel ratio from exhaust constituents. With the actual air-fuel ratio, the data may be assessed in terms of the equivalence ratio. By using the equivalence ratio, emissions from engines operating on varying oxygenate content fuels may be directly compared since the varying stoichiometric air-fuel ratios are stabilized.The primary results indicate that increasing the concentration of ethanol in gasoline is effective in reducing regulated carbon monoxide emissions from small engines designed to operate on nonoxygenated fuels but ineffective in reducing regulated combined hydrocarbon and nitrogen oxide emissions. This result has implications on one small engine emissions reduction strategy~blending a specialized "lawn and garden"" highly oxygenated fuel for delivery through alternative distribution outlets.The secondary results indicate evidence that the overhead- valve technology engine exhibits lower hydrocarbon and carbon monoxide emissions characteristics but has no discernible effect on nitrogen oxides and negligible effect on combined hydrocarbon and nitrogen oxides emissions. This result has implications on another small engine emissions reduction strategy~the shift from side-valve engines to overhead-valve engines in small engine applications.

Carteret, M., et al. (2012). "Emission factors of gaseous pollutants from recent kerosene space heaters and fuels available in France in 2010." Indoor Air 22(4): 299-308.
Laboratory measurements of the gaseous emission factors (EF) from two recent kerosene space heaters (wick and injector) with five different fuels have been conducted in an 8-m^3 environmental chamber. The two heaters tested were found to emit mainly CO_2, CO, NO, NO_2, and some volatile organic compounds (VOCs). NO_2 is continuously emitted during use, with an EF of 100–450 μg per g of consumed fuel. CO is normally emitted mainly during the first minutes of use (up to 3 mg/g). Formaldehyde and benzene EFs were quantified at 15 and 16 μg/g, respectively, for the wick heater. Some other VOCs, such as 1,3-butadiene, were detected with lower EFs. We demonstrated the unsuitability of a 'biofuel' containing fatty acid methyl esters for use with the wick heater, and that the accumulation of soot on the same heater, whatever the fuel, leads to a dramatic increase in the CO EF, up to 16 mg/g, which could be responsible for chronic and acute CO intoxications. Practical Implications Our results show that in spite of new technologies and emission standards for unvented kerosene space heaters, as well as for the fuels, the use of these heaters in indoor environments still leads to NOx levels in excess of current health recommendations. Whereas injection heaters generate more nitrogen oxides than wick heaters, prolonged use of the latter leads to a soot buildup, concomitant with high CO emissions, which could be responsible for acute and chronic intoxications. The use of a biofuel in a wick heater is also of concern. Maintenance of the heaters and adequate ventilation of the room during use of kerosene space heaters are therefore of prime importance to reduce personal exposure.

Christensen, A., et al. (2001). "Measurement of Regulated and Unregulated Exhaust Emissions from a Lawn Mower with and without an Oxidizing Catalyst: A Comparison of Two Different Fuels." Environmental Science & Technology **35**(11): 2166-2170.
Relatively few emission characterization studies have been made on small engines used in garden equipment. The present investigation focuses on exhaust characterization from a lawn mower engine fueled with two different fuels in combination with and without an oxidizing catalyst. The compounds measured in the exhaust are carbon monoxide, hydrocarbons, nitrogen oxides, particulates, polycyclic aromatic hydrocarbons, methane, ethane, ethene, ethanol, and nitrous oxide. A significant reduction can be achieved by the use of a catalyst. By selection of the fuel, a significant reduction of certain carcinogenic compounds ("probably carcinogenic to humans" according to the IARC; benzo[a]pyrene and benzo[a]anthracene) may be achieved. The highest reduction improvement is achieved through the combination of an environmentally improved fuel, i.e., alkylate fuel, and a catalyst system. The data presented show that emissions from lawn mower engines are still relatively large although there is the potential for further improvements.

Dernotte, J., et al. (2009). "Evaluation of Butanol–Gasoline Blends in a Port Fuel-injection, Spark-Ignition Engine." Oil & Gas Science and Technology – Revue de l'Institut Français du Pétrole **65**(2): 345-351.
This paper assesses different butanol–gasoline blends used in a port fuel-injection, spark-ignition

engine to quantify the influence of butanol addition on the emission of unburned hydrocarbons, carbon monoxide, and nitrogen oxide. Furthermore, in-cylinder pressure was measured to quantify combustion stability and to compare the ignition delay and fully developed turbulent combustion phases as given by 0 %–10 % and 10 %–90 % Mass Fraction Burned (MFB). The main findings are: 1) a 40 % butanol/60 % gasoline blend by volume (B40) minimizes HC emissions; 2) no significant change in NOx emissions were observed, with the exception of the 80 % butanol/20 % gasoline blend; 3) the addition of butanol improves combustion stability as measured by the COV of IMEP; 4) butanol added to gasoline reduces ignition delay (0 %–10 % MFB); and 5) the specific fuel consumption of B40 blend is within 10% of that of pure gasoline for stoichiometric mixture.

