CARBON MONOXIDE ALARM
CONFORMANCE TESTING TO
UL 2034: STANDARD FOR SAFETY
FOR CARBON MONOXIDE ALARMS

PHASE II
FY 2013 TEST RESULTS

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Prepared By Matthew J. Brookman

Directorate for Laboratory Sciences
United States Consumer Product Safety Commission
5 Research Place
Rockville, MD 20850

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Abstract

In 2004, the U.S. Consumer Product Safety Commission (CPSC) recommended changes to UL 2034, *Standard for Safety for Carbon Monoxide Alarms,* to require end-of-life signaling, provisions for rapid buildup of carbon monoxide (CO) levels, more realistic environmental test conditions, and display accuracy (UL 2034, 2008). All retail UL-certified CO alarms manufactured after August 2009 are required to incorporate these new changes. A two-phase carbon monoxide alarm conformance testing activity began in FY 2012 to evaluate the performance of currently available retail CO alarms relative to CO sensitivity and environmental condition requirements in UL 2034.

In FY 2012, the project focused on three key sections of UL 2034 that are related to CPSC's prior recommendations: Section 39 - Sensitivity Test, Section 46.1 - Variable Ambient Temperature Test, and Section 36.8 - Concentration Display Accuracy. CPSC staff chose CO alarms representing brands and models available on the current retail market. The samples performed well when tested for sensitivity, low and high temperatures, and display accuracy. These results are detailed in the Phase I report (Brookman, 2012).

Following the FY 2012 effort, additional alarm performance testing was identified to be completed in FY 2013. The FY 2013 testing is detailed in this Phase II report and includes tests from the following UL 2034 sections: Section 42.1(B) - 30 ppm Stability Test, Section 42.1(C) - Cyclic Temperature Test, Section 47.1 - Humidity Test, Section 53 - Undervoltage Test, and Section 46.1 - Variable Ambient Temperature Test. CPSC staff performed the low temperature test of Section 46.1 with a new dehumidification system, which provided the required humidity range.

The alarms tested in Phase II provided limited acceptability relative to UL 2034 criteria. CPSC staff used two methods to evaluate performance. The alarms were compared to the criteria required by UL 2034 and the UL basis of acceptability. The alarms were also evaluated based on the number of failures due to delayed or no activation. Two models tested produced numerous failures due to delayed or no activation, while the other four models had limited failures based on the delayed or no activation. The tested models that performed the best used electrochemical sensors; whereas, the tested models that failed more often used biomimetic and semiconductor sensors. Only one model met the basis for acceptability specified by UL 2034 for the tests performed, while three other models came close to the acceptability criteria.

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Introduction and Background

General Overview

Residential fuel-burning appliances, engine-driven products, and automobiles can be potential sources for hazardous elevated carbon monoxide levels. Properly vented and operated fuel-burning appliances are safe. However, if fuel-burning appliances are not properly installed, used or maintained, the carbon monoxide from these products can accumulate to unsafe levels. In addition, automobiles and engine-driven tools, such as portable generators, which may cause exhaust build up in the residence, shed, or garage, can create unsafe concentrations of carbon monoxide.

In 2009, there were an estimated 146 unintentional non-fire carbon monoxide (CO) poisoning deaths associated with consumer products under the U.S. Consumer Product Safety Commission's (CPSC, Commission) jurisdiction. The estimated annual average from 2007 to 2009 was 169 deaths, with approximately 79 percent of these deaths occurring in a home. These home locations include a residence, such as a detached house, townhouse, apartment, or mobile home, and external structures to a residence, such as detached garages or sheds (Hnatov, 2012). In 2011, staff reviewed the national estimates of households using CO alarms from two housing market data studies. From these studies, staff estimates that U.S. homes using CO alarms range from 36.4 percent (U.S. Census Bureau, 2011) to 50.0 percent (Jarden, 2009). CPSC recommends installation of a CO alarm in the hallway near the bedrooms in each separate sleeping area in every home. These CO alarms should be battery-operated or plug-in with battery back-up. The CO alarms should be certified to the requirements of the most recent Underwriters Laboratories Inc. (UL), International Approval Services (IAS), or Canadian Standards Association (CSA) standard for CO alarms.

Carbon monoxide is called "the invisible killer" because of the colorless and odorless characteristics of the gas. Early onset of CO poisoning has symptoms similar to the flu, including headache, fatigue, shortness of breath, nausea, and dizziness. High-level CO poisoning results in progressively more severe symptoms that include mental confusion, vomiting, loss of muscular coordination, loss of consciousness, and death. Symptom severity is related to both the CO level and the duration of exposure.

CPSC's public safety information[1] on the hazards of CO state that the most important factor for reducing the risk of CO is the proper installation, operation, and maintenance of fuel-burning appliances in the home. CPSC recommends that portable generators be operated outdoors and as far as possible away from open doors, windows, and vents, to prevent CO exhaust from coming indoors.

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[1] http://www.cpsc.gov/Safety-Education/Safety-Education-Centers/Carbon-Monoxide-Information-Center/.

Project Goal

In 2004, the CPSC successfully recommended changes to UL 2034, *Standard for Safety for Carbon Monoxide Alarms,* to require end-of-life signaling, provisions regarding performance of the alarm during rapid buildup of CO levels, more realistic test conditions, and display accuracy (UL 2034, 2008). All retail UL-certified CO alarms manufactured after August 2009, are required to incorporate all of these new changes. This project evaluated current alarm performance relative to sensitivity requirements and environmental conditions specified in the 2008 edition of UL 2034. CPSC staff may recommend changes or additions to the UL standard, based on the test results and analysis of the test procedures.

The Carbon Monoxide Alarm Conformance Testing (COACT) project began in FY 2012 to evaluate the performance of currently available retail CO alarms relative to CO sensitivity and environmental conditions. Fiscal year 2012 testing focused on the basic sensitivity tests in various specified environmental conditions in UL 2034 to determine how currently available CO alarms are performing in comparison to the previous alarms tested by CPSC. Fiscal year 2013 testing is an extension of the testing performed in FY 2012. Both the FY 2012 and FY 2013 test series will be used to evaluate the performance of the test samples as an indication of the marketplace's current CO alarm conformance to the standard and to identify areas in the standard related to test methods and procedures that may warrant further details or clarification.

