Carbon Monoxide

CAS number:	630-08-0
OSHA PEL:	50 ppm (57 mg/m^3) 8-Hour TWA, General Industry, Construction, Shipyard
IDLH:	1200 ppm (1374 mg/m^3)
Procedure:	Expose a personal gas monitor using a carbon monoxide (CO) electrochemical sensor to workplace air.
Recommended sampling time:	Full shift (up to approximately 8 hours with new batteries)
Reporting limit:	2 ppm
Working range:	2-2000 ppm
Uncertainty (u):	14% (8-Hour TWA; 26% when nitric oxide is ≥ 4 ppm and ≤ 25 ppm) 7.6% (IDLH; 7.8% when nitric oxide is ≥ 4 ppm and ≤ 100 ppm))
Special requirements:	Determine the air concentration of nitric oxide (NO) if it is present at the monitoring site. Do not use this method when hydrogen, acetylene, or ethene are present.
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1 Introduction

The methodologies described in this method replace OSHA's use of OSHA Method ID-209.[1] That method requires the monitoring of CO using a Dräger Model 190 CO Datalogger. This method uses an updated direct-reading monitor with an electrochemical sensor for on-site monitoring of CO.

2 Monitoring Procedure

Follow all safety practices that apply to the work area where monitoring occurs.

2.1 Apparatus

- A multiple-gas personal gas monitor with a one-second or less datalogging interval and a ten-hour operating time (i.e., Dräger X-am 5600 Multi-Gas Detector with a firmware version of 7.8 or equivalent)
- CO electrochemical sensor with a manufacturer-listed working range of 0-2000 ppm and an internal selective filter for minimizing interferences (i.e., Dräger XXS CO LC or equivalent)
- Electrochemical sensors for monitoring interferents (i.e., Dräger nitric oxide electrochemical sensor or equivalent)
- Calibration adapter with 1/4-inch I.D. polytetrafluoroethylene or fluoroelastomer tubing
- Calibration gas cylinders of CO at 50 and 200 ppm with a manufacturer-listed accuracy of ≤ ±5%
- Calibration gas cylinders of NO at 25 ppm with a manufacturer-listed accuracy of ≤ ±5%
- Compatible calibration gas regulators with a fixed gas flow of 0.5 L/min
- Data communication adapter and cable
- Battery packs with rechargeable or non-rechargeable batteries
- NIST traceable temperature and barometric pressure monitor (i.e., Kestrel Instruments 5000 Environmental Meter or equivalent)
- Monitor-specific software (i.e., Dräger CC-Vision Basic)

2.2 Technique

2.2.1 Safety Alarm

Set safety alarms to the immediately dangerous to life or health (IDLH) value or maximum indication range to avoid unnecessary interruptions during monitoring.

2.2.2 Time Synchronization

Synchronize the monitor with local time within 24 hours prior to use.

2.2.3 Calibration

Equilibrate the monitor to the ambient temperature of the monitoring site for at least 15 minutes. Power on the monitor and wait for completion of warm-up. Zero-calibrate the monitor by directly exposing it to clean air. Next, place the monitor into a calibration adapter supplied with 200-ppm CO calibration gas and wait until the reading is stabilized before span calibration. If a nitric oxide interference is suspected, calibrate the monitor with 25-ppm NO calibration gas.

Immediately following the span calibration, verify the monitor calibration using a 50-ppm CO calibration gas as a continuous calibration verification (CCV). Re-calibrate the monitor if the stabilized reading is not within 50 ± 5ppm.

Leave the monitor on until just prior to monitoring.

2.2.4 Monitoring

Turn off the monitor and install new batteries in the monitor. Wait until the completion of warm-up. Position the monitor securely in the worker's breathing zone. Record the time, atmospheric pressure, and temperature at the start and end of monitoring on the Form OSHA-91A.

At the end of monitoring, re-verify the monitor calibration using a 50-ppm CO calibration gas.

Turn off the monitor and return the monitoring equipment to the OSHA Technical Center with the Form OSHA-91A.

