

Measured Carbon Monoxide Emission Rates from Stock and Reduced- Emission Prototype Portable Generators

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Content submitted to and published by:
Proceedings of 13th International Conference on
Indoor Air Quality and Climate, Indoor Air 2014, July 7-12, 2014 Hong Kong,
Paper number: HP0573

U.S. Department of Commerce
Penny Pritzker, Secretary of Commerce



National Institute of Standards and Technology
Willie E May, Acting Director

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SUMMARY

To better understand and to reduce the occurrence of carbon monoxide fatalities, this paper presents measured CO emission rates from both stock and reduced-emission prototype portable generators operating in an enclosed space under real weather conditions. For two different unmodified generators, CO emissions ranged from around 500 g/h at near ambient O₂ levels to nearly 4000 g/h as O₂ approached 17 %. Two important parameters affecting the rates of CO generation and O₂ consumption in these unmodified generators were the O₂ level in the space and the actual electrical output of the generator. Tests performed below 17 % O₂ showed a drop off in CO emissions due to poor engine performance. Tests of two modified generators showed CO emission reductions of over 90 % depending on the specific emission controls and operating conditions, with no trend toward higher emission rates as O₂ levels dropped to 18 %.

Keywords: Carbon monoxide, Indoor air quality, Pollutant sources, Portable generators, Residential buildings

INTRODUCTION

Based on currently available data, about 97 % of generator-related carbon monoxide (CO) fatalities in residential buildings in the United States are caused by operating currently marketed, carbureted spark-ignited gasoline-powered generators (not equipped with emission controls) in enclosed spaces. Very limited study has been conducted directly on CO emission and O₂ consumption rates associated with gasoline-powered generators running indoors. Brown (2006) studied the CO emission rates from four different commercially-available generators in an enclosed experimental chamber, where air temperature and air change rate were controlled to provide different operating conditions. However, the air change rates were generally quite high compared with typical residences. Operating a generator in an enclosed space such as a garage or a storage shed, as opposed to a laboratory chamber, will be subject to uncontrolled temperatures and to lower ventilation rates determined by ambient weather conditions.

To determine generator CO emission rates, tests were conducted in a single-zone shed on generators operating in the unmodified carbureted configuration as well as in the low CO emission prototype configuration. A literature search did not reveal previous studies on CO emission from generators in real conditions, where O₂ levels can become significantly lower than ambient, and thereby impact CO emission. To better understand and to reduce the occurrence of these fatalities, research is needed to quantify CO generation rates, develop and test CO emission control devices, and evaluate CO transport and exposure when operating a generator in an enclosed space. Currently, there are no regulations on acceptable CO emission rates from generators although the U.S. Consumer Product Safety Commission is considering establishing such a requirement. As part of these efforts, this paper presents measured CO emission rates from both stock (i.e., without emission reduction technology) and reduced-emission prototype portable generators operating in an enclosed space under real weather

conditions. Measurements included CO and O₂ concentrations, air change rates determined by tracer gas decay tests, temperature, humidity and electrical loads met by the generators.

METHODOLOGIES

Equipment and Instrumentation

Experiments were conducted in a shed (a single-walled, uninsulated timber structure), with dimensions of 4.88 m (L) × 3.05 m (W) × 2.90 m (H), for the purpose of measuring the CO emission rate and O₂ consumption rate of the generators. The shed also had two operable windows at both sidewalls and an exhaust fan, which were used to vary the air change rate (measured air change rates during the tests typically were between 0.5 h⁻¹ and 10 h⁻¹). Separate sample lines were placed mid-height in the center of the shed (midway between the walls) for CO, O₂, and SF₆ (sulphur hexafluoride, for tracer gas decay measurement of air change rates). Non-dispersive infrared and electrochemical sensor CO analyzers and a portable O₂ analyzer were used to measure CO and O₂ respectively. A gas divider/diluter was also used to dilute the sampled CO for the CO analyzer for some tests. SF₆ concentrations were measured with a gas chromatograph equipped with an electron capture detector. Several gas concentration uniformity tests were conducted by collecting samples at five different locations in the shed. It was found that the thermal plume, which was driven by the heat from the running generator, mixed the shed very well throughout testing. The variations among the five sample locations were less than 5 % for SF₆.