Test Samples

CPSC staff collected six models of CO alarms currently available in the retail market. Three manufacturers, two models from each manufacturer, and 17 alarms of each model (or a total of 102 alarms) were collected. The number of alarms collected was based on previous "out-of-the-box" testing performed by the Gas Technology Institute (GTI) that determined within their sample lot, approximately 30 percent of alarms malfunctioned out-of-the-box (Clifford, P.K., Siu, D.J., 1998). The number of alarms collected was a sufficiently sized sample lot to perform all tests in Phase I and Phase II. Table 1 below provides a description of the alarms used for testing.

Table 1. CO Alarm Samples

Sample Nos.	Manuf. Date	Sensor	Digital Display	Power
A1-A17	Sept2011	Electrochemical	Yes	AC plug-in
B1-B17	Jul 2011- Dec 2011	Electrochemical	No	Battery
C1-C17	Apr, 2011	Electrochemical	Yes	AC plug-in
D1-D17	Mar 2011	Electrochemical	No	Battery
E1-E17	Jan, 2012	Semiconductor	Yes	AC plug-in
F1-F17	Apr 2011	Biomimetic	No	Battery

Experimental Setup

The CO alarms were tested inside CPSC's CO alarm testing environmental chamber (Cincinnati Sub-Zero model Z-32 plus), located in room 154 at the CPSC's National Product Testing and Evaluation Center (NPTEC) in Rockville, MD. The interior volume of the chamber is 0.91 m^3 (32 ft^3), and the walls are constructed of stainless steel. The test chamber has both temperature control and humidity control. The door on the test chamber is equipped with a glass window, permitting visual observations of each sample during testing.

The test chamber was modified to allow for the injection of CO into the test chamber and the removal of gas for analysis and chamber evacuation. Two mass flow controllers (Alicat Scientific, model 500 SCCM-D and model 20 SCCM-D) are used to control the injection rate of pure CO into the chamber volume. Gas samples are continually withdrawn from the chamber through a sample line located within the test chamber. Outside of the test chamber, a pump conveys the mixed gas sample to a nondispersive infrared (NDIR) CO analyzer (Rosemount, model NGA 2000). Before analysis, any water vapor in the gas sample is removed by using a Drierite column and subsequent filters.

The CO concentration versus time data are recorded using a data acquisition system, which consists of a personal computer, data acquisition interface hardware, and data acquisition software (OPTO 22 Snap PAC, PAC Display Runtime 9.3). The CO concentration inside the test chamber was recorded every 10 seconds. In addition to collecting data, the data acquisition system controlled the injection rate of CO into the test chamber to maintain the required set points.

The response time of the CO alarms was logged using a sound detection system developed by CPSC staff with LabVIEW software. The Audible Signal Detection (ASD) system is used to detect the audible signal emitting from the alarm during normal activation and trouble conditions. The system is capable of differentiating between different signals from one individual alarm due to a high sampling rate in the LabVIEW program. The system also filters out ambient noise and signals from other alarms such that each alarm is connected to its own independent channel. The ASD schematic is provided in the Appendix.

Power for the CO alarms is provided by batteries or by power strips inside of the chamber. To deactivate the alarms remotely, a relay system was installed inside the chamber with a switch outside the chamber to disconnect the battery power or battery backup power. The AC power systems were deactivated through the chamber control system. All alarms could be deactivated and reactivated simultaneously without opening the chamber.

Experimental Procedure

The tests performed in this project adhere to the procedures detailed in UL 2034, *Standard for Safety for Carbon Monoxide Alarms (UL2034, 2008).* The table below lists the tests performed as part of the Phase II project.

Table 2. Project Test Summary

Test #	Specifications	Description
1	Section 42.1 (B) 30 PPM Stability Test	To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm when exposed to 30 ppm CO for 30 days.
2	Section 42.1 (C) Cyclic Temperature Test	To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm during exposure to extreme cyclic temperature variation from 32 °F to 120 °F.
3	Section 47.1 Humidity Test	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 125 $\pm$5 °F, 95 $\pm$4 % relative humidity and 72 $\pm$5 °F, 10 $\pm$3 % relative humidity.
4	Section 53 Undervoltage Test	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity with an inadequate power supply voltage based on UL2034 Table 39.1 and section 53 specifications.
5	Section 46.1 Variable Ambient Temperature Test (Low Temperature)	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 32 °F, 15 +5 % relative humidity.

Prior to testing, all samples were conditioned for a minimum of 48 hours at 73.4 $\pm$ 5 °F and 50 $\pm$ 20 % relative humidity (RH) per the requirements of UL 2034. Electrical power was not supplied to the units during conditioning and all batteries were removed. All samples were stored in covered bins during conditioning to minimize any potential contamination. A data log was maintained for temperature and humidity in the conditioning area. The selection of test samples for each test was based on the requirements of UL2034. Some tests require new, unused alarms; whereas, other tests do not specify this requirement.

To begin testing, the test chamber was turned on and set to the desired conditions. The system was permitted to stabilize while the analyzers were calibrated. In general, the analyzers were set to the appropriate concentration range, then zeroed with nitrogen and finally spanned with a primary standard gas mixture. The analyzers were then purged, the sample pump was activated, and flow was adjusted to 1.5 standard liters per minute (slpm).

After the chamber reached a steady state with the set points of temperature and humidity, the alarms were installed in the chamber. Installation of the alarms includes plugging in all AC leads, installing new batteries into all alarms, testing the alarms for proper function, placing the activation sensor over the audible signaling device, and evenly distributing the alarms throughout the chamber. Once all alarms were properly installed the chamber was closed and the ASD system was tested.

Each alarm was triggered into alarm mode using the test feature while the data acquisition system recorded the audible signal. Each ASD channel was tested to ensure a secure and reliable detection signal. If an unreliable signal was noted, the microphone lead for the ASD would be replaced and any additional issues would be repaired immediately.

After all of the alarms were installed, gas analyzer calibrations completed, and the ASD was tested and operational, CPSC staff sealed the chamber. The temperature and humidity levels were restabilized, and the alarms were subjected to the specified conditions for a predetermined amount of time to achieve equilibrium with the environment. UL 2034 specifies the environmental conditions required for each test.

Upon completion of the equilibration period, the DAQ systems were reset and the CO injection system was primed. The mass flow controllers then injected CO into the chamber to achieve the desired concentration within the target time period. The ASD system monitored alarm activation and recorded each signal on an independent data channel. Most CO concentration modifications were performed by the control program, but on occasion CPSC staff needed to make manual adjustments to achieve the target concentration within three minutes. The computer system would then take control and stabilize the concentration at the required set point.

