System Assessment and Validation for Emergency Responders (SAVER)

Handheld Multi-Gas Detectors Application Note

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System Assessment and Validation for Emergency Responders

Prepared by Sandia National Laboratories

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FOREWORD

The U.S. Department of Homeland Security (DHS) established the System Assessment and Validation for Emergency Responders (SAVER) Program to assist emergency responders making procurement decisions. Located within the Science and Technology Directorate (S&T) of DHS, the SAVER Program conducts objective assessments and validations on commercially available equipment and systems and develops knowledge products that provide relevant equipment information to the emergency responder community. The SAVER Program mission includes:

- Conducting impartial, practitioner-relevant, operationally oriented assessments and validations of emergency response equipment
- Providing information, in the form of knowledge products, that enables decision-makers and responders to better select, procure, use, and maintain emergency response equipment.

SAVER Program knowledge products provide information on equipment that falls under the categories listed in the DHS Authorized Equipment List (AEL), focusing primarily on two main questions for the responder community: “What equipment is available?” and “How does it perform?” These knowledge products are shared nationally with the responder community, providing a life—and cost—saving asset to DHS, as well as to Federal, state, and local responders.

The SAVER Program is supported by a network of Technical Agents who perform assessment and validation activities. As a SAVER Program Technical Agent, Sandia National Laboratories has been tasked to provide expertise and analysis on handheld multi-gas detectors. In support of this tasking, Sandia conducted research on handheld multi-gas detectors and their use by emergency responders. Handheld multi-gas detectors fall under AEL reference number 07CD-01-DPMG, titled Detector, Multi-Sensor Meter, Point, Chemical.

For more information on the SAVER Program or to view additional reports on other technologies, visit www.dhs.gov/science-and-technology/SAVER.

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1. INTRODUCTION

Handheld multi-gas detectors are important tools for emergency responders when responding to calls where dangerous levels of gases may be present, such as unknown odor, fuel spill, clandestine laboratory, or arson investigations. Two challenges faced by responders in these environments are (1) whether the air is acceptable for normal, unprotected breathing, and (2) whether the air is clear of potential contaminants. Handheld multi-gas detectors are usually the first line of screening for environmental hazards such as oxygen (O_2) deficiency or enrichment and elevated levels of combustible and/or toxic gases.

2. HANDHELD MULTI-GAS DETECTORS OVERVIEW

Handheld multi-gas detectors are usually equipped with sensors to monitor O_2 levels and detect the presence of combustible and toxic gases in the environment. The number of sensors available on a detector varies widely and the sensors are typically interchangeable to monitor for different gases. Handheld multi-gas detectors use these sensors to analyze the surrounding air and report the concentration of monitored gases and/or general toxic risks in real-time. Handheld multi-gas detectors feature visual, audible, and/or tactile alarms to warn the user when dangerous environmental conditions are present. Additional considerations include the detector's sensitivity, operating ranges, selectivity, and data logging capabilities.

2.1 O_2 Monitoring

O_2 sensors monitor O_2 levels in the environment to detect deficiency or enrichment. O_2 sensors typically display readings as a percent of O_2 by volume in the air and can also indicate whether another gas is present. For example, if there is a 1 percent drop in the normal rate of O_2 in the air, it likely means that some other gas is present. O_2 sensors are either lead wool or solid polymer electrolyte (SPE). Lead wool O_2 sensors have a lifespan of about 2 years and SPE O_2 sensors generally last 3 to 5 years. While they may last longer than lead wool O_2 sensors, SPE O_2 sensors have higher power requirements, typically shortening the battery runtime of the detector.