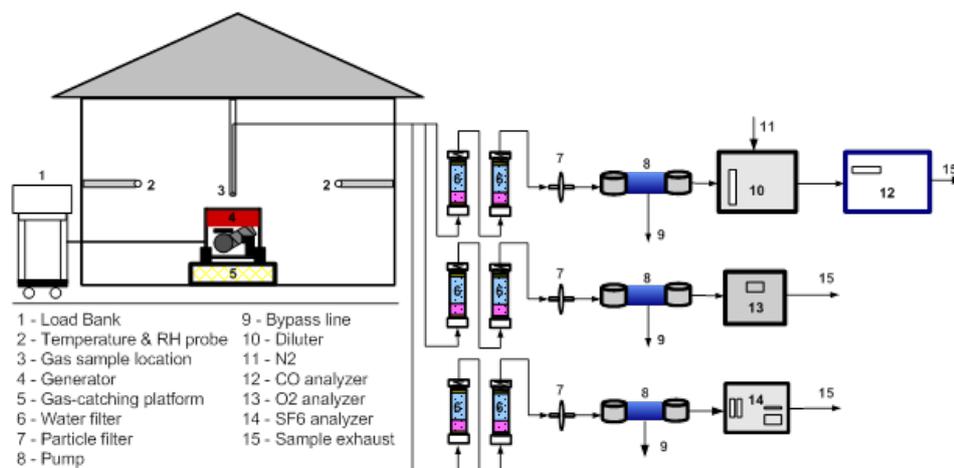


Figure 1. Schematic of experimental setup in shed.

Generators were selected with electrical power output ratings in the size range most commonly involved in fatal consumer incidents, i.e., 5.0 kW to 6.5 kW (Hnatov 2012). Tests were conducted with three different generators that were configured in multiple ways. Two unmodified ‘stock’ (i.e., in their as-purchased condition) generators were tested. The first generator (referred to here as Gen B) has a full-load power rating of 5.5 kW with a 10 horsepower, carbureted, single cylinder gasoline engine and no specific CO emission control technology. This same generator was also tested by the U.S. Consumer Product Safety Commission (CPSC) in a small chamber as reported on by Brown (2006).

The second generator is powered by a carbureted 11 horsepower single-cylinder gasoline engine made by a different manufacturer than Gen B and has an advertised full-load electric power rating of 5.0 kW. This generator was tested in both unmodified condition (referred to

as unmod Gen X) and as a modified low-CO emission prototype (referred to as mod Gen X). The unmodified generator operates at air-fuel ratios (AFR, 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. The generator was modified by the University of Alabama (UA) by adding an engine management system (EMS) with associated sensors and actuators for electronic fuel injection (replacing the carburetor) and a muffler with a small catalyst integrated in 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 primarily targets reduction of oxides of nitrogen (NO_x) and has relatively low catalytic activity because the EMS significantly reduces the available oxidation constituents in the exhaust stream.

For the third generator (referred to as Gen SO1), a model similar to Gen X was obtained which had the same model engine but with an alternator with an output rating of 7 kW. It was tested after UA modified it using the same fuel control strategy and largely the same emission control hardware that was used in mod Gen X. One difference is that Gen SO1 had a different model ECU than that used on mod Gen X. Another difference noted during the testing is that its manufacturer included programming to maintain rich AFR operation until the oil temperature rose above approximately 60 °C, resulting in an initial “spike” of CO when the engine was started cold. This ECU also included an algorithm developed by UA that can be switched on or off by the test operator for testing purposes. The algorithm was intended to sense when the generator was operating in an enclosed space, based on engine operation parameters and when enabled, was intended to shut off the engine before a life-threatening CO hazard develops. All the tests with Gen SO1 that are reported in this paper were performed with the algorithm disabled. Gen SO1 was also tested in a configuration with a muffler that did not contain a catalytic converter (referred to as the noncat muffler). The purpose of testing with the two different muffler versions was to measure the CO emissions produced in the engine due to the fuel control strategy alone (from tests with the noncat muffler) as well as get an indication of the catalyst’s performance in further lowering those emissions (from tests with the cat muffler). A full description of the prototype configuration of both mod Gen X and Gen SO1 is provided in UA’s report to CPSC (CPSC, 2012).