3 Data Processing Procedure

3.1 Data Examination

Examine the downloaded monitoring data and identify all possible events including powering on and off, time synchronization, calibration, CCVs, monitoring duration, abnormal monitor readings, etc. Identify any responses over the IDLH.

3.2 Determination of TWA

Calculate the time-weighted average (TWA) air concentration (C_S) in terms of parts of analyte per million parts of air (ppm) at the monitoring site temperature and pressure by summating all data points and dividing by the number of data points collected over the monitoring period. For example, divide by 14,400 when monitoring with a data collection rate of one second for 240 minutes. Use 2,000 ppm for any response over the maximum indication value of 2,000 ppm.

3.3 Determination of IDLH

Identify the highest air concentration (C_S) value in terms of parts of analyte per million parts of air (ppm) at the monitoring site temperature and pressure.

3.4 Calculation

Calculate the air concentration (C) in terms of ppm at 760 mmHg and 25 °C using Equation 1, where C_S is the measured monitoring site air concentration (ppm), P is the monitoring site atmospheric pressure (mmHg), and T is the monitoring site temperature (°C).

$$C = C_s \times \frac{P}{760\ mmHg} \times \frac{298.15\ K}{T + 273.15\ K} \tag{1}$$

The OSHA Integrated Management Information System (IMIS) number for CO is 0560.

4 Method Validation

The procedures used to develop the method validation data are described in OSHA Technical Center's Guideline 2 *Direct-Reading Methods*.[2] The target concentration (T_C) values for method evaluation were the OSHA 8-hour TWA permissible exposure limit (PEL) and the IDLH value for carbon monoxide.

Dynamically generated controlled test atmospheres were created in a walk-in hood for all validation tests. House air was regulated using a flow-temperature-humidity control system. A measured flow of 10% carbon monoxide was introduced near the entrance of the test atmosphere, where it was mixed into a measured flow of dilution air from the flow-temperature-humidity control system. The carbon monoxide and dilution air flowed into a mixing chamber, and then into a testing chamber. Monitors were placed into the testing chamber. Temperature and humidity measurements were obtained near the exit of the testing chamber.

4.1 Time of Response

The time needed for the response to reach 63% of the final steady-state measured value (t_{63}) was determined by sampling dynamically generated controlled test atmospheres containing carbon monoxide at 204 and 1023 ppm. The relative humidity and temperature of the air sampled were 15% and 21 °C. The t_{63} value was determined from signal rise of three monitors quickly placed into the test atmosphere, and signal decay of three monitors quickly removed after signal stabilization. Tests were performed six times at each concentration for each monitor. Results were calculated as described in *Direct-Reading Methods*.[2] Results obtained are provided in Table 1. The t_{63} value was determined to be 7 seconds. (Note: the time of response decreases with increasing humidity. The time of response determined above is designated to provide a sufficient time for obtaining a stable reading at low relative humidity.)

Table 1. Time of response for carbon monoxide (ppm values listed at 644 mmHg and 21 °C).

monitor no.	204 ppm rise in sec (%CV)	204 ppm decay in sec (%CV)	1023 ppm rise in sec (%CV)	1023 ppm decay in sec (%CV)	mean t_{63} in sec
monitor 1	7.0 (1.35%)	7.3 (1.42%)	7.0 (2.93%)	7.2 (1.09%)	7.1
monitor 2	7.0 (1.05%)	7.2 (1.64%)	7.1 (1.28%)	7.3 (1.11%)	7.2
monitor 3	6.7 (1.78%)	7.0 (1.59%)	7.0 (8.68%)	6.9 (2.54%)	6.9

4.2 Limit of Detection and Reporting Limit

The limit of detection (LOD) was determined by sampling dynamically generated controlled test atmospheres where the relative humidity and temperature of the air sampled were 81% and 22 °C. The LOD is the concentration that produces a response greater than 3.3× the standard error of estimate ($S_{y/x}$) divided by the slope of the line produced from three monitors used at six evenly spaced levels across a concentration range of 0 to 5 times the monitor resolution. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The reporting limit (RL) is designated to be 2 ppm, the nearest reading above the LOD resulting in a recovery ≤ ±25%. Results obtained are provided in Table 2 and plotted in Figure 1.