After the test was completed, the chamber was purged until the gas analyzers indicated CO concentrations less than 1 ppm and the alarms were permitted to reset while being powered. If the alarm required a manual reset with a front panel button, this action was performed after the alarm stopped any audible signal production.

Results

UL 2034 Section 42.1 B 30 ppm Stability Test

Test Requirements

Two representative alarms from each model shall be conditioned for 48 hours under the ambient conditions specified in Section 39.2.1 of UL 2034 (73.4 ± 5 °F, 50 ± 20 % RH). The alarms shall then be placed in the test chamber with conditions specified in Section 39.2.1 and subjected to 30 ± 3 ppm CO for 30 days. This level of carbon monoxide must be reached with 3 minutes of injection and is to be maintained for the entire test period. The alarms shall not activate.

Stability Test Analysis

The 30 ppm Stability test is used to evaluate the potential for nuisance activations from transient levels of carbon monoxide. The alarms cannot activate for the presence of CO for the duration of 30 days when exposed to 30 ppm CO.

The control system maintained all environmental conditions and CO concentration requirements. CPSC staff regularly checked the analyzers for drift and performed calibrations before and after the test. All alarms passed and did not activate for the presence of 30 ppm CO. It is of note that both model F alarms tested developed a trouble signal during the test. The batteries were tested for low voltage and were found to be sufficiently above the threshold for a low battery signal. The development of a trouble signal does not constitute a failure.

UL 2034 Section 42.1 C Cyclic Temperature Test

Test Requirements

Two samples of each model shall be subjected to a cyclic temperature change. Ten cycles of temperature variation between 32 °F and 120 °F are to be conducted such that the alarms remain at each specified temperature for a minimum of 15 minutes. This test is to begin at 32 °F and the time period to achieve the next temperature setting is to be between 5 and 60 minutes. A false alarm condition may not occur for any sample for the duration of the test.

Cyclic Temperature Test Analysis

The cyclic temperature test evaluates the potential for nuisance alarm development due to extreme temperatures and temperature fluctuations. For this test, the temperature values were stabilized for 20 minutes. The time to achieve the temperature extremes was approximately 10 minutes per cycle change. All alarms in this study passed and did not develop a false alarm condition. Figure 1 is a graph of the temperature modulation for the test.
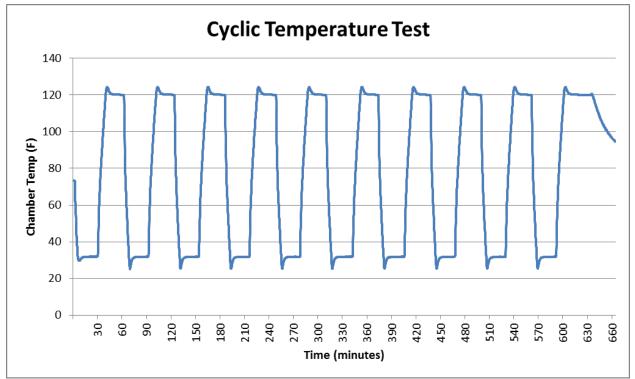

Figure 1. UL 2034 Section 42.1 C Cyclic Temperature Test Temperature Modulation.

UL 2034 Section 47.1 Humidity Test

Test Requirements

Two samples of each model shall operate for their intended signaling performance when exposed for 168 hours to a high humidity and low humidity condition. The specifications for the environmental conditions are 125 ± 5 °F at 95 ± 4 % RH for the high humidity test and 72 ± 5 °F at 10 ± 3 % RH for the low humidity test. Each batch of alarm samples shall remain in the specified condition for 168 hours prior to testing. The conditions must be maintained during the subsequent general sensitivity tests. The 30 day 30 ppm test shall be performed for 8 hours.

Humidity Test Results

High Humidity Test Results

Table 3. High Humidity Activation Times (failures noted in red)

High RH Activation Times (min)			
Sample No.	70 ppm	150 ppm	400 ppm	30 ppm
	60-240 min	10-50 min	4-15 min	N/A
A11	86.72	28.25	0.00	N/A
A16	90.97	29.25	0.32	N/A
B7	81.08	29.28	5.50	N/A
B16	86.25	30.23	6.47	N/A
C6	74.00	19.72	6.83	N/A
C14	77.03	25.38	6.87	N/A
D3	73.62	20.92	6.90	N/A
D12	73.05	22.00	6.88	N/A
E7	0.25	0.00	19.57	3.73
E8	N/A	N/A	6.82	N/A
F7	74.00	19.78	6.08	133.12
F8	N/A	N/A	N/A	N/A

*N/A = No Activation.

Low Humidity Test Results

Table 4. Low Humidity Activation Times (failures noted in red)

Low RH Activation Times (min)			
Sample No.	70 ppm	150 ppm	400 ppm	30 ppm
	60-240 min	10-50 min	4-15 min	N/A
A4	92.20	28.32	6.02	N/A
A12	88.28	28.13	5.82	N/A
B5	112.93	32.93	7.62	N/A
B17	N/A	39.98	8.13	N/A
C11	83.13	25.82	7.78	N/A
C16	93.72	25.82	7.77	N/A
D10	71.65	25.13	7.37	N/A
D17	71.57	25.05	6.53	N/A
E14	N/A	38.50	8.73	N/A
E17	N/A	52.63	10.58	N/A
F1	97.08	46.52	N/A	N/A
F3	90.82	53.78	N/A	N/A

*N/A = No Activation.

Humidity Test Analysis

The humidity test evaluates the performance of CO alarms at dry and nearly saturated relative humidity levels. Modifications were made to the test chamber to provide the control needed to stabilize the environment to 10 percent RH.

The high humidity test, 125 ± 5 °F at 95 ± 4 % RH, subjected the alarms to a highly water-saturated environment. Models B, C, and D passed all sensitivity tests. Model A activated early for the 400 ppm test. Model E had several notable failures. Sample E7 was producing an alarm signal when no CO was present prior to the 70 ppm and 150 ppm test. It then activated late for the 400 ppm test and activated during the 30 ppm nuisance alarm test. Model E8 did not activate for the 70 ppm and 150 ppm levels; however, it did activate properly for the 400 ppm test and did not activate, thereby passing, the 30 ppm test. Sample F7 activated properly for all tests with the exception of activating during the 30 ppm test. Sample F8 did not activate for any of the concentrations. The lack of activation seen in models E and F are dangerous failure modes. The failure was not shared by any set of samples. For instance, model E had one alarm that activated early and the other alarm did not activate at all. High humidity clearly impacts the performance of residential CO alarms.

The low humidity test, 72 ± 5 °F at 10 ± 3 % RH, resulted in five failures to activate. Models A, C, and D met the basis for acceptability of the general sensitivity test. Model B had one alarm that did not activate in the presence of 70 ppm. Both Model E alarms did not activate for the 70 ppm test. Model E also had one alarm that activated slightly late for the 150 ppm concentration. Both model F alarms did not activate for the 400 ppm test and one activated late for the 150 ppm test. No alarms activated during the 30 ppm nuisance alarm test.

UL 2034 Section 53 Undervoltage Test

Test Requirements

Three alarms from each model shall operate for their intended signaling performance when energized by a supply of 85 percent of the test voltage specified by the manufacturer. For units powered from a primary battery, the test shall be conducted at the battery trouble signal. For units with a battery backup or standby battery, the test is to be conducted at 85 percent of the charged battery voltage.

The general sensitivity test specified in Table 39.1 of UL 2034 was performed with the exception that the 30 day, 30 ppm test is only operated for 8 hours. Section 53 specifies this shorter duration for the 30 ppm test. The alarms must perform to the requirements established in the sensitivity test while energized at the voltages specified in Section 53.

Undervoltage Test Results

Table 5. Undervoltage Activation Times (failures noted in red)

Activation Times (min)			
Sample No.	70 ppm	150 ppm	400 ppm	30 ppm
	60-240 min	10-50 min	4-15 min	N/A
A3	91.97	29.17	5.53	N/A
A6	95.23	29.75	6.28	N/A
A7	86.83	28.28	5.52	N/A
B1	80.05	28.30	5.08	N/A
B9	76.45	27.20	4.12	N/A
B16	71.42	26.73	3.65	252.30
C5	81.92	25.93	7.87	N/A
C6	83.48	25.90	7.87	N/A
C12	77.53	25.77	7.77	N/A
D5	73.33	25.67	7.72	N/A
D6	74.95	26.50	6.87	N/A
D14	74.98	26.43	7.98	N/A
E3	162.43	17.63	2.67	N/A
E7	N/A	N/A	11.03	N/A
E12	161.92	17.68	0.85	N/A
F5	80.78	34.40	5.85	118.97
F10	86.28	29.53	5.67	196.78
F12	80.77	34.58	5.28	232.70

*N/A = No Activation.

Undervoltage Test Analysis

This test evaluates the effects of a low energy condition from the power supply on the sensitivity of the system to carbon monoxide. The supply voltages were determined either by reducing the input voltage by 15 percent from the manufacturer recommended supply, or by testing for the low battery signal threshold using a variable power supply.

To determine the low battery signal threshold, a variable power supply was connected to the alarm through the battery circuit. The voltage was initially input at the manufacturers recommended voltage based on the required amount and type of batteries. The power supply was then turned down in small increments to determine when the low battery signal would activate.

Table 6. Undervoltage Supply Voltages

Sample:	Supply Voltage (VDC)
A3, A6, A7	7.65
B1, B9, B16	3.00
C5, C6, C12	2.55
D5, D6, D14	2.30
E3, E7, E12	7.65
F5, F10, F12	7.30

The alarms were subjected to the general sensitivity test while supplied with the voltages shown above using a variable power supply. Models A, C, and D passed all sensitivity levels and the 8 hour, 30 ppm nuisance alarm test. Model B had one alarm activate early for the 400 ppm concentration. This same alarm activated during the 30 ppm test. Model E had one alarm that did not activate for the 70 ppm or 150 ppm concentration. Another model E alarm activated early for the 400 ppm concentration. All model F alarms activated during the 8 hour, 30 ppm test. The actions noted for models B, E, and F are considered failures based on the specifications of the code.

UL 2034 Section 46.1 Variable Ambient Temperature Test (Low Temperature)

Test Requirements

Two alarms from each model shall operate for their intended signaling performance when tested at an ambient condition of 32 °F and 15 ± 5 % RH. The alarms must remain in this condition for a minimum of 3 hours prior to beginning the general sensitivity test. The 30 day, 30 ppm test shall be performed for 8 hours.

Variable Ambient Temperature, Low Temperature Test Results

Table 7. Variable Ambient Temperature, Low Temperature Activation Times (failures noted in red)

Activation Times (min)			
Sample No.	70 ppm	150 ppm	400 ppm	30 ppm
	60-240 min	10-50 min	4-15 min	N/A
A1	103.97	33.13	7.78	N/A
A2	102.12	32.22	7.32	N/A
B1	121.90	36.28	8.72	N/A
B2	118.93	36.32	9.23	N/A
C1	106.47	36.68	9.95	N/A
C2	N/A	37.07	11.22	N/A
D1	75.68	26.72	10.18	N/A
D3	73.27	35.97	9.88	N/A
E1	24.35	8.22	5.05	N/A
E2	57.93	11.08	6.50	N/A
F1	65.23	27.78	17.18	71.08
F3	60.95	27.73	20.25	69.63

*N/A = No Activation.

Variable Ambient Temperature, Low Temperature Test Analysis

This test evaluates the effects of continual low temperature, low humidity on the sensitivity of the CO alarms. The alarms are tested to the general sensitivity test after a 3 hour period in an environment of 32 °F and 15 ± 5 % RH.

Models A, B, and D passed all sensitivity tests and the 30 ppm nuisance alarm test. Model C had one alarm that did not activate in the presence of 70 ppm. Both model E alarms tested activated early for the 70 ppm concentration and one of the alarms also activated early for the 150 ppm test. Both model F alarms activated late for the 400 ppm test and also activated during the 30 ppm nuisance alarm test.

Discussion

CPSC staff used two methods to evaluate the results of the tests presented above. First, the alarms were compared to the criteria established in UL2034. Next, a performance analysis relative to the number of delayed or no activation failure modes was conducted. The two most dangerous failure modes for this product are failures due to delayed or no activation. Continued exposure beyond the durations and concentrations specified in the general sensitivity test of Section 39 may cause significant health effects as well as death.