The generators were operated using reformulated gasoline with 10 % ethanol. A portable alternating current resistive load bank connected to the generator’s 240-volt receptacle was used to draw electrical power and thereby 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.

Analysis

CO emission and O₂ consumption rates were calculated from the concentrations measured during the tests based on a single-zone mass balance model. Assuming a gas component, C , is either generated ($S_C > 0$) or consumed ($S_C < 0$) in the zone, a differential mass balance equation for C during a period of $\Delta t = t_2 - t_1$ can be expressed as

$$\rho_{C,in} V_s \frac{dC}{dt} = S_C - \rho_{C,in} C Q_{out} + \rho_{C,out} C_{out} Q_{in} \quad (1)$$

by assuming the gas component, C , is an ideal gas; the concentration of C is uniform in the zone; ρ_C , S_C , and Q are constant during Δt ; and the mass of fuel added from the generator to the zone air does not affect the air density and the air change rate of the shed.

After determining the air change rate of the space from the decay rate of the SF_6 (see Wang and Emmerich 2010 for details), S_{CO} can be solved from Eq. (1) for the time period of t_1 to t_2

$$S_{CO} = \rho_{CO,in} A_{out} V_s \frac{C_{CO,t2} - C_{CO,t1} e^{-A_{out}\Delta t}}{1 - e^{-A_{out}\Delta t}} \quad (2)$$

More details on the methodologies including equipment, instrumentation and measurement uncertainty analysis can be found in Emmerich et al. (2013).

RESULTS AND DISCUSSION

Generator B

Using the same generator (B), Brown (2006) found that CO emission rate was closely related to generator load and O_2 level in small chamber tests. In the current study, 13 tests of Gen B were conducted for load settings of 2.5 kW (half of the maximum load of the generator) and 5.0 kW (full load) for different air change rates (which result in different O_2 levels).

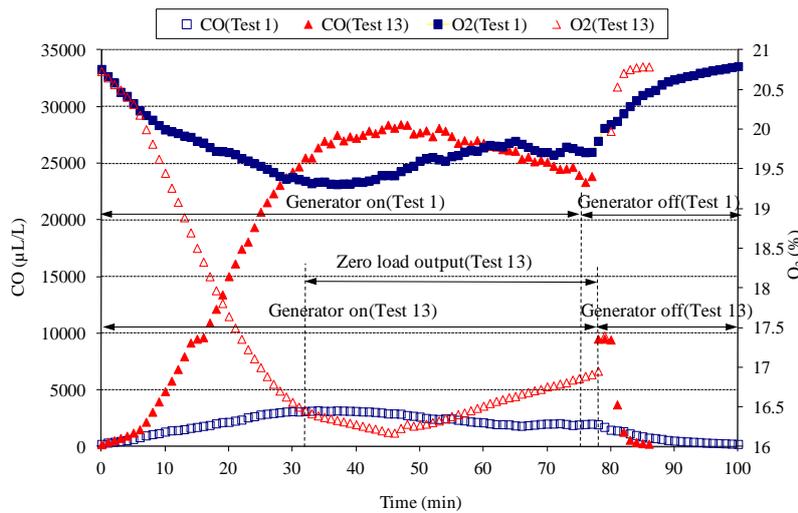


Figure 2. Measured CO and O_2 concentrations of Tests 1 and 13.

As an illustration of individual shed tests, Figure 2 shows the CO and O_2 measured for Tests 1 and 13. The patterns of CO concentration in both tests are almost an inverse to that of the O_2 level for this unmodified generator. The CO level is low at the beginning of generator startup and increases steadily as the O_2 level drops. As the O_2 drops further and causes a very rich fuel mixture in the engine, CO reaches a maximum level. Test 13 in Figure 2 shows an extreme case in which the generator eventually produces a zero electrical load when the O_2 drops to around 16.4 %, although it was set at a full load and the crankshaft was still rotating.

Figure 2 also shows that steady state was never reached for either test. A relatively stable period occurred at about 40 min for Test 1 and 45 min for Test 13, but they only held for a few minutes. These results differed from chamber experiments, where CO concentrations becomes constant after a period of time as complete steady state can be achieved under the

controlled environment and higher air change rate. While these chambers tests are useful, the results from the shed confirm the importance of studying CO emission as a transient process under real weather conditions and more realistic air change rates to better understand generator performance in the field.