Table 2. LOD and RL data for carbon monoxide (ppm values listed at 642 mmHg and 22 °C).

concn (ppm)	monitor no.	response (ppm)
0.00	monitor 1	0
0.00	monitor 2	0
0.00	monitor 3	0
1.03	monitor 1	0
1.03	monitor 2	0
1.03	monitor 3	0
1.96	monitor 1	2
1.96	monitor 2	2
1.96	monitor 3	2
3.03	monitor 1	3
3.03	monitor 2	3
3.03	monitor 3	3
4.03	monitor 1	4
4.03	monitor 2	4
4.03	monitor 3	4
5.00	monitor 1	5
5.00	monitor 2	5
5.00	monitor 3	5

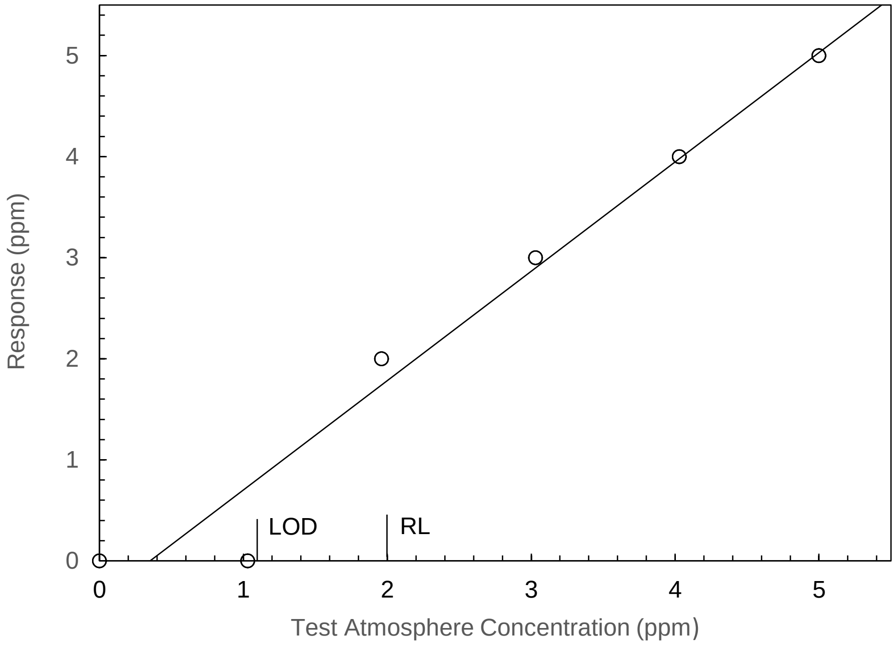

Figure 1. Plot of data used to determine the LOD and RL for carbon monoxide ($y = 1.08x - 0.380,\ S_{y/x} = 0.378$, LOD = 1.15 ppm, RL = 2 ppm).

4.3 Working Range

The working range was tested by sampling dynamically generated controlled test atmospheres where the relative humidity and temperature of the air sampled were 81% and 22 °C. Three monitors were used at ten evenly spaced levels across a concentration range of the RL to 90% of the maximum indication value of 2000 ppm. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). Results obtained are provided in Table 3.

Table 3. Working range data for carbon monoxide (ppm values listed at 652 mmHg and 22 °C).

concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
1.96	102.0	102.0	102.0	102.0
199	102.5	102.5	102.5	102.5
399	102.3	102.3	102.3	102.3
600	101.7	101.7	101.7	101.7
795	101.9	101.3	101.9	101.7
994	101.6	101.6	101.6	101.6
1187	100.3	100.3	101.1	100.6
1385	101.1	100.4	101.1	100.9
1581	101.8	101.2	101.8	101.6
1771	101.1	101.1	101.1	101.1

4.4 Method Precision and Bias

The 8-hour TWA method precision and bias was determined by monitoring dynamically generated controlled test atmospheres for 240 minutes. Three monitors were used at five levels across a concentration range of 0.1 to 5× the 8-hour TWA T_C. The results of these tests are provided in Table 4, along with the concentration, temperature, and relative humidity of each test atmosphere. The coefficient of variation of the means of the five levels tested (CV_{m_TWA}) was 1.1%, and the pooled coefficient of variation of each of the five levels tested (CV_{pl_TWA}) was 0.29%. The resulting 8-hour TWA method precision (u_{mp_TWA}) for carbon monoxide was determined to be 1.1%. The mean recovery of all fifteen results was 102.9%, resulting in a method bias (B_{mp_TWA}) of 2.9% and a percent coefficient of variation (CV_{mb_TWA}) of 1.0%.

Table 4. Method precision data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

concn (ppm)	temp (°C)	RH (%)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
5.02	22	80	103.2	103.2	103.2	103.2
25.0	22	80	103.2	104.0	103.6	103.6
50.1	22	79	101.2	100.8	101.8	101.3
102	22	80	104.0	103.8	104.1	104.0
251	22	79	102.4	102.4	102.2	102.3

The IDLH method precision and bias was determined by monitoring dynamically generated controlled test atmospheres for 30 minutes. Three monitors were used at five levels across a concentration range of 0.75 to 1.25× the IDLH T_C. The results of these tests are provided in Table 5, along with the concentration, temperature, and relative humidity of each test atmosphere. The coefficient of variation of the means of the five levels tested (CV_{m_IDLH}) was 0.75%, and the pooled coefficient of variation of each of the five levels tested (CV_{pl_IDLH}) was 0.25%. The resulting IDLH method precision (u_{mp_IDLH}) for carbon monoxide was determined to be 0.78%. The mean recovery of all fifteen results was 101.1%, resulting in a method bias (B_{mp_IDLH}) of 1.1% and a percent coefficient of variation (CV_{mb_IDLH}) of 0.71%.

Table 5. Method precision data for carbon monoxide (IDLH, ppm values listed at 760 mmHg and 25 °C).

concn (ppm)	temp (°C)	RH (%)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
913	22	81	101.2	100.9	100.9	101.0
1094	22	81	101.5	100.8	100.8	101.0
1211	22	78	100.4	100.1	100.1	100.2
1340	22	80	102.5	102.3	102.0	102.3
1529	22	80	100.9	101.2	100.9	101.0

4.5 Effect of Face Velocity

The 8-hour TWA effect of face velocity was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the 8-hour TWA T_C. The relative humidity and temperature of the air monitored were 82% and 22 °C. Three monitors were used at five levels across a velocity range of 0.1 to 1.0 m/s. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 8, along with the concentration of each test atmosphere. The effect of face velocity (Δ_{v_TWA}), calculated as the absolute difference between the maximum mean recovery and the minimum mean recovery through all tested face velocities was 1.9%.

Table 6. Face velocity data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

face velocity (m/s)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
0.1	50.3	101.4	103.1	103.1	102.5
0.3	49.4	103.3	103.3	103.3	103.3
0.5	49.7	102.6	102.6	102.6	102.6
0.7	50.7	102.3	102.3	102.3	102.3
1.0	50.6	104.2	104.2	104.2	104.2

The IDLH effect of face velocity was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the IDLH T_C. The relative humidity and temperature of the air monitored were 82% and 22 °C. Three monitors were used at five levels across a velocity range of 0.1 to 1.0 m/s. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 7, along with the concentration of each test atmosphere. The effect of face velocity (Δ_{v_IDLH}), calculated as the absolute difference between the maximum mean recovery and the minimum mean recovery through all tested face velocities was 2.6%.

Table 7. Face velocity data for carbon monoxide (IDLH, ppm values listed at 760 mmHg and 25 °C).

face velocity (m/s)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
0.1	1193	99.3	100.0	99.3	99.5
0.3	1189	101.1	101.1	101.8	101.3
0.5	1187	100.5	100.5	100.5	100.5
0.7	1203	100.6	100.6	100.6	100.6
1.0	1208	102.4	101.6	102.4	102.1

4.6 Effect of Orientation

The 8-hour TWA effect of orientation was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the 8-hour TWA T_C. The relative humidity and temperature of the air monitored were 82% and 22 °C. Three monitors were used to test two flow directions of 0° and 90° relative to the diffusion orifice. The face velocity was 0.5 m/s. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 8, along with the concentration of each test atmosphere. The effect of orientation (Δ_{o_TWA}), calculated as the absolute difference between the two orientations tested was 1.2%.