Dutton, S. J., et al. (2001). "Indoor Pollutant Levels from the Use of Unvented Natural Gas Fireplaces in Boulder, Colorado." Journal of the Air & Waste Management Association (Air & Waste Management Association) **51**(12): 1654-1661.
High CO and NO_2 concentrations have been documented in homes with unvented combustion appliances, such as natural gas fireplaces. In addition, polycyclic aromatic hydrocarbons (PAH) are emitted from incomplete natural gas combustion. The acute health risks of CO and NO_2 exposure have been well established for the general population and for certain high-risk groups, including infants, the elderly, and people with heart disease or asthma. Health effects from PAH exposure are less well known, but may include increased risk of cancer. We monitored CO emissions during the operation of unvented natural gas fireplaces in two residences in Boulder, CO, at various times between 1997 and 2000. During 1999, we expanded our tests to include measurements of NO_2 and PAH. Results show significant pollutant accumulation indoors when the fireplaces were used for extended periods of time. In one case, CO concentrations greater than 100 ppm accumulated in under 2 hr of operation; a person at rest exposed for 10 hr to this environment would get a mild case of CO poisoning with an estimated 10 % carboxyhemoglobin level. Appreciable NO_2 concentrations were also detected, with a 4-hr time average reaching 0.36 ppm. Similar time-average total PAH concentrations reached 35 ng/m^3. The results of this study provide preliminary insights to potential indoor air quality problems in homes operating unvented natural gas fireplaces in Boulder.

Eccleston, B. H. and R. W. Hurn (1972). Exhaust Emissions from Small, Utility, Internal Combustion Engines. Warrendale, PA, SAE International.
This material reports findings of an exploratory experimental study designed to add information on the contribution to air pollution of exhaust emissions from small, utility engines, and to evaluate the procedures used to test small engines. Gross measurements of hydrocarbon, carbon monoxide, and nitric oxide are reported for 29 4-cycle and 7 2-cycle engines; sizes of the engines ranged 2-22 hp. Emissions measurements were made on each engine for nine combinations of load and air-fuel adjustments; only one speed point~full governed~was covered in the tests. Test procedures are described. An overall average of the data indicate that, operated at full-load and optimum air-fuel ratio, the four-cycle engines emitted about 8 g HC, 180 g CO, and 5 g NO_2 per horsepower-hour. Under comparable conditions, the 3-6 hp two-cycle engines emitted an average of 140 g HC, 240 g CO, and 2 g NO_2 per horsepower-hour.

Fan, C.-W. and J. Zhang (2001). "Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures." Atmospheric Environment **35**(7): 1281-1290.
A series of source tests were conducted to characterize emissions of particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and total hydrocarbon (THC) from five types of portable combustion devices. Tested combustion devices included a kerosene lamp, an oil lamp, a kerosene space heater, a portable gas range, and four unscented candles. All tests were conducted either in a well-mixed chamber or a well-mixed room, which enables us to determine emission rates and emission factors using a single-compartment mass balance model. Particle mass concentrations and number concentrations were measured using a nephelometric particle monitor and an eight-channel optical particle counter, respectively. Real-time CO concentrations were measured with an electrochemical sensor CO monitor. CO_2, CH_4, and THC were measured using a GC-FID technique. The results indicate that all particles emitted during steady burning in each of the tested devices were smaller than 1.0 μm in diameter with the vast majority in the range between 0.1 and 0.3 μm. The PM mass emission rates and emission factors for the tested devices ranged from 5.6±0.1 to 142.3±40.8 mg h^{-1} and from 0.35±0.06 to 9.04±4.0 mg g^{-1}, respectively. The CO emission rates and emission factors ranged from 4.7±3.0 to 226.7±100 mg h^{-1} and from 0.25±0.12 to 1.56±0.7 mg g^{-1}, respectively. The CO_2 emission rates and emission factors ranged from 5500±700 to 210,000±90,000 mg h^{-1} and from 387±45 to 1689±640 mg g^{-1}, respectively. The contributions of CH_4 and THC to emission inventories are expected to be insignificant due both to the small emission factors and to the relatively small quantity of fuel consumed by these portable devices. An exposure scenario analysis indicates that every-day use of the kerosene lamp in a village house can generate fine PM exposures easily exceeding the US promulgated NAAQS for PM2.5.