2.2 Combustible Gas Detection

Lower explosive limit (LEL) sensors, also referred to as combustible gas sensors, monitor the environment to detect elevated levels of combustible gases. These sensors are used to measure the LEL of the gas for which they are calibrated. Most LEL sensors are calibrated for pentane (C_5H_{12}), and can also be calibrated for other combustible gases, such as natural gas or methane (CH_4) or propane (C_3H_8). Different types of LEL sensors are available and include metal oxide semiconductor (MOS), catalytic bead, and infrared (IR). MOS LEL sensors are the most sensitive and therefore perhaps most useful in determining the source of small gas leaks. Detectors with MOS LEL sensors will shut off when the LEL of a monitored gas is exceeded to protect the sensor, since the longer the sensor is exposed to gas above the LEL, the faster it will deteriorate and require replacement. Catalytic bead LEL sensors will also shut the detector off when the LEL of a monitored gas is exceeded. However, these sensors are more durable since they feature a dual-sensor construct that compensates for ambient temperature, humidity, and atmospheric pressure, all of which can shorten sensor life. Both MOS and catalytic bead LEL sensors require sufficient O_2 levels in the environment to monitor combustible gases, whereas IR LEL sensors can monitor combustible gases in O_2 deficient atmospheres. In addition, IR sensors can withstand relatively longer exposure to combustible gases than MOS or catalytic bead sensors and are therefore capable of reporting the percent by volume of a monitored gas even after levels exceed the LEL.

2.3 Toxic Gas Detection

Many multi-gas detectors feature sensors for carbon monoxide (CO) and hydrogen sulfide (H_2S), and some offer detection capabilities for additional toxic gases, such as ammonia (NH_3), chlorine (Cl), formaldehyde (CH_2O), carbon dioxide (CO_2), nitrogen oxides (NO and NO_2), sulfur dioxide (SO_2), and ozone (O_3). Toxic gases are monitored with either electrochemical toxic gas sensors, MOS toxic gas sensors, or photoionization detectors (PIDs). Electrochemical toxic gas sensors are small, easily interchangeable, consume very little battery power, and are highly specific to the target gas being monitored. A limitation of electrochemical toxic gas sensors is that gases with similar properties of a monitored gas may cause false positives. For example, when monitoring for Cl, the sensor may detect other chemicals within the halogen group that have similar properties (e.g., bromine [Br]) and provide a positive reading for Cl. MOS toxic gas sensors and PIDs are less specific and therefore able to identify a wide range of toxic gases. This low level of specificity could be an advantage in situations where unknown toxic gases may be present. Limitations of MOS toxic gas sensors include high battery consumption and the potential for false positives (i.e., mistaking some background gases for toxic ones). PIDs are more sensitive than MOS sensors and will detect toxic gases at lower levels, providing results more rapidly; however, PIDs require frequent calibration. Humidity affects the sensitivity of both MOS toxic gas sensors and PIDs. With increased humidity, PIDs become less sensitive and therefore less likely to detect the presence of a toxic gas in the environment, whereas MOS toxic gas sensors become more sensitive and may therefore overstate the presence of a toxic gas. Additionally, very low humidity can decrease the sensitivity of MOS toxic gas sensors, potentially hindering their ability to detect the presence of a toxic gas.

GAS \ SENSOR	Carbon Monoxide	Hydrogen Sulfide	Sulfur Dioxide	Nitrogen Dioxide	Chlorine	Chlorine Dioxide	Hydrogen Cyanide	Hydrogen Chloride	Phosphine	Nitric Oxide	Hydrogen	Ammonia
Carbon Monoxide	100	2	1	0	0	0	0	0	0	0	20	0
Hydrogen Sulfide	10	100	1	-8	-3	-25	200	60	3	10	20	10
Sulfur Dioxide	0	10	100	0	0	0	—	40	—	0	0	-40
Nitrogen Dioxide	-20	-20	-100	100	12	—	-70	—	—	30	0	0
Chlorine	-10	-20	-25	90	100	20	-20	6	-10	0	0	0
Chlorine Dioxide	—	—	—	—	20	100	—	—	—	—	—	—
Hydrogen Cyanide	15	10	50	1	0	0	100	35	1	0	30	5
Hydrogen Chloride	3	0	0	0	2	0	0	100	0	15	0	0
Phosphine	—	—	—	—	—	—	0	300	100	—	—	—
Nitric Oxide	10	1	1	0	—	—	-5	45	—	100	30	50
Hydrogen	60	0.05	0.5	0	0	0	0	0	0	0	100	0
Ammonia	0	0	0	0	0	0	0	0	0	0	0	100
Acetylene	150	<1	140	<1	—	—	—	—	—	<1	—	—