The UL2034 sensitivity tests require that the alarms activate within a certain period of time depending on the concentration of CO present. This includes a period of time in which they cannot activate to prevent nuisance alarms from transient levels of carbon monoxide. The standard also provides test methods in which the alarms are exposed to 30 ppm CO for 30 days or 8 hours, depending on the particular test. During this period, the alarms cannot activate. These criteria were established to prevent premature activation, which may lead to a lack of consumer confidence in the performance of the alarms. A reduction in the perceived reliability of CO alarms could lead to consumers disregarding the alarm entirely, even when dangerous levels of CO were present and detected. Table 8 shows the failure rates of the alarms tested based on the activation period specified in UL2034.

The data provided from the tests was also used to evaluate failures due to delayed or no activation. This scenario is one of the most dangerous of failure modes. Table 9 shows the performance of the alarms tested relative to these criteria. The failure rates due to delayed or no activation are significantly lower.

Models A, B, C, and D performed moderately well for all tests when evaluated using both performance criteria. Both model A alarms tested to the high humidity test of Section 47.1 failed the 400 ppm concentration by activating early. They activated at approximately the same time that the CO concentration was stabilized. Model B had three failures, each during a different test. One alarm out of two did not activate during the 70 ppm low humidity test in Section 47.1. One alarm out of three tested for the undervoltage test in Section 53 activated slightly early during the 400 ppm test and also activated during the 8 hour 30 ppm nuisance alarm test. Both failures from model B during the undervoltage test were due to activation, but did not present a hazardous failure. Model C only had one alarm failure for all tests performed in Phase II. One alarm out of two failed to activate during the low temperature test in Section 46.1. This type of failure may allow a consumer to be exposed long enough to develop CO poisoning. According to the basis of acceptability defined in UL 2034, model D were the only alarms that conform to the standard relative to the tests performed.

Models E and F had several failures throughout this test series. Both models had eight failures due to delayed or no activation. Five of the delayed activations were only a few minutes late, but this type of performance may lead to dangerous CO exposure. Based on the UL2034 performance criteria, model E failed 15 tests out of a total of 40. The results show that environmental conditions such as temperature and humidity have a significant effect on the

performance of both models. The undervoltage test results showed that low voltage also adversely influenced performance. Model E had one alarm out of three fail all three injections, but passed the 30 ppm nuisance alarm test when supplied with a lower than recommended voltage. Two of these failures were due to no activation. Model F passed the activation tests during the undervoltage test, but all three alarms failed the 30 ppm nuisance alarm test. Both models displayed a nearly even mix of failures due to early activation and failures due to delayed or no activation.

In comparison to the testing performed in more extreme environmental conditions, models E and F performed better during the General Sensitivity Test of Section 39 in Phase I, with ambient conditions (Brookman, 2012). The tests performed in Phase II focused on the effects of environmental conditions on alarm sensitivity and the results show that models E and F do not perform as well in harsh conditions.

All models passed the 30 ppm 30 day test of Section 42.1 B and the Cyclic Temperature Test of Section 42.1 C.

Table 8. UL2034 Tested CO Alarm Failure Rates

Model	42.1 B 30 ppm Stability Test	42.1 C Cyclic Temp Test	46.1 Variable Ambient Temp Test (Low)				47.1 Humidity Test (High)				47.1 Humidity Test (Low)				53 Undervoltage Test				Total
			70	150	400	30	70	150	400	30	70	150	400	30	70	150	400	30	
A	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2
B	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	3
C	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	2	1	0	0	2	2	1	1	2	1	0	0	1	1	1	0	15
F	0	0	2	0	2	0	1	1	1	1	0	1	2	0	0	0	0	3	14

Table 9. CO Alarm Failure Rates Due to Delayed or No Activation

Model	46.1 Variable Ambient Temp Test (Low)			47.1 Humidity Test (High)			47.1 Humidity Test (Low)			53 Undervoltage Test			Total
	70	150	400	70	150	400	70	150	400	70	150	400	
A	0	0	0	0	0	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	1	0	0	0	0	0	1
C	1	0	0	0	0	0	0	0	0	0	0	0	1
D	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	1	1	1	2	1	0	1	1	0	8
F	0	0	2	1	1	1	0	1	2	0	0	0	8

Conclusions

The results of this test series show that most of the tested alarms performed to the specifications of the UL2034 standard. However, relative to the basis of acceptability defined in UL2034, only one model passed all tests in Phase II.

Many of the failures during testing were due to early activations relative to the time periods required by UL 2034. CPSC staff considered early activations a technical failure based on UL 2034, because, while this mode of failure indicates the presence of CO prior to reaching dangerous exposure limits, it may reduce may reduce consumer confidence in CO alarms.

Only two models tested showed a relatively high instance of delayed or no activation failure modes. Model E, based on a semiconductor sensor, and Model F, based on a biomimetic sensor, produced eight potentially hazardous failures each out of 21 test scenarios. These two models produced the most failures overall and the most delayed or no activation failures. All other models tested used electrochemical sensor technology. The results of this test set indicate that electrochemical sensor technology may be more robust than the other two technologies tested.

Most tested alarms activated properly, even in the presence of harsh environmental conditions or at less than recommended supply voltage. The electrochemical sensor based CO alarms produced a total of six failures while the semiconductor CO alarms produced 15 failures and the biomimetic CO alarms produced 14 failures. It is important to note that four electrochemical CO alarm models were tested while only one semiconductor CO alarm model and one biomimetic CO alarm were tested in this series.