Francisco, P. W., et al. (2010). "Measured concentrations of combustion gases from the use of unvented gas fireplaces." Indoor Air **20**(5): 370-379.
Measurements of combustion product concentrations were taken in 30 homes where unvented gas fireplaces were used. Measurements of CO, CO_2, NOx, NO_2, O_2 (depletion), and water vapor were taken at 1-min interval. The analyzers were calibrated with certified calibration gases for each placement and were in operation for 3–4 days at each home. Measured concentrations were compared to published health-based standards and guidelines. The two combustion gases that exceeded published values were NO_2 and CO. For NO_2, the Health Canada guideline of 250 ppb (1-h average) was exceeded in about 43 % of the sample and the World Health Organization (WHO) guideline of 110 ppb (1-h average) was exceeded in 80 % of the sample. Carbon monoxide levels exceeded the U.S. EPA 8-h average standard of 9 ppm in 20 % of the sample. Moisture problems were not evident in the test homes. An analysis of the distribution of CO showed that the CO is dispersed throughout the home almost immediately upon operation of the fireplace and that the concentrations throughout the home away from the immediate vicinity of the fireplace are 70–80 % of the level near the fireplace. Decay analysis of the combustion gases showed that NO was similarly stable to CO and CO_2 in the indoor environment but that both NO_2 and water vapor were removed from the air at much greater rates. Practical Implications Previous

studies on unvented gas fireplaces have made assumptions of how they are operated by users. This article presents the results of field monitoring of 30 unvented gas fireplaces under normal operation, regardless of whether users follow industry recommendations regarding installation, usage patterns, and maintenance. The monitoring found that health-based standards and guidelines were exceeded for CO in 20 % of homes and for NO_2 in most homes. There were no identified moisture problems in these homes. Nearly, half of the fireplaces were used at least once for longer than 2 h, counter to manufacturers' intended usage as supplemental heating. This demonstrates that given actual usage patterns and compared to current health-based thresholds, these appliances can produce indoor air concentrations considered to be unhealthy to at least sensitive or at-risk individuals.

Gabele, P. (1997). "Exhaust Emissions from Four-Stroke Lawn Mower Engines." Journal of the Air & Waste Management Association **47**(9): 945-952.
Emissions were characterized from 10 four-stroke lawn mower engines. The ages of the engines ranged from new to 15 years, and each was tested using two gasoline fuels: a 1990 national average blend and a reformulated gasoline. Reformulated gasoline usage resulted in lower organic and carbon monoxide emissions that contributed to lower reactivity-weighted emission rates. Aggregate toxic emissions were also reduced because benzene emissions were lower. On the other hand, increases in nitrogen oxide emission rates were observed with the reformulated gasoline. Compared to the newer engines, older engines had dramatically higher organic and carbon monoxide and lower nitrogen oxide emissions.

Gautam, A. S., et al. (2012). A Comparison of the Emissions from Gasoline vs. Compressed Natural Gas for an Electronic Fuel Injected Two Cylinder, Four-Stroke Engine. Warrendale, PA, SAE International.
Natural gas is a viable alternative to gasoline and diesel fuel because it is a clean burning fuel that is available from a large domestic reserve through a mature infrastructure. The heavy dependence of the small engine sector on oil, much of which is imported from foreign countries and the small engine sector's negative impact on the air quality in urban areas are two pervasive problems that can be helped by using Compressed Natural Gas (CNG) as a small engine fuel. In addition, CNG is typically over 80 % methane, which is produced by the decay of organic material, so while natural gas is not renewable its use enables much of the infrastructure required for a methane-based renewable energy system.

Guo, L., et al. (2008). "Emissions from Irish domestic fireplaces and their impact on indoor air quality when used as supplementary heating source." Global NEST Journal **10**(2): 209-216.
A field study on the impact of fireplace on the indoor air quality was carried out between 2004 and 2006, where two main contaminants, CO and particulate matters, were investigated in twenty seven randomly selected Irish houses. The results show that while the physical environment has been improved by increasing the room air and radiant temperature, indoor air quality is significantly decreased when fireplace is used as additional heating source to the central heating. The operation of fireplace increased transient concentrations of CO and airborne particle to several times higher than the normal house average level. Statistical analysis showed significant

difference of the average PM10 concentration between house groups with and without using fireplace. However fireplace did not demonstrate a significant influence on average CO level from our samples. When comparisons were made between houses with various emission sources, i.e. fireplace, smoking and open fire gas cooking, and houses free of the above sources, smoking and open fire gas cookers were proved to be other major sources of particles and CO. Particularly when they exist at the same time with fireplace, significant elevation of CO and airborne particle levels is observed in analysis. Cumulative probability analysis in some houses revealed high percentage of time exceeding health guidelines which indicated the potential health risk in these houses. Mass balance equation was employed to estimate particle emission rates from fireplace, namely 0.66 mg min^{-1} (PM10) and 0.20 mg min^{-1} (PM2.5) respectively in terms of mass concentration. Emission rates on particle numbers were also estimated despite the relatively smaller sample. Gas fuel fireplaces tended to emit fewer particles both in mass and in number comparing to fireplaces using solid fuels.