Figure 2-1. Cross Sensitivity Chart

Image courtesy of Industrial Scientific

While many toxic gas sensors are quite specific, cross sensitivity does occur. Cross sensitivity is a sensor's reaction to an interfering gas. Exposing a sensor to a gas that is not the target gas can cause an unwanted response, either positive or negative. With a positive cross sensitivity, the user can get the impression that more of a target gas is present, than actual. This may cause the responder to induce ventilation or take corrective action to remove the actual gas hazard, which may not be necessary. When a cross sensitivity is negative, it is a greater concern. In this case, a cross-sensitive gas causes the sensor to react in a negative manner. If this is the only gas present, the user will see a negative number on the display and may elect to zero the instrument or assume there is a problem with the detector. Even worse, if a negative cross-sensitive gas and the target gas exist together, you may have a cancelling effect. This can be potentially dangerous if you are unaware of this phenomenon or do not know the potential gases in a sample. Most multi-gas detector manufacturers publish toxic gas sensor cross sensitivity charts. These charts can help the user understand and anticipate cross-sensitive conditions with their gas meters and empower them to act accordingly.

2.4 Calibration and Bump Testing

All electrochemical sensors will eventually lose sensitivity over time with exposure to work conditions. Calibration is used to compensate for the loss of sensitivity and adjust the readings to the new sensitivity output level. Drift is the amount that sensor output changes over time. All sensors experience drift. Once the sensitivity becomes too low, it becomes more difficult to assess exact differences in gas concentrations. Sensors typically have a fixed sensitivity limit assigned by the detector; once that limit is reached, they will not pass calibration.

Calibration is an adjustment of the sensor output to match the known traceable calibration gas concentration. Full calibration ensures maximum accuracy of the instrument. Environmental conditions such as over-exposures, introduction of poisons, heavy impacts, or other extreme environmental changes can cause sensors to become less accurate. Calibration allows the instrument to manage these changes in sensitivity. Sensors should be calibrated at least once monthly, and after each use in the field. In addition, manufacturers recommend that a calibration occur if the unit falls, is dropped, or experiences other significant impact; is exposed to water; fails a bump test; or has been repeatedly exposed to an over-range (positive or negative) gas concentration. A calibration is also recommended after the installation of a new (or replacement) sensor.

Figure 2-2. Calibrating a Detector

Image courtesy of RKI Instruments

The only way to verify proper sensor and alarm operation is to perform a bump test. Bump testing is the process of briefly exposing sensors to an expected concentration of calibration gas that is greater than the low alarm set point. Bump tests are meant to verify that the sensors and the alarms function properly and that the sensors respond within acceptable margins. Gases or vapors must be able to reach the sensor. Bump tests confirm that gas flow paths to the sensor on the detector are clear and the sensors are functioning from a qualitative standpoint. Bump testing will alert users if a gas inlet has become blocked, even if the blockage is not visible. The bump test, however, is not meant to adjust the device's accuracy. Bump testing should be done immediately prior to each use in the field.

2.5 Calibration and Docking Stations

Most manufacturers have either a calibration or docking station for the multi-gas detectors. Both station types will perform basic functions to include bump testing and calibration. While these tests can also be performed manually, both the calibration and docking stations provide added features and benefits.

While characteristics may vary among manufacturers, a calibration station generally provides simple functionality and portability and most commonly:

- