Test Program for Engine-Driven Tools Project

Phase 1 Test Plan

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I. Background

The U.S. Consumer Product Safety Commission (CPSC) has a strategic goal of reducing carbon monoxide (CO) poisoning deaths associated with consumer products by 20% from the 1999-2000 average by 2013. The Engine-Driven Tools project is one of several projects underway to achieve this goal. Engine-driven tools include tools such as portable generators, walk-behind and riding power lawn mowers, garden tractors, power sprayers and washers, sump pumps, snow blowers, and floor buffers. Each of these tools uses a fuel-burning engine (typically gasoline, except floor buffers, which commonly use propane) to drive the tool. Because the engine's exhaust contains high levels of CO, CO poisoning is a potential hazard associated with use of these products. As of March 2004, CPSC's databases contained records of 258 deaths from CO poisoning associated with the use of these products in the 14-year period from 1990 through 2003. Eighty-eight percent of these deaths were associated with generators, so these products are the focus of this project.

This document describes the first phase of a two-phase test program to support this project. Phase 1 characterizes the health hazard posed by the CO emissions from portable generators. Phase 2 of the test program will explore options for reducing the risk of CO poisoning associated with the use of portable generators.[1]

II. Purpose and Approach

Phase 1 of this test program is intended to characterize the health hazard posed by various models of portable generators when operated in enclosed spaces. Four models of generators were selected for testing. The first step in characterizing the health hazard is to determine the rate at which each generator produces carbon monoxide. This will be done by operating each portable generator in an environmental test chamber of known volume and known ventilation rate and measuring the amount of CO produced. Test variables include various conditions of generator electrical load, chamber ambient temperature, and when possible, air exchange rate since these factors affect engine performance and consequently, the CO output. For each set of test conditions (i.e., electrical load, chamber temperature, and air exchange rate), the generator's CO generation rate will be calculated from (1) the equilibrium concentration of CO in the chamber, and/or (2) the change in CO concentration in the chamber with time. The equations used to calculate the CO generation rate are described in Section V at the end of this test plan. The calculated CO generation rate will then be used to predict the CO concentration when the generator is operated in a larger space, such as a basement, and at the same electrical load and ambient temperature. The predicted concentration for the generator operating in a larger space can then serve as the exposure profile for an occupant in that space. The health effects of that exposure profile on the occupant will then be characterized. Additionally, the infiltration of CO from that theoretical basement to other adjoining areas of a house will be modeled using the EPA RISK 1.9.22 Indoor Air Modeling Program. The resulting CO time course profiles for various rooms in the house will be used in a model to estimate the carboxyhemoglobin levels attained by persons in those rooms in the house.

[1] This document has been reviewed by experts within the U.S. Government, outside of CPSC, and the experts' comments have been incorporated.

The purpose of Phase 2 of the test program will be to explore options for reducing the risk of CO poisoning determined in Phase 1. Specifically, staff will explore the feasibility of a gas-sensing interlock device that will quickly, accurately, and repeatedly shutoff the engine when a hazardous CO environment is on the verge of being created from the generator's running engine. A detailed test plan for Phase 2 of the program will be developed upon completion of Phase 1 testing.

III. Test Articles and Test Facility

Table 1 displays the specifications of the four generators selected for testing. Generators A and B (nominally 5500 watts continuous) were selected for several reasons. In CPSC's in-depth investigations of reported CO deaths associated with a generator, units rated in the 5 kilowatt range were most commonly involved in those investigated deaths in which the generator's rating was documented. Staff also believes this size unit is the most popular among consumers and retailers for meeting home power needs. Generator C (1850 watts max) was selected because of its engine's side valve configuration since engine valve configuration affects engine emission rates and the other three generator engines have overhead valves. Generator D (1000 watts max) was selected because staff believes its power rating is at the low end of the range of units that consumers may use. The results from these generators may provide a nominal means of bounding the CO emission rates from generators most commonly used by consumers.

All four generators were purchased new in 2002 and will be tested as received with no adjustments made to the factory settings on the carburetors.

The environmental test chamber in which the portable generators will be operated is approximately 339 ft^3 in volume. It can attain a maximum air exchange rate of approximately 29 air changes per hour (ACH). The chamber temperature can be controlled with heat removal by means of a fin-and-tube heat exchanger with chilled water circulated through it. An adjustable resistive load bank will be used to load the generator. The chamber is instrumented to measure chamber concentrations of CO, carbon dioxide (CO_2), oxygen (O_2), and hydrocarbons (HC). Generator output voltage and current, as well as engine oil sump temperature, will also be recorded. A detailed description of the environmental chamber and its operating characteristics are contained in the CPSC report, "Medium-Sized Combustion Chamber System Characterization Tests".[2]

IV. Planned Test Conditions

As stated above, three variables are believed to be capable of impacting the generator engine's CO generation rate during testing. These factors are generator load, chamber temperature, and chamber air exchange rate. As a result, the effects of these variables on generator performance and CO production will be investigated.