Jetter, J. J., et al. (2002). "Characterization of emissions from burning incense." Science of The Total Environment **295**(1–3): 51-67.
The primary objective of this study was to improve the characterization of particulate matter emissions from burning incense. Emissions of particulate matter were measured for 23 different types of incense using a cyclone/filter method. Emission rates for PM2.5 (particulate matter less than 2.5 μm in aerodynamic diameter) ranged from 7 to 202 mg/h, and PM2.5 emission factors ranged from 5 to 56 mg/g of incense burned. Emission rates were also determined using an electrical low pressure impactor (ELPI) and a small electrostatic precipitator (ESP), and emission rates were compared to those determined using the cyclone/filter method. Emission rates determined by the ELPI method were consistently lower than those determined by the cyclone/filter method, and a linear regression correlation was found between emission rates determined by the two methods. Emission rates determined by the ESP method were consistently higher than those determined by the cyclone/filter method, indicating that the ESP may be a more effective method for measuring semivolatile particle emissions. A linear regression correlation was also found between emission rates determined by the ESP and cyclone/filter methods. Particle size distributions were measured with the ELPI, and distributions were found to be similar for most types of incense that were tested. Size distributions by mass typically ranged from approximately 0.06 to 2.5 μm in aerodynamic diameter, with peak values between 0.26 and 0.65 μm. Results indicated that burning incense emits fine particulate matter in large quantities compared to other indoor sources. An indoor air quality model showed that indoor concentrations of PM2.5 can far exceed the outdoor concentrations specified by the US EPA's National Ambient Air Quality Standards (NAAQS), so incense smoke can pose a health risk to people due to inhalation exposure of particulate matter. Emissions of carbon monoxide (CO), nitric oxide (NO), and sulfur dioxide (SO2) were also measured for seven types of incense. Emission rates of the gaseous pollutants were sufficient to cause indoor concentrations, estimated using the indoor air quality model, to exceed the outdoor concentrations specified by the NAAQS under certain conditions. However, the incense samples that were tested would fill a room with thick smoke under these conditions.

Leigh-Smith, S. (2004). "Carbon Monoxide Poisoning in Tents—A Review." Wilderness & Environmental Medicine **15**(3): 157-163.
This review discusses the overlooked problem of carbon monoxide (CO) poisoning within small tents. It summarizes previous case reports, reviews the toxicity of CO, and attempts to draw conclusions from experimental work. Finally, practical recommendations are developed on avoiding CO poisoning within tents. The term carbon monoxide was used in a search of the Medline database covering the years 1966 to 2003. The results were combined with the terms atmosphere or camps or stoves or climbs or mountains or tents or poisons. The resulting articles were reviewed, and those relevant to this problem were obtained. Hard copies were hand searched for further relevant articles until no more citations could be found. Three original articles were impossible to obtain but have been cited to assist others seeking to find them. Other data and articles were obtained from the Ministry of Defence but are unpublished for security reasons. samples that were tested would fill a room with thick smoke under these conditions.

Leigh-Smith, S., et al. (2004). "Does Pan Diameter Influence Carbon Monoxide Levels During Heating of Water to Boiling Point With a Camping Stove?" Wilderness & Environmental Medicine **15**(3): 171-174.
Objectives To determine whether pan diameter influences carbon monoxide (CO) concentration during heating of water to boiling point with a camping stove. The hypothesis was that increasing pan diameter increases CO concentration because of greater flame dispersal and a larger flame. *Method* This was a randomized, prospective study. A Coleman Dual Fuel 533 stove was used to heat pans of water to boiling point, with CO concentration monitored every 30 seconds for 5 minutes. The stove was inside a partially ventilated 200-L cardboard box model that was inside an environmental chamber at −6°C. Water temperature, water volume, and flame characteristics were all standardized. Ten trials were performed for each of 2 pan diameters (base diameters of 165 mm [small] and 220 mm [large]). *Results* There was a significant difference ($P = .002$) between the pans for CO levels at each measurement interval from 60 seconds onward. These differences were markedly larger after 90 seconds, with a mean difference of 185 ppm (95 % CI 115, 276 ppm) for all the results from 120 seconds onwards. *Conclusion* This study has shown that there is significantly higher CO production with a large-diameter pan compared with a small-diameter pan. These findings were evident by using a camping stove to heat water to boiling point when a maximum blue flame was present throughout. Thus, in enclosed environments it is recommended that small-diameter pans be used in an attempt to prevent high CO levels.

Palke, D. R. and M. A. Tyo (1999). The Impact of Catalytic Aftertreatment on Particulate Matter Emissions from Small Motorcycles. Warrendale, PA, SAE International.
This paper presents the results of an exploratory study examining the production of particulate matter (PM) by 2-wheel vehicles and the impact of catalytic aftertreatment on these emissions. Information is presented demonstrating the efficacy of catalytic aftertreatment for significantly reducing not only hydrocarbons (HC) and carbon monoxide (CO), but also PM emissions from motorcycles equipped with small 2-stroke engines. The generation of PM by 5 test vehicles during realistic driving conditions is discussed and the impact of catalyst performance characteristics on the reduction of these releases is examined. Vehicle based test data, obtained with a mini-dilution

tunnel, clearly demonstrates the benefits to the environment achievable through the use of catalytic aftertreatment.