Table 8. Orientation data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

flow direction to diffusion orifice (°)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
0	50.8	103.8	103.8	103.8	103.8
90	49.7	102.6	102.6	102.6	102.6

The IDLH effect of orientation was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the IDLH T_C. The relative humidity and temperature of the air monitored were 82% and 22 °C. Three monitors were used to test two flow directions of 0° and 90° relative to the diffusion orifice. The face velocity was 0.5 m/s. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 9, along with the concentration of each test atmosphere. The effect of orientation (Δ_{o_IDLH}), calculated as the absolute difference between the two orientations tested was 0.90%.

Table 9. Orientation data for carbon monoxide (IDLH, ppm values listed at 760 mmHg and 25 °C).

flow direction to diffusion orifice (°)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
0	1211	101.4	101.4	101.4	101.4
90	1187	100.5	100.5	100.5	100.5

4.7 Effect of Humidity

The 8-hour TWA effect of low humidity was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the 8-hour TWA T_C for 240 min (calculated to be 52.2 ppm at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 21% and 21 °C. Results for carbon monoxide as a percentage of expected recovery of the three monitors was 102.3%, 102.5%, and 102.5%. The mean percentage of expected recovery was 102.4%. The effect of humidity (Δ_{h_TWA}), calculated as the absolute difference between the mean dry recovery and the mean humid recovery of 101.3% taken from the 50.1 ppm method precision test described in Section 4.4, was 1.1%.

The IDLH effect of low humidity was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the IDLH T_C for 30 min (calculated to be 1214 ppm at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 21% and 22 °C. Results for carbon monoxide as a percentage of expected recovery of the three monitors was 99.0%, 98.7%, and 98.6%. The mean percentage of expected recovery was 98.8%. The effect of humidity (Δ_{h_IDLH}), calculated as the absolute difference between the mean dry recovery and the mean humid recovery of 100.2% taken from the 1211 ppm method precision test described in Section 4.4, was 1.4%.

4.8 Effect of Interferents

The 8-hour TWA effect of interference with nitric oxide was tested by monitoring a dynamically generated controlled test atmosphere containing both carbon monoxide and nitric oxide nominally at the respective 8-hour TWA T_C (calculated to be 49.5 ppm for carbon monoxide and 25.0 ppm for nitric oxide at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 82% and 22 °C. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). Results for carbon monoxide as a percentage of expected recovery of the three monitors was 139.2%, 137.4%, and 140.6%. The mean percentage of expected recovery was 139.1%. The effect of interference of nitric oxide (Δ_{i_TWA}), calculated as the absolute difference between the mean recovery with nitric oxide present and the mean humid recovery of 101.3% taken from the 50.1 ppm method precision test described in Section 4.4, was 38%.

The IDLH effect of interference with nitric oxide was tested by monitoring a dynamically generated controlled test atmosphere containing both carbon monoxide and nitric oxide nominally at the respective IDLH T_C (calculated to be 1190 ppm for carbon monoxide and 99.8 ppm for nitric oxide at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 83% and 22 °C. Results for carbon monoxide as a percentage of expected recovery of the three monitors was 103.6%, 102.9%, and 102.9%. The mean percentage of expected recovery was 103.1%. The effect of interference of nitric oxide (Δ_{i_IDLH}), calculated as the absolute difference between the mean recovery with nitric oxide present and the mean humid recovery of 100.2% taken from the 1211 ppm method precision test described in Section 4.4, was 2.9%.

4.9 Effect of Intermittent Exposure

The effect of intermittent exposure was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the 8-hour TWA T_C (calculated to be 50.2 ppm at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 19% and 22 °C. All monitors were exposed to the test atmosphere for 16 seconds (i.e., $t = 2.3 \times t_{63}$) followed by clean air recovery, where the exposure cycle was repeated ten times for a 160-second intermittent exposure. Subsequently, the monitors were exposed to the test atmosphere for a 160-second steady exposure. Results as a percentage of expected recovery of the three monitors are provided in Table 10. The effect of intermittent exposure (Δ_{ie}), calculated as the absolute difference between the mean intermittent exposure recovery and the mean steady exposure recovery, was 19%.