Recommendations

While semiconductor and biomimetic sensor technologies are less common than electrochemical sensors in the current market for CO alarms, the performance shown in the results of this project suggest that these technologies may not be performing adequately according to the current requirements of UL 2034. CPSC staff recommends additional testing focusing on semiconductor and biomimetic sensor technologies' conformance to UL 2034. Additional investigation beyond the tests performed in this project, such as the selectivity test, are also recommended.
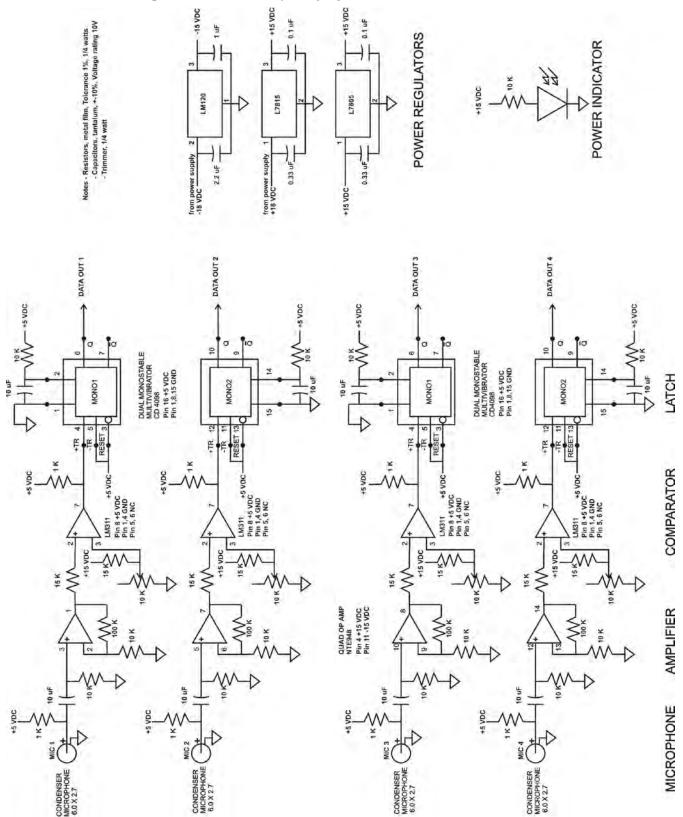
References

"2009 Jarden Home Safety Survey," LCWA Research Group: Feb 2009 ed. 23.

"American Housing Survey for the United States: 2009," United States Census Bureau, Current Housing Reports, Series H-150/09: March, 2011.

Brookman, M., *"Carbon Monoxide Conformance Testing TO UL 2034: Standard for Safety For Carbon Monoxide Alarms,"* U.S. Consumer Product Safety Commission, Rockville, MD: 2012.

Clifford, P.K., Siu, D.J., *"Performance Testing of Residential CO Alarms,"* The Gas Research Institute Environment and Safety Business Unit, Report No. GRI-98/0284: December 1998.

Hnatov, M., *"Non-Fire Carbon Monoxide Deaths Associated with the Use of Consumer Products 2009 Annual Estimates,"* U.S. Consumer Product Safety Commission, Bethesda, MD: 2012. http://www.cpsc.gov//PageFiles/136146/co12.pdf.

Tucholski, D.R., *"Carbon Monoxide Alarm Long-Term Testing Program: FY2006 Test Results,"* Directorate for Laboratory Sciences, United States Consumer Product Safety Commission, Washington, D.C.: December 2006.

UL 2034 *"Standard for Safety for Single and Multiple Station Carbon Monoxide Alarms,"* Third Edition, Underwriters Laboratories Inc. (UL), Northbrook, IL: February 28, 2008.

Appendix

A.1 Audible Signal Detection (ASD) System Schematic

A.2 Test Procedures

Test Series Summary

Standard Number	UL 2034 2008	
Standard Name	Single and Multiple Station Carbon Monoxide Alarms	
Test #	Specifications	Description
1	Section 42.1 (B) 30 PPM Stability Test	To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm when exposed to 30 ppm CO for 30 days.
2	Section 42.1 (C) Cyclic Temperature Test	To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm during exposure to extreme cyclic temperature variation from 32 °F to 120 °F.
3	Section 47.1 Humidity Test	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 125 ±5 °F, 95 ±4 % relative humidity and 72 ±5 °F, 10 ±3 % relative humidity.
4	Section 53 Undervoltage Test	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity with an inadequate power supply voltage based on UL2034 Table 39.1 and section 53 specifications.
5	Section 46.1 Variable Ambient Temperature Test (Low Temperature)	To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 32 °F, 15 ±5 % relative humidity.

Test Details

Standard Number			UL 2034 2008
Standard Name			Single and Multiple Station Carbon Monoxide Alarms
Test #	Samples	Section	Description
1	12	42.1(B)	Specimens consist of 3 manufacturers, 2 models from each and 2 samples of each model. New samples.
Goal			
To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm when exposed to 30 ppm CO for 30 days.			
Test Method Summary			
Preparation: Condition alarms for not less than 48 hours under the ambient conditions specified in section 39.2.1 (73.4 $\pm$5 °F or a higher temperature if specified by the manufacturer, 50 $\pm$20 % relative humidity, 20.9 $\pm$1 % oxygen). Turn on computer and activate Chamber BMS exhaust on BMS computer, ensure chamber is clear of all unnecessary equipment, seal chamber door, shut down purge system, open cylinders 5, 16, and 22, and calibrate CO analyzer.			
Test: Place two representative CO alarm samples, set at maximum sensitivity, in the test chamber with ambient conditions specified in section 39.2.1 and provide power to the alarms for 15 $\pm$5 minutes. The test chamber is then to be sealed. Carbon monoxide is then to be introduced into the test chamber slowly and circulated in the chamber to produce a uniform concentration of 30 $\pm$3 ppm. This level of carbon monoxide is to be established within 3 minutes after sealing the chamber and is to be maintained throughout the remainder of the test. Once the specified carbon monoxide level has been established, the alarms shall not activate in this environment for 30 days. An audible alarm pickup circuit on each alarm will be connected to a DAQ system to monitor the activation of each alarm.			
Safety Considerations: Two CO lab trained personnel must be on site at all times if lab is occupied. Safety glasses and personal CO monitors are required.			
Equipment List			
- Alarm Chamber - Alarm Chamber Computer System - Conditioning Chamber - BMS System - Alarm Chamber Analyzer Rack - N2, 0.1% CO, 100% CO - Personal CO alarms - Audible Signal Detection System (12) - Audible Alarm Pickup DAQ			

Standard Number		UL 2034 2008	
Standard Name		Single and Multiple Station Carbon Monoxide Alarms	
Test #	Samples	Section	Description
2	12	42.1(C)	Specimens consist of 3 manufacturers, 2 models from each and 2 samples of each model.

Goal
To determine the capability of a sample of CO alarms currently available on the consumer market to avoid false alarm during exposure to extreme cyclic temperature variation from 32 F to 120 F.