Phipps, R., et al. (2006). Not just hot air: Methods and preliminary results for the intensive monitoring of emissions and by-products from two types of domestic heaters, International Society of Indoor Air Quality and Climate. Proceedings of Healthy Buildings 2006
Intensive air quality measurements were made for up to a week in a sample of 33 homes drawn from a 500 home Heating, Housing and Health interventional community trial. Measures include nitrogen dioxide, formaldehyde, carbon monoxide and dioxide, fungi, moisture, temperature and heater usage. Families with an asthmatic child and where their primary means of heating was a plug-in electric or unflued gas heater were enrolled in the trial. Baseline measures were completed in 2005 and in 2006 a randomly selected 250 households will be given a heat pump, flued gas heater or pellet wood fire. All environmental measures will be repeated in 2006.

Priest, M. W., et al. (2000). "Emissions from in-use lawn-mowers in Australia." Atmospheric Environment 34(4): 657-664.
Concern over the levels of pollutants emitted from small engines has led to recent legislation in the United States that regulates exhaust emissions from lawn and garden equipment. Particular attention has focused on the high levels of hydrocarbons emitted by these engines. The present study establishes emission factors for lawn-mowers in use in Australia. The estimates were calculated on the basis of a series of controlled emission tests conducted on commonly used lawn-mowers. Ten two-stroke and six four-stroke lawn-mower engines were operated under simulated power requirements while fuel usage and gas emissions were monitored. Fuel consumption rates from the tests were compared to those ascertained under actual mowing conditions in field tests conducted on 19 two-stroke and ten four-stroke lawn-mowers. Basic emission factors were established for CO, CO_2, CH_4, NMHC and NOx, and combined with data on machine population and annual usage collected in a survey of lawn care practices and lawn-mower usage conducted in the Newcastle area. When compared to transport sources in the Newcastle study region, lawn-mowers contribute 5.2 and 11.6% of CO and NMHC emissions, respectively.

Schwartz, R. B., et al. (2001). "A comparison of carbon monoxide levels during the use of a multi-fuel camp stove." Wilderness & Environmental Medicine **12**(4): 236-238.
Objective The use of camp stoves in an enclosed or poorly ventilated space is clearly not recommended due to the risk of carbon monoxide (CO) poisoning. Instances may arise, however, when use for a limited time is necessary. We sought to find differences in CO levels between various fuels used to power a commercially available camp stove. *Methods* A comparison was made between unleaded gasoline, kerosene, and white gas (Coleman fuel). The stove, fuels, and CO detector were all purchased from local retailers. A 0.4-m^3 space was constructed with a cardboard box. Three trials were performed using each fuel in which water was heated over the stove for 5 minutes. Measurement of the CO level within the box was taken every 30 seconds. *Results* Kerosene created CO levels of 714 (SD = 113.5) parts per million (ppm) at 2 1/2 minutes but was out of the measurable range of >999 ppm within 4 minutes on each of its trials. White gas burned the cleanest, with an average of 212 ppm (SD = 27.8) at 2 1/2 minutes and 348 ppm (SD =

76.0) at 5 minutes. Unleaded gasoline created 305 ppm (SD = 27.1) at 2 1/2 minutes and 464 ppm (SD = 31.6) at 5 minutes. *Conclusion* All of the fuels created a high level of CO in a short period of time. White gas burned the cleanest and would be preferred to unleaded gasoline or kerosene in the event that the unvented use of a camp stove was necessary.

Thomassen, Ø., et al. (2004). "Carbon monoxide poisoning while using a small cooking stove in a tent." The American Journal of Emergency Medicine **22**(3): 204-206.
Carbon monoxide (CO) is formed wherever incomplete combustion of carbonaceous products occurs.(1) CO is the leading cause of poisoning in the United States, and common sources of CO poisoning include housefires, automobile exhaust, water heaters, kerosene space heaters, and furnaces.(2) Stoves used for cooking and heating during outdoor activities also produce significant amounts of CO. Mountain climbers have been reported to succumb to fumes generated by small cook stoves.(3) The aim of this study was to investigate if burning a cooking stove inside a tent is a potential health hazard. Seven healthy male volunteers used a cooking stove inside a small tent for 120 minutes. CO levels in the ambient tent air were measured in addition to hearth rate (HR) and pulse oximetry (SpO2). Venous blood samples were obtained every 15 minutes for measurement of carboxyhemoglobin (COHb). After 2 hours, all the subjects had significant CO levels in their blood (mean COHb = 21.5 %). Mean SpO2, also fell from 98 % to 95.3 % (P <.05), whereas mean HR increased from 63 to 90 beats/min (P <.05). Kerosene camping stoves do produce CO when burned in a small tent. The concentration is high enough to cause significant COHb levels in venous blood after 120 minutes' stay in the tent.