Table 10. Intermittent exposure data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

total exposure time (s)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
160 (intermittent)	124.2	122.3	122.3	123.2
160 (steady)	104.3	103.7	103.3	103.7

4.10 Effect of Temperature

The effect of temperature was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the 8-hour TWA T_C (calculated at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 79% and 23 °C. Prior to obtaining readings, all monitors were equilibrated at 5 °C, 23 °C, and 50 °C for one hour. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 11, along with the concentration of each test atmosphere. The effect of temperature (Δ_{T_TWA}), calculated as the absolute difference between the minimum mean recovery and the maximum mean recovery through all tested temperatures, was 4.6%.

Table 11. Temperature data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

temperature (°C)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
5	49.9	101.6	99.9	101.6	101.0
23	50.2	101.0	101.0	101.0	101.0
50	50.2	106.2	104.4	106.2	105.6

The IDLH effect of temperature was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at the IDLH T_C (calculated at 760 mmHg and 25 °C). The relative humidity and temperature of the air sampled were 79% and 23 °C. Prior to obtaining readings, all monitors were equilibrated at 5 °C, 23°C, and 50 °C for one hour. Monitor response was determined after exposure to the test atmosphere for 70 seconds (i.e., $t = 10 \times t_{63}$). The results of these tests are provided in Table 12, along with the concentration of each test atmosphere. The effect of temperature (Δ_{T_IDLH}), calculated as the absolute difference between the minimum mean recovery and the maximum mean recovery through all tested temperatures, was 3.0%.

Table 12. Temperature data for carbon monoxide (IDLH, ppm values listed at 760 mmHg and 25 °C).

temperature (°C)	concn (ppm)	monitor 1 (%)	monitor 2 (%)	monitor 3 (%)	mean (%)
5	1198	99.7	98.3	98.3	98.8
23	1206	101.9	101.1	101.1	101.4
50	1202	101.5	100.8	103.0	101.8

4.11 Effect of Oversaturation

The effect of oversaturation was tested by monitoring a dynamically generated controlled test atmosphere containing carbon monoxide nominally at 2× the maximum indication value of 2000 ppm for 10 minutes (calculated to be 4004 ppm at 651 mmHg and 22 °C). The relative humidity and temperature of the air sampled were 80% and 22 °C. After oversaturation for 10 minutes, followed by recovery with clean air for 60 minutes, no monitor response drift was observed.

4.12 Reproducibility

A dynamically controlled test atmosphere was generated, containing carbon monoxide nominally at the 8-hour TWA T_C (calculated to be 50.8 ppm at 760 mmHg and 25 °C). The relative humidity and temperature of the air monitored were 81% and 22 °C. The test atmosphere was monitored by Production Team for 240 min using the monitoring procedure described in Section 2 of this method. The monitor results were then submitted to the OSHA Technical Center for analysis using the data processing procedure described in Section 3 of this method. The monitoring results are provided in Table 13. No sample result for carbon monoxide fell outside the permissible bounds set by the expanded uncertainty determined in Section 4.13.

Table 13. Reproducibility data for carbon monoxide (8-hour TWA, ppm values listed at 760 mmHg and 25 °C).

monitored (ppm)	recovery (%)	deviation (%)
51.5	101.4	+1.4
51.5	101.4	+1.4
51.6	101.6	+1.6

4.13 Estimation of Uncertainty

Carbon monoxide relative standard uncertainty components (u_i) are provided in Table 14 for both the 8-hour TWA and IDLH levels. The combined percent relative standard uncertainty of the monitoring procedure (u) was determined to be 14% for the 8-hour TWA and 7.6% for the IDLH. The expanded uncertainty (U) was determined to be 28% for the 8-hour TWA and 15% for the IDLH.

When nitric oxide was present, that is the air concentration was ≥ 4 ppm where interference on CO sensors has been initially observed, the combined percent relative standard uncertainty of the monitoring procedure (u) was determined to be 26% for the 8-hour TWA and 7.8% for the IDLH. The expanded uncertainty (U) was determined to be 52% for the 8-hour TWA and 16% for the IDLH.