Test Method Summary
Preparation: Condition alarms for not less than 48 hours under the ambient conditions specified in section 39.2.1 (73.4 $\pm$5 °F or a higher temperature if specified by the manufacturer, 50 $\pm$20 % relative humidity, 20.9 $\pm$1 % oxygen).
Test: Set alarms to maximum sensitivity. Ten cycles of temperature variation between 32 and 120 F are to be conducted. The time of cycling from one extreme to another is to be a maximum of 1 hour and a minimum of 5 minutes, and not less than 15 minutes at each temperature level. *Precondition the chamber to 32 °F. No humidity control needed. When chamber reaches 32 °F, distribute alarms inside. Allow chamber to reestablish 32 F setpoint and allow alarms to set for a minimum of 15 minutes at this point. At the end of this time period, increase the temperature to 120 °F at a rate between 5 and 60 minutes. Allow alarms to set for a minimum of 15 minutes at 120 °F. At the end of this time period, bring the chamber temperature down to 32 °F and repeat this cycle 9 additional times. A false alarm condition may not occur for any sample. An audible alarm pickup circuit on each alarm will be connected to a DAQ system to monitor the activation of each alarm.*
Safety Considerations: Safety glasses required.

Equipment List
- Alarm Chamber   - Alarm Chamber Computer System   - Conditioning Chamber   - Audible Signal Detection System(12)   - Audible Alarm Pickup DAQ

Standard Number	UL 2034 2008		
Standard Name	Single and Multiple Station Carbon Monoxide Alarms		
Test #	Samples	Section	Description
3	24	47.1	Specimens consist of 3 manufacturers, 2 models from each and 2 samples of each model for each of the two environmental conditions. Unused samples are to be used.

Goal
To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 125 $\pm$5 F, 95 $\pm$4 % relative humidity and 72 $\pm$5 F, 10 $\pm$3 % relative humidity.

Test Method Summary
Preparation: Condition alarms for not less than 48 hours under the ambient conditions specified in section 39.2.1 (73.4 $\pm$5 °F or a higher temperature if specified by the manufacturer, 50 $\pm$20 % relative humidity, 20.9 $\pm$1 % oxygen). Turn on computer and activate Chamber BMS exhaust on BMS computer, ensure chamber is clear of all unnecessary equipment, seal chamber door, shut down purge system, open cylinders 5, 16, and 22, and calibrate CO analyzer.

Test: Two alarms, one at maximum and one at minimum sensitivity, shall operate for their intended signaling performance when exposed for 168 hours to air having a relative humidity of 95 $\pm$4 % at a temperature of 125 $\pm$5 °F while energized from a source of supply in accordance with 35.3.1(High Humidity Test). See table below for power supply specifications.

Voltage, nameplate	Alarm rated test voltage
110 to 120	120
220 to 240	240
Other	Marked rating

Two alarms, one at maximum and one at minimum sensitivity, shall operate for their intended signaling performance when exposed for 168 hours to air having a relative humidity of 10 $\pm$3 % at a temperature of 72 $\pm$5 °F while energized from a source of supply in accordance with 35.3.1(Low Humidity Test). See table above for power supply specifications.

Sensitivity measurements are to be recorded before and during the Humidity Test, Section 47.1, using the CO values listed in Table 39.1, Part A – Alarm, and Part B – False Alarm, except the 30 day test is to be conducted for 8 hours. All alarm samples tested as part of the tests in this section shall comply with these requirements.

Table 39.1
Carbon monoxide concentration versus time for alarm test points based on 10 percent Carboxyhemoglobin (COHb)

A. Carbon monoxide concentration and response time	
Concentration, ppm	Response time, minutes
70 ±5	60 – 240
150 ±5	10 – 50
400 ±10	4 – 15
B. False alarm – carbon monoxide concentration resistance specifications	
Concentration, ppm	Exposure time, (no alarm)
30 ±3	30 days
70 ±5	60 minutes

Perform the sensitivity tests shown in Table 39.1 at the conditions specified in section 39.2.1 with the 30 day test run for only 8 hours. This test will confirm that the alarms were functioning properly prior to the Humidity Test.

Place two representative, conditioned CO alarm samples per model, one set at maximum sensitivity and one set at minimum sensitivity, in the test chamber with a relative humidity of 95 ±4 % at a temperature of 125 ±5 °F. Allow the alarms to remain in the specified conditions for 168 hours. Upon completion of 168 hours, perform the tests specified in Table 39.1 again. Maintain the specified conditions during the testing.

After this test is complete, remove the tested alarms and set the environmental conditions to a relative humidity of 10 ±3 % at a temperature of 72 ±5 °F. Place two new representative, conditioned CO alarm samples per model, one set at maximum sensitivity and one set at minimum sensitivity, in the test chamber for 168 hours. Upon completion of 168 hours, perform the tests specified in Table 39.1 again. Maintain the specified conditions during the testing.

Both units shall operate as intended in both ambient conditions. The sensitivity readings shall not, in any case, exceed the limits specified in Table 39.1 with the exception that the 30 day test is only operated for 8 hours. An audible alarm pickup circuit on each alarm will be connected to a DAQ system to monitor the activation of each alarm.

Safety Considerations: Two CO lab trained personnel must be on site at all times if lab is occupied. Safety glasses and personal CO monitors are required.

Equipment List
- Alarm Chamber
- Alarm Chamber Computer System
- Conditioning Chamber
- BMS System
- Alarm Chamber Analyzer Rack
- N2, 0.1% CO, 100% CO
- Personal CO alarms
- Audible Signal Detection System (12)
- Audible Alarm Pickup DAQ

Standard Number	UL 2034 2008		
Standard Name	Single and Multiple Station Carbon Monoxide Alarms		
Test #	Samples	Section	Description
4	18	53	Specimens consist of 3 manufacturers, 2 models from each and 3 samples of each model for each of the two environmental conditions. Unused samples are to be used.
Goal			
To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity with an inadequate power supply voltage based on UL2034 Table 39.1 and section 53 specifications.			
Test Method Summary			

Preparation: Condition alarms for not less than 48 hours under the ambient conditions specified in section 39.2.1 (73.4 $\pm$5 °F or a higher temperature if specified by the manufacturer, 50 $\pm$20 % relative humidity, 20.9 $\pm$1 % oxygen). Turn on computer and activate Chamber BMS exhaust on BMS computer, ensure chamber is clear of all unnecessary equipment, seal chamber door, shut down purge system, open cylinders 5, 16, and 22, and calibrate CO analyzer.