Traynor, G. W., et al. (1985). "Indoor Air Pollution Due to Emissions from Unvented Gas-Fired Space Heaters." Journal of the Air Pollution Control Association **35**(3): 231-237.
Operation of an unvented combustion appliance indoors can elevate pollutant concentrations Under laboratory conditions, oxygen consumption rates and pollutant emission rates of CO, CO_2, NO, NO_2, HCHO and submicron suspended particles emitted from eight unvented gas-fired space heaters operated with well adjusted air shutters at partial and full fuel consumption rates were determined in a 27-m^3 chamber. Emission rates were also determined for some heaters operating under poorly tuned conditions. Four of the eight heaters were subsequently tested in a 240-m^3 research house with 0.36-1.14 air changes per hour. Based on measurements near steady state, steady state pollutant and oxygen levels were projected: 1930-11,100 ppm for CO2, 1.0-26 ppm for CO (under well-tuned conditions), 0.40-1.46 ppm for NO_2, and 19.1-20.7% for O2. Concentrations of CO_2, CO, and NO_2 sometimes exceeded outdoor or occupational guidelines. Analysis showed that CO, NO, and NO_2 emission rates can vary with time and that, while short-term emission rates derived from laboratory tests were consistent with initial emission rates observed in the field, they did not always correspond to steady state emission rates.

Tutupalli, L. V., et al. (1997). Standard test method for the measurement of emissions from the combustion of manufactured fireplace logs in zero-clearance fireplaces, Air & Waste Management Assoc.
A standard test method is developed for measuring emissions from the combustion of manufactured fireplace logs in zero-clearance fireplaces. In order to be reliable and cost effective,

This publication is available free of charge from: http://dx.doi.org/10.6028/NIST.TN.1834

the test method followed the EPA method 5G very closely. However, in addition to the particulate matter, CO measurement is incorporated into the protocol because CO is a criteria pollutant for which there are ambient air quality and indoor level standards. The test method includes automated data collection, and data processing to produce final reports similar to those of the EPA method.

Volckens, J., et al. (2008). "Carbonaceous species emitted from handheld two-stroke engines." Atmospheric Environment **42**(6): 1239-1248.
Small, handheld two-stroke engines used for lawn and garden work (e.g., string trimmers, leaf blowers, etc.) can emit a variety of potentially toxic carbonaceous air pollutants. Yet, the emissions effluents from these machines go largely uncharacterized, constraining the proper development of human exposure estimates, emissions inventories, and climate and air quality models. This study samples and evaluates chemical pollutant emissions from the dynamometer testing of six small, handheld spark-ignition engines—model years 1998–2002. Four oil–gas blends were tested in each engine in duplicate. Emissions of carbon dioxide, carbon monoxide, and gas-phase hydrocarbons were predominant, and the PM emitted was organic matter primarily. An ANOVA model determined that engine type and control tier contributed significantly to emissions variations across all identified compound classes; whereas fuel blend was an insignificant variable accounting for <5% of the observed variation in emissions. Though emissions rates from small engines were generally intermediate in magnitude compared with other gasoline-powered engines, numerous compounds traditionally viewed as motor vehicle markers are also present in small engine emissions in similar relative proportions. Given that small, handheld two-stroke engines used for lawn and garden work account for 5–10 % of total US emissions of CO, CO2, NOx, HC, and PM2.5, source apportionment models and human exposure studies need to consider the effect of these small engines on ambient concentrations in air polluted environments.

Wang, J., et al. (1988). "Remote Measurement of Motorcycle Exhaust Using Fourier Transform Infrared System." Spectroscopy Letters **21**(9-10): 935-946.
We have explored the basic theory and quantitative methods for the measurement of motorcycle exhaust using a Fourier transform infrared interferometer system. Remote sensing direct measurements were made and the species carbon monoxide, carbon dioxide, nonmethane paraffinic carbon(CHx) and unburned additional harmful species in motorcycle exhaust were determined. Typical concentrations observed in absorption for carbon monoxide, carbon dioxide and nonmethane paraffinic carbon were about 1.11 %, 1.91 %, 0.54 % respectively. Furthemore, this paper describes the remote sensing Fourier transform infrared spectrometer system. The system covers the infrared spectral region from 700 to 6000 cin^{-1} at a maxim resolution of 0.06 cm^{-1} for beamsplitter of gerrniuiirun coated zinc selenide and receiver telescope with zinc selriide leis. For air multipollutant monitoring the analytica1 methods have the potential and become important. The remote measurements using the Fourier transform infrared spectroscopy could become more practical.

APPENDIX B: Draft Test Method

Equipment and Test Procedures to Perform Generator Emission Rate Test in a Chamber at Reduced Oxygen Level

Warning: Carbon monoxide is a poisonous gas. Operating an internal combustion engine in a confined space can create an accumulation of carbon monoxide and unburnt hydrocarbons. These procedures are not intended to address the safety concerns associated with their use. Appropriate safety measures need to be taken by those using these procedures before, during, and after testing.