Table 14. Uncertainty.

uncertainty component (u_i)	8-hour TWA (%)	IDLH (%)	notes
calibration standards (u_{cs})	2.9	2.9	$u_{cs} = 5\%/\sqrt{3}$, assumes an accuracy of ±5%
method precision (u_{mp})	1.1	0.78	$u_{mp} = \sqrt{(CV_m)^2 + (1-1/n) \times (CV_{pl})^2}$, where CV_{m_TWA} = 1.1%, CV_{pl_TWA} = 0.29%, CV_{m_IDLH} = 0.75%, CV_{pl_IDLH} = 0.25%, and n = 3, see Section 4.4
method bias (u_{mb})	3.4	3.1	$u_{mb} = \sqrt{(B_{mb}/\sqrt{3})^2 + (CV_{mb}/\sqrt{n})^2 + (u_{rc})^2}$, where B_{mb_TWA} = 2.9%, CV_{mb_TWA} = 1.0%, B_{mb_IDLH} = 1.1%, CV_{mb_IDLH} is 0.71%, and n = 15, see Section 4.4; u_{rc} = 3% see Reference 3
effect of face velocity (u_v)	1.1	1.5	$u_v = \Delta_v/\sqrt{3}$, where Δ_{v_TWA} = 1.9% and Δ_{v_IDLH} = 2.6%, see Section 4.5
effect of orientation (u_o)	0.69	0.52	$u_o = \Delta_o/\sqrt{3}$, where Δ_{o_TWA} = 1.2% and Δ_{o_IDLH} = 0.90%, see Section 4.6
effect of humidity (u_h)	0.64	0.81	$u_h = \Delta_h/\sqrt{3}$, where Δ_{h_TWA} = 1.1% and Δ_{h_IDLH} = 1.4%, see Section 4.7
effect of interference with NO (u_i)*	22	1.7	$u_i = \Delta_i/\sqrt{3}$, where Δ_{i_TWA} = 38% and Δ_{i_IDLH} = 2.9%, see Section 4.8
effect of intermittent exposure (u_{ie})	11	N/A	$u_{ie} = \Delta_{ie}/\sqrt{3}$, where Δ_{ie} = 19%, see Section 4.9
effect of temperature (u_T)	2.7	1.7	$u_T = \Delta_T/\sqrt{3}$, where Δ_{T_TWA} = 4.6% and Δ_{T_IDLH} = 3.0%, see Section 4.10
resolution (u_r)	0.58	0.24	$u_r = [Res/(2 \times \sqrt{3} \times T_C)] \times 100\%$, where Res_{TWA} = 1 ppm, T_{C_TWA} = 50 ppm, Res_{IDLH} = 10 ppm, T_{C_IDLH} = 1200 ppm
monitor response drift (u_{dr})	5.8	5.8	$u_{dr} = 10\%/\sqrt{3}$, assumes a maximum monitor response drift of ±10%
temperature measurement (u_{AT})	0.098	0.098	$u_{AT} = 0.17\%/\sqrt{3}$, assumes a measured accuracy of ±0.5 °C at 25 °C
pressure measurement (u_{bp})	0.12	0.12	$u_{bp} = 0.20\%/\sqrt{3}$, assumes a measured accuracy of ±1.5 mmHg at 760 mmHg

uncertainty component (u_i)	8-hour TWA (%)	IDLH (%)	notes
standard uncertainty (u)	14	7.6	$u = \sqrt{\sum(u_i^2)}$, where u_i represents each uncertainty component as shown above
expanded uncertainty (U)	28	15	$U = k \times u$, where k = 2

***** Uncertainty on effect of interference from nitric oxide is excluded from the standard uncertainty and applied only when the nitric oxide concentration is ≥ 4 ppm.

References

1. Adler, R. G. Carbon Monoxide in Workplace Atmospheres (Direct-Reading Monitor, OSHA Method ID-209), 1990. United States Department of Labor, Occupational Safety & Health Administration website. https://www.osha.gov (accessed March 2024).

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