Test: Three alarms shall operate for their intended signaling performance when energized by a supply of 85 % of the test voltage specified by the manufacturer. For units powered from a primary battery, the test shall be conducted at the battery trouble signal voltage level. Sensitivity measurements at the reduced voltage shall not exceed the limits specified in section 39.1.1.

Sensitivity measurements are to be recorded during the undervoltage test, section 53, using the CO values listed in Table 39.1, Part A – Alarm, and Part B – False Alarm, except the 30 day test is to be conducted for 8 hours. All alarm samples tested as part of the tests in this section shall comply with these requirements.

Table 39.1
Carbon monoxide concentration versus time for alarm test points based on 10 percent
Carboxyhemoglobin (COHb)

A. Carbon monoxide concentration and response time	
Concentration, ppm	Response time, minutes
70 ±5	60 – 240
150 ±5	10 – 50
400 ±10	4 – 15
B. False alarm – carbon monoxide concentration resistance specifications	
Concentration, ppm	Exposure time, (no alarm)
30 ±3	30 days
70 ±5	60 minutes

For operation at the reduced voltage, three alarms are to be energized from a source of supply in accordance with 35.3.1(below), following which the voltage is to be reduced to 85 % of the test voltage specified in 35.3.1 for AC operated alarms, or the battery trouble level voltage for battery operated alarms, and then tested for signaling operation and sensitivity. For alarms

intended for connection in a multiple station configuration, the maximum number of alarms specified by the installation instructions is to be interconnected with either 10 ohms resistance between alarms, or the maximum resistance specified in the installation instructions, and tested for intended operation. If the alarm is provided with a standby battery, the test is to be conducted at 85 % of the charged battery voltage. If the standby battery provides a trouble signal requiring replacement at higher than 85 % of the charged battery voltage, the test is to be conducted at the battery trouble signal voltage.

Voltage, nameplate	Alarm rated test voltage
110 to 120	120
220 to 240	240
Other	Marked rating

Place three representative, conditioned CO alarm samples per model, energized based on the preceding conditions, in the test chamber with the environmental conditions specified above. Perform the sensitivity test described in Table 39.1, above.

All alarms shall operate as intended in both ambient conditions. The sensitivity readings shall not, in any case, exceed the limits specified in Table 39.1 with the exception that the 30 day test is only operated for 8 hours. An audible alarm pickup circuit on each alarm will be connected to a DAQ system to monitor the activation of each alarm.

Safety Considerations: Two CO lab trained personnel must be on site at all times if lab is occupied. Safety glasses and personal CO monitors are required.

Equipment List
- Alarm Chamber
- Alarm Chamber Computer System
- Conditioning Chamber
- BMS System
- Alarm Chamber Analyzer Rack
- N2, 0.1% CO, 100% CO
- Personal CO alarms
- Audible Alarm Pickup Circuit (12)
- Audible Alarm Pickup DAQ

Standard Number			UL 2034 2008
Standard Name			Single and Multiple Station Carbon Monoxide Alarms
Test #	Samples	Section	Description
5	12	46.1 Low Temperature	Specimens consist of 3 manufacturers, 2 models from each and 2 samples of each model.

Goal
To determine the capability of a sample of CO alarms currently available on the consumer market to operate as intended of signaling performance when tested for sensitivity at conditions of 32 F, 15 ±5 % relative humidity.

Test Method Summary

Preparation: Condition alarms for not less than 48 hours under the ambient conditions specified in section 39.2.1 (73.4 ±5 °F or a higher temperature if specified by the manufacturer, 50 ±20 % relative humidity, 20.9 ±1 % oxygen). Turn on computer and activate Chamber BMS exhaust on BMS computer, ensure chamber is clear of all unnecessary equipment, seal chamber door, shut down purge system, open cylinders 5, 16, and 22, and calibrate CO analyzer.

Test: An alarm shall operate for its intended signaling performance when tested at ambient conditions of 32 °F, 15 ±5 % relative humidity. Two alarms per model are to be maintained at the specified ambient temperature and humidity for at least 3 hours so that thermal equilibrium is reached. The units are then to be tested for sensitivity while connected to a source of supply that is in accordance with 35.3.1 (see table below). If battery operated, manufacturer's specified voltage shall be used.

Voltage, nameplate	Alarm rated test voltage
110 to 120	120
220 to 240	240
Other	Marked rating

Sensitivity measurements are to be recorded before and during the Variable Ambient Temperature Test, Section 46, using the CO values listed in Table 39.1, Part A – Alarm, and Part B – False Alarm, except the 30 day test is to be conducted for 8 hours. All alarm samples tested as part of the tests in this section shall comply with these requirements.

Table 39.1
Carbon monoxide concentration versus time for alarm test points based on 10 percent
Carboxyhemoglobin (COHb)

A. Carbon monoxide concentration and response time	
Concentration, ppm	Response time, minutes
70 ±5	60 – 240
150 ±5	10 – 50
400 ±10	4 – 15
B. False alarm – carbon monoxide concentration resistance specifications	
Concentration, ppm	Exposure time, (no alarm)
30 ±3	30 days
70 ±5	60 minutes

Perform the sensitivity tests shown in Table 39.1 at the conditions specified in section 39.2.1 with the 30 day test run for only 8 hours. This test will confirm that the alarms were functioning properly prior to the Variable Ambient Temperature Test.

Set chamber to 32 °F, 15 $\pm$5 % relative humidity. Place the conditioned alarms into the chamber and allow 3 hours at these conditions for the alarms to reach thermal equilibrium. After 3 hours, perform the tests specified in Table 39.1 again. Maintain 32 °F, 15 $\pm$5 % relative humidity.

Both units shall operate as intended in both ambient conditions. The sensitivity readings shall not, in any case, exceed the limits specified in Table 39.1 with the exception that the 30 day test is only operated for 8 hours. An audible alarm pickup circuit on each alarm will be connected to a DAQ system to monitor the activation of each alarm.

Safety Considerations: Two CO lab trained personnel must be on site at all times if lab is occupied. Safety glasses and personal CO monitors are required.

Equipment List
• Alarm Chamber   • Alarm Chamber Computer System   • Conditioning Chamber   • BMS System   • Alarm Chamber Analyzer Rack   • N2, 0.1% CO, 100% CO   • Personal CO alarms   • Optical/Audible Alarm Pickup Circuit (12)   • Pickup DAQ