A. Equipment

1. Chamber: Emission tests shall be performed in a single zone test chamber. (Note: The actual chamber size needed will depend on meeting the test requirements of Section C and on the size of the engine that is powering the generator being tested, among other factors. See Appendix 1 for guidance on selecting chamber size and ventilation rate.) The chamber shall be constructed of materials that are non-reactive for the engine exhaust gasses and that are acceptable for use at a sustained temperature of 90 °C (200 °F). The chamber shall be constructed to be sufficiently airtight such that the chamber ventilation fan (see subsection A.2) can maintain a negative pressure differential between the chamber and its surroundings of at least 2.5 Pa at all chamber operating conditions. Mixing fans may be provided as needed to meet the uniformity requirements of Part B below.

2. Chamber ventilation fan and measurement: The chamber shall be ventilated by an exhaust fan capable of providing a range of ventilation rates sufficient to satisfy the requirements of Section C for the generators to be tested. Means shall be provided to measure the chamber ventilation rate with an accuracy of ±5 %. The volumetric airflow rate may be directly measured in the duct of the exhaust fan. Alternatively, the air change rate may be measured using a tracer gas decay test in compliance with ASTM Standard E741-11 *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.*

3. Gas concentration measurement of CO and O_2
   a. Gas concentration measurement equipment shall be provided to measure CO and O_2 gas concentrations with a manufacturer's specified accuracy of 1 % of range. The peak CO concentration during a test must reach at least 25 % of instrument range being used during that test.
   b. Sampling: Gas concentration sample lines shall be made of non-reactive materials and shall be located to enable verification of the uniformity requirements of Part B.3. Particle and water filtration of gas sample lines may be provided to meet the specifications of the CO and O_2 measurement equipment. Note: Ensure that any filters used do not interfere with concentrations of any gases being measured. Gas concentrations shall be measured and recorded at least once per minute.

4. Air temperature and humidity: Air temperature and humidity sensors shall be provided with accuracies of ± 1 °C and ± 5 % RH or better, respectively. Recommended locations are on two opposite walls at the midpoint of the chamber height.

5. Load bank and power meter: An AC electric resistor load bank shall be used to simulate electric loads on the generator. The load bank shall be capable of meeting the generator's rated continuous output at ambient oxygen and standard temperature and pressure conditions. The load bank shall be capable of a load setting that is within 5 % of each specified load condition. The delivered load may decrease during the test, but the load bank setting shall not be adjusted. A power meter shall be provided to measure the actual electrical load delivered by the generator with an accuracy of ± 5 %.

6. Fuel and lubricants: Generators shall be tested with a full tank of fuel. Fuel and lubricants meeting manufacturer's specifications for the generator being tested shall be used.

B. **Experimental Set-up Verification**

1. Calibration: All test equipment shall be calibrated per manufacturer's instructions. Proper operation of test equipment (including a zero and span check with calibrated gas and a leak test of the gas sampling system) shall be verified for each test per manufacturer's instructions.

2. Volume: The chamber volume may be determined by direct measurement if it is a single, unchangeable volume. If the chamber volume is modified, the volume shall be determined in accordance with Appendix X5 of ASTM E741-11 *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*.

3. Gas concentration uniformity: Gas concentrations at representative locations (a minimum of three evenly spaced locations) throughout the chamber shall differ by less than 10 % of the average gas concentration in the chamber. Uniformity shall be verified during testing at least once for each chamber volume, ventilation rate, and generator loading combination.

C. **Test Procedure [Repeat steps 1 through 9 for two load conditions –rated continuous output at ambient oxygen and standard temperature and pressure conditions and 50 % of the generator's rated continuous output at ambient oxygen and standard temperature and pressure conditions.]**

1. Setup and confirm normal instrumentation function per manufacturer's instructions.

2. Establish an initial chamber air temperature of 20 °C ± 10 °C and relative humidity of 50 % ± 15 % RH at start of test. Note: temperature and humidity do not need to be controlled during the test, however, maintaining near ambient temperature conditions during the test may aid in stability and repeatability.

3. Verify initial air concentrations in the chamber and in ventilation air are at ambient conditions (< 5 ppm CO and 20.9 % O_2) within instrument accuracy.

4. Place generator in center of chamber, activate chamber ventilation system, start generator and operate until warm per manufacturer's instructions. Turn off the generator and continue to ventilate the chamber until chamber returns to ambient conditions. The post warm-up chamber ventilation rate can be greater than the test ventilation rate to achieve the desired initial conditions more quickly. The generator may instead be warmed up outside of the chamber.