The load will be varied by three current outputs at 120 volts (or 240 volts on Generators A and B) that represent the following:

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[2] Brown, Christopher, "Medium-Sized Combustion Chamber System Characterization Tests," U.S. Consumer Product Safety Commission, July 2004.

(1) No load
(2) 50% of full load
(3) Full load

Note: Full load is defined as the maximum load the generator can sustain without tripping the generator's breaker. This may or may not be the manufacturer's continuous load rating and will have to be determined experimentally.

The chamber temperature will be varied by three temperatures:

(1) 25 ^{o}C (77 ^{o}F) (baseline temperature*)
(2) 37^{o}C (100 ^{o}F) (to simulate warm weather use*)
(3) 4 ^{o}C (40^{o}F) or the lowest temperature the chamber can maintain while the generator is operating.+

* - Because the chamber temperature can only be controlled by heat removal, the 25 ^{o}C and 37^{o}C temperature conditions will not be set prior to generator start-up. They will be achieved and maintained after the running engine has heated the chamber to these temperatures.

\+ - Initially, a temperature below freezing to simulate cold weather was part of this test plan. However, due to limited capacity of the chilled water system in the chamber, it was determined that the below freezing temperature condition would not be feasible. Given the heat load produced by the operating generators, the coldest temperatures achievable will have to be determined experimentally.

When possible, the chamber air exchange rate will be varied by two rates:

(1) 29 ACH (chamber ACH of 29 represents 0.82 ACH in a 12,000 ft^3 house).
(2) 11 ACH (represents 0.31 ACH in a 12,000 ft^3 house).

All test conditions may not be achievable for all four generators. For instance, in preliminary testing done on Generator A at full load and maximum ACH conditions, the generator's CO output exceeded both the chamber CO analyzer's maximum range and the laboratory's safety guidelines before equilibrium conditions were reached in the chamber. Also, while operating Generator A with no load, the lowest chamber temperature that could be sustained was approximately 15^{o}C.

Engine manufacturers recommend running the engine through a "break-in period" at partial or no-load for the first 5-8 hours of engine operation to allow the piston rings and cylinder walls to "seat" properly. After this break-in period, manufacturers recommend changing the oil to remove any metal particles that may have been scored off the cylinder walls or rings during that time. Since the test generators are new, the series of test conditions that will be conducted during the initial engine break-in period (the first 5 to 8 hours of total run time) are shown in Table 2. The full load condition is excluded from these tests. After engine break-in, the series of tests shown in Table 3, including the full load condition, will be conducted. These tests will determine if the CO generation rate changes after the break-in period.

Each test will be run until (1) the chamber CO concentration approaches 7500 ppm, (2) an equilibrium CO concentration has been reached in the chamber, or (3) the ambient CO in Building G, which houses the test chamber, reaches 15 ppm in the unlikely event that the chamber has a leak. Equilibrium is considered attained when the CO reading remains constant within +/- 5% over a 10-minute interval. During each test, the chamber CO, O_2, CO_2, and HC concentrations will be recorded electronically and the humidity will be recorded manually. Also, the generator output voltage, current, and engine oil sump temperature will be recorded electronically.

For any test (in either Table 2 or Table 3) in which a load is to be applied, per the manufacturer's instructions, the generator will initially be run at no load for a few minutes to permit the engine and generator to stabilize and to check for proper operation. Before stopping the engine after each test is run, the generator will be run at no load for several minutes to stabilize the internal temperatures of the engine and generator. The engine will never be started with electrical loads turned on. Also, before conducting each test, the engine oil temperature must be at chamber ambient temperature. To prevent engine block warpage which could result if the engine is cooled too quickly between tests, engine cooling will only be achieved by allowing it to cool without forced means other than those used to attain the chamber ambient temperature.

The tests in Tables 2 and 3 will be conducted for each of the four generators in random order. If all conditions are run, without any test duplication, this amounts to a maximum of 30 tests on each generator, for a total of 120 tests. Test duplication will not be necessary unless data analyses dictate otherwise. As previously mentioned, fewer tests could be run on each generator depending upon limitations of the test chamber or the gas sample analysis system.

CPSC staff may change this test plan if needed.