In order to generalize these test results to other conditions beyond this particular test facility, it is important to convert the results into CO emission and O₂ consumption rates. As seen in these tests, many factors can affect these rates directly or indirectly: space ventilation conditions, combustion conditions in the engine, O₂ level in the space, load setting, and the time over which the generator has been running.

Figure 3 illustrates how 5-min average CO emission rates ($\Delta t = 5$ min in Eqs. (1) and (2)) change with O₂ levels in the thirteen shed tests. (Note: O₂ consumption rates were all determined for all tests and are available in Emmerich et al. 2013.) Figure 3 shows that for both full and half load settings CO emission rates increase with decreasing O₂, reach maximum values when O₂ drop to about 17 % to 18 %, and then decline at lower O₂ levels. Under the extreme case of Test 13 (5.0kw-CW-LA), the CO rate decreases dramatically as the O₂ level reaches around 16.4 % with an electrical output of zero.

The solid points in Figure 3 are data points for a half-load setting (2.5 kW) and the hollow ones for a full load setting (5.0 kW). As seen in previous small chamber test results in Brown (2006), a higher load setting generally results in more CO generated until the O₂ level reaches about 17 %, where data for full and half loads come together. This overlap corresponds to the drop in electrical output with the decrease of O₂. Note that Figure 3 also shows the calculated uncertainty for each data point of CO emission rates, which was mostly less than 20 % with a confidence level of 95 %.

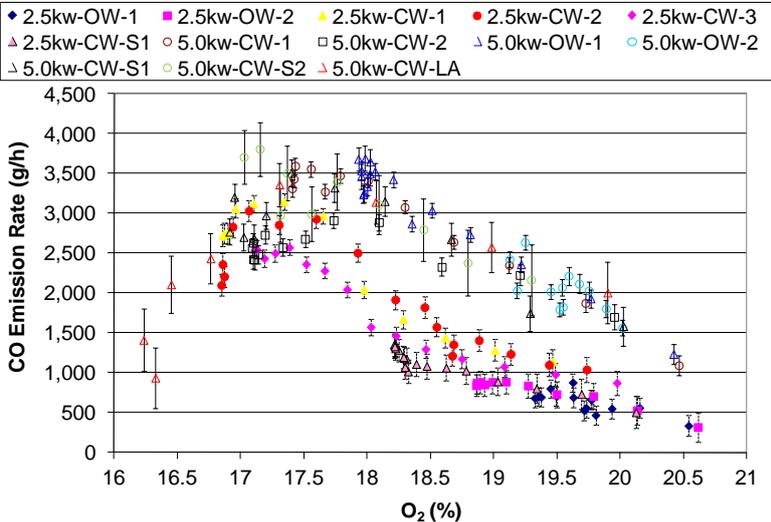


Figure 3. Five-minute averaged CO emission rates at different O₂ levels for Gen B. **Generator X**

Generator X was tested in both unmodified and modified (low CO emission) configurations. The primary difference between the tests with Gen X and Gen B was the generator loading. Gen X was tested at load points selected to approximately match the points of the load profile used by UA during the durability testing of their low CO emission prototype generator. Figure 4 presents the CO emission rates as a function of O₂ levels for unmodified Generator X. Although the tests of Gen X and Gen B were not identical, Figure 4 shows similar results in

that the CO emission rates range from a low of around 500 g/h at near ambient conditions to a high of nearly 4000 g/h as O₂ approaches 17 %. Unlike Gen B, however, the emission rate is only clearly load-dependent when the O₂ drops below about 19 %. Fewer tests were performed on Generator X below 17 % O₂ but the results indicate a similar drop off in CO emissions due to poor engine performance under these conditions.

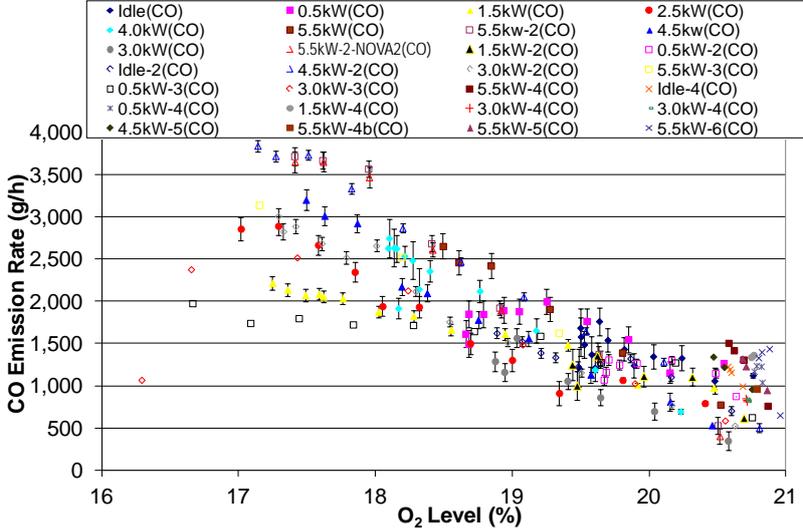


Figure 4. CO emission rates at different O₂ levels for unmodified Generator X.

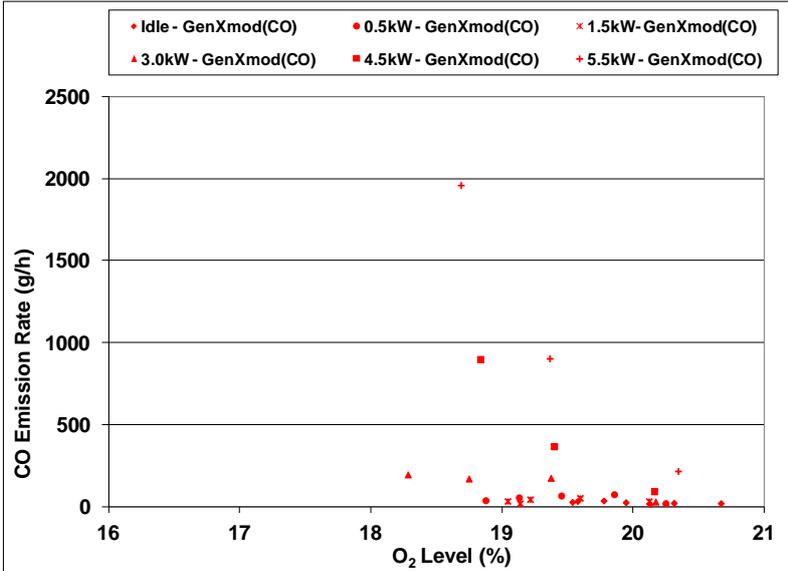


Figure 5. CO emission rates at different O₂ levels for modified Generator X.

Figure 5 presents the CO emission rates as a function of O₂ levels for modified Generator X. Although modified Gen X was not tested as many times as unmodified Gen X, comparing Figure 5 to Figure 4 shows the dramatic reduction in CO emission rates due to the low CO emission modifications included on the prototype. Most of the modified Gen X CO emission rates were well below 500 g/h. Although not enough low O₂ tests were performed to be conclusive, the CO emission rates at the highest loads did tend to increase as O₂ dropped.

Generator SO1

Generator SO1 was tested at the same load points as Generator X but was tested only in two modified configurations – with and without a catalyst integrated in the muffler (referred to as cat muffler and noncat muffler, respectively). Figure 6 presents the CO emission rates as a function of O₂ levels for Generator SO1 with the cat muffler. Comparing Figure 6 to Figure 5 shows that Gen SO1 cat performed better than modified Gen X. All measured CO emission rates for Gen SO1 cat were well below 500 g/h, and no trend toward higher emission rates was seen as O₂ levels dropped to 18 %. However, as with Gen X, no tests were performed at levels as low as 17 %.

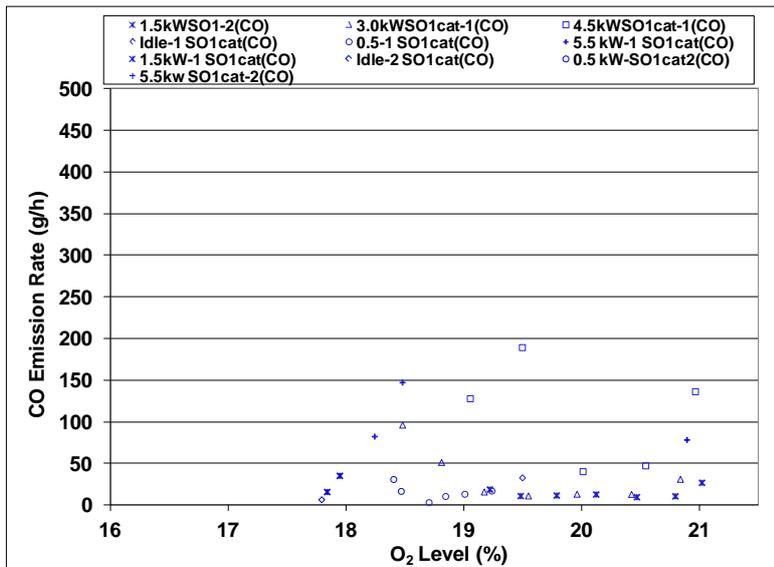


Figure 6. CO emission rates at different O₂ levels for Generator SO1 with cat muffler.

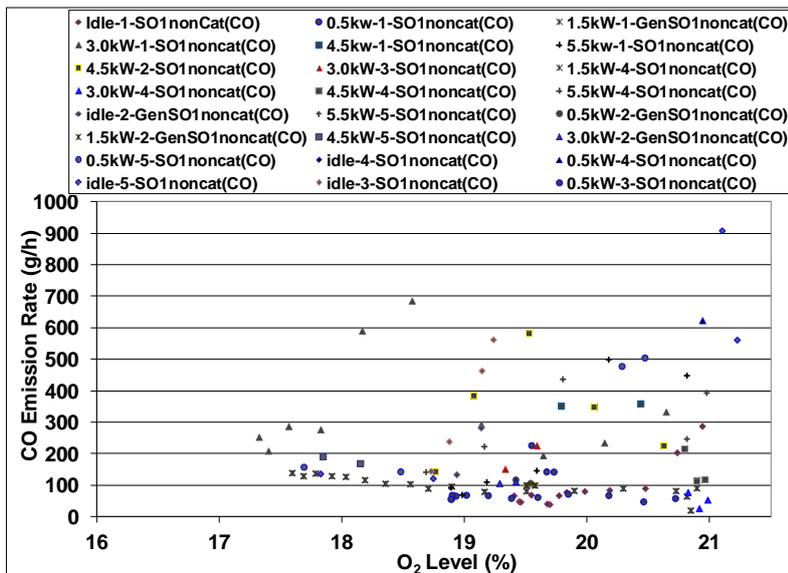


Figure 7. CO emission rates at different O₂ levels for Generator SO1 with noncat muffler.

Figure 7 presents the CO emission rates as a function of O₂ levels for Generator SO1 with the noncat muffler (referred to as Gen SO1 noncat). Comparing Figure 7 to Figure 6 shows that Gen SO1 noncat had higher CO emission rates than Gen SO1 cat. However, the measured

CO emission rates for Gen SO1 noncat were still substantially lower than the emission rates of the unmodified generators, and no trend toward higher emission rates was seen as O₂ levels dropped close to 17 %.

CONCLUSIONS

For two different unmodified generators (i.e., without CO emission controls), it was found that CO emissions ranged from a low of around 500 g/h at near ambient O₂ levels to a high of nearly 4000 g/h as O₂ approaches 17 %. The rates of CO generation and O₂ consumption in these unmodified generators were affected by multiple parameters, with the O₂ level in the space and the actual electrical output of the generator being two of the most important. Tests performed below 17 % O₂ showed a drop off in CO emissions due to poor engine performance under these conditions. Tests of two modified low CO emission prototype generators (i.e., with CO emission controls) showed reductions of CO emissions of over 90 % depending on the specific emission controls and operating conditions and no trend toward higher emission rates was seen as O₂ levels dropped to 18 %.

ACKNOWLEDGEMENT

This research was supported by the U.S. Consumer Product Safety Commission (CPSC) under interagency agreement CPSC-I-06-0012. The authors would like to acknowledge the contributions of CPSC staff, and Gregory Linteris and Steven Nabinger from NIST.

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