5. Set test ventilation rate of chamber. See Appendix 1 for guidance on selecting ventilation rate.

6. Start generator and within 2 minutes apply desired setting on load bank.

7. Operate the generator with constant load setting at least 60 minutes and until the equilibrium CO concentration (defined as occurring when the concentration at the end of a 30 minute period is within 10 % of the concentration at the beginning of that 30 minute period) is reached, or for 180 minutes.

    a. If O_2 level decreases below 17.5 % in less than 30 minutes, the test (steps 1 through 7) shall be repeated with a higher ventilation rate (see Appendix 1 for guidance).
    b. If O_2 level does not decrease below 18.5 %, the test (steps 1 through 7) shall be repeated with a lower ventilation rate (see Appendix 1 for guidance).
        i. *Exception*: for partial load settings at or below 1 kW, the test does not need to be repeated if the O_2 level reaches below 19.5 %.
    c. If the temperature within the test chamber rises above 90 °C (200 °F) prior to achieving CO concentration equilibrium, the test must be aborted and performed with a ventilation rate or chamber volume sufficient to prevent the temperature from exceeding 90 °C (200 °F).

8. If the generator stalls or drops the load during the test prior to meeting the end condition above, the test can be restarted up to 4 times (a higher ventilation rate may be used – see Appendix 1 for guidance).

9. Redo test if instrumentation fails or if the peak CO concentration exceeds the analyzer range.

D. **Calculation Procedures**.

1. Excluding the 2 minutes allowed for the generator to be operating without the load applied, calculate the CO emission rate in g/h using Equation 1:

Equation 1: $$S_{CO} = \frac{0.001 A_{out} V C_{CO,t2}}{1 - e^{-A_{out} \Delta t}}$$

where the nomenclature is per Table 1:

Table 1 Nomenclature for Equation 1

A_{out}	Air change rate of chamber (volumetric flow rate through the chamber divided by chamber volume), h^{-1}
$C_{CO,\ t2}$	Equilibrium CO concentration (concentration at beginning of 30 minute equilibrium period or at end of 180 minute test period if equilibrium is not achieved), ppm(v)
S_{CO}	CO emission rate, g/h
V	Chamber volume , m^3
Δt	Time interval to reach initial equilibrium CO concentration condition (or 3 hours if equilibrium is not achieved), h

2. Sample calculations

a. For a given test, the chamber volume is 30 m^3 and the ventilation rate is measured to be 2.0 h^{-1}. The measured CO concentration reaches 1250 ppm(v) after one hour. Thirty minutes later, the concentration is 1325 ppm(v). Since 1325 ppm(v) is within ± 10 % of 1250 ppm(v), equilibrium is considered to have been reached at one hour. From Equation 1, the CO emission rate is

$$S_{CO} = \frac{0.001 * 2.0 * 30 * 1250}{1 - e^{-2.0*1}} = 87 \text{ g/h of CO}$$

b. For a given test, the chamber volume is 40 m^3 and the ventilation rate is measured to be 2.5 h^{-1}. The measured CO concentration reaches 2250 ppm(v) after three hours. The CO concentration increased more than 10 % over the previous 30 minutes and the O2 level has dropped to 18 %. The CO emission rate may be calculated at the three hour mark. From Equation 1, the CO emission rate is

$$S_{CO} = \frac{0.001 * 2.5 * 40 * 2250}{1 - e^{-2.5*3}} = 225 \text{ g/h of CO}$$

References

ASTM. 2011. ASTM E741-11 Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.

Appendix 1 – Guidance on selecting chamber size and ventilation rate

Known O_2 Consumption Rate

If the portable generator's O_2 consumption rate is known (e.g., calculated from theoretical engine characteristics, determined from a previous test or estimated from tests of similar equipment), the suggested initial test chamber ventilation rate (in h^{-1}) for an O_2 target of 18 %, can be calculated from the O_2 consumption rate (in g/h) and chamber volume (in m^3) according to equation A1.

Equation A1: $A_i = \frac{S_{O2}}{35V}$

Sample calculation

For a given portable generator test, the chamber volume is 30 m^3 and the O_2 consumption rate is 6000 g/h. From Equation A1, the suggested initial ventilation rate to achieve the target O_2 concentration is:

$$A_i = \frac{S_{O2}}{35V} = \frac{6000}{35 * 30} = 5.7 \text{ h}^{-1}$$

Unknown O_2 Consumption Rate

If the portable generator's O_2 consumption rate is unknown, the suggested initial test chamber ventilation rate (in h^{-1}) to achieve the target O_2 concentration may be estimated by dividing the generator load setting (in W) by 25 times the known chamber volume (in m^3). See Table A1 for example results depending on load setting which can be used to specify chamber and initial ventilation rate or to choose ventilation rate for a given chamber size. [Note: This approximation is for a generator operating at near stoichiometric air to fuel ratio (AFR), and the needed ventilation rate is expected to be higher for generators operating at richer AFR.]

Table A1

Load Setting (W)	Chamber Volume (m^3)	Ventilation Rate (h^{-1})
2000	10	8
2000	20	4
6000	20	12
6000	40	6
10000	40	10
10000	60	5