V. Equations to Determine the CO Generation Rate

The CO generation rate (source strength) can be calculated using two slightly different equations. Both equations are derived from a simple mass balance of the CO in the chamber and are both applied at steady state. The expressions for the source strength shown in Equation 1 and Equation 2 below were derived based on the following assumptions: (a) the air in the chamber is well mixed, (b) CO does not get absorbed inside the chamber, (c) the background concentration of CO is near zero, and (d) the initial concentration of CO is near zero.[3]

Equation 1 (continuous calculation) provides the constant source strength needed to achieve a given chamber concentration. It reflects a weighted average of the source strength over the entire test run. If the generator is run under variable conditions (i.e. no load, full load), the result of this equation may not reflect the steady state source strength of the generator under either condition.

$$S_V = \frac{\mathrm{V}}{\mathrm{k\ C_{ss}}} \tag{1}$$

Therefore, the CO generation rate (S_V) can be calculated directly from Equation 1, if the volume (V) is known, if the air exchange rate (k) is known, and if the steady state concentration (C_{ss}) is known.

[3] For details on the derivations of Equations 1 and 2, please refer to Appendix A of "Medium-sized Combustion Chamber System Characterization Tests," U.S. Consumer Product Safety Commission, Christopher Brown, July 2004.

Equation 2 (incremental calculation) can be applied between any two time intervals (t_i and t_{i+1}) to obtain the source strength. This equation provides results that represent the average weighted source strength over a chosen interval.

$$S_{t_{i+1}} = \frac{Vk\left[C_{t_{i+1}} - C_{t_i} e^{-k\left(t_{i+1} - t_i\right)}\right]}{\left[1 - e^{-k\left(t_{i+1} - t_i\right)}\right]} \tag{2}$$

where,

$S_{t\ i+1}$	=	the source strength of CO at time t_{i+1}
V	=	the volume of the chamber
k	=	the air exchange rate
$C_{t\ i+1}$	=	the concentration of CO at time t_{i+1}, and
$C_{t\ i}$	=	the concentration of CO at time t_i

Table 1. Summary of portable generator specifications for each generator to be tested

Generator (Manufacturer make and model omitted)	Engine	AC Output	DC Output	Fuel Tank	Dry Weight
Generator A 5550 watts	• 10 HP • Single -cylinder • Overhead valve • Air-cooled • 4-stroke, gasoline	• 120/240 Volts • 60 hertz • 8550 watts (max surge) • 5550 watts (rated continuous)	• not applicable	• 5 gallons	• 148 lbs
Generator B 5500 watts	• 10 HP • Single -cylinder • Overhead valve • Air-cooled • 4-stroke, gasoline	• 120/240 Volts • 60 hertz • 8500 watts (max surge) • 5500 watts (rated continuous)	• not applicable	• 5 gallons	• 148 lbs
Generator C 1850 watts	• 3.5 HP • Single cylinder • Side-valve • Air-cooled • 4-stroke, gasoline	• 120/240 Volts • 60 hertz • 1850 watts (max surge) • 1500 watts (rated continuous)	• 12 volts • 1800 watts	• 0.94 gallons	• 68 lbs
Generator D 1000 watts	• 1.8 HP • Single cylinder, • Overhead Valve • Air Cooled • 4-stroke, gasoline	• 120 Volts • 60 Hz • 1000 watts (max) • 900 watts (rated)	• 12V • 96 watts	• 0.61 gallons	• 29 lbs

Note: Generators A and B are sold under different trade names but are essentially identical generators, driven by engines made by the same manufacturer and with the same HP rating. Generator A was added as an official test article in the test plan after initial results from identical test conditions on both Generators A and B yielded significantly different CO emission rates. The differing emission rates may be explained, at least in part, by the fact that the engines have different family designations as stated by the manufacturer on the engines' nameplates.

Table 2. Test conditions to be run in random order during generator engine break-in period (first 5-8 hours of total run time accumulated on the engine).

	1	2	3	4	5	6	7	8	9	10	11	12
Load (% rated)	No load	No load	No load	No load	No load	No load	50	50	50	50	50	50
ACH (hr^{-1})	High	11	High	11	High	11	High	11	High	11	High	11
Chamber temp (^oC)	25	25	Cold	Cold	37	37	25	25	Cold	Cold	37	37

High means the highest air exchange rate the chamber can sustain with adequate mixing while maintaining a sufficient negative pressure differential in the chamber to reduce the risk of CO leakage out of the chamber. Chamber characterization testing indicates air exchange rate results in approximately 29 air changes per hour.
Cold chamber temperature is the lowest temperature that can be sustained in the chamber with the generator operating.

Table 3. Test conditions to be run in random order after generator engine has accumulated 5-8 hours total run time and break-in oil change has been performed.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Load (% rated)	No load	No load	No load	No load	No load	No load	50	50	50	50	50	50	100	100	100	100	100	100
ACH (hr^{-1})	High	11	High	11	High	11	High	11	High	11	High	11	High	11	High	11	High	11
Chamber temp (^oC)	25	25	Cold	Cold	37	37	25	25	Cold	Cold	37	37	25	25	Cold	Cold	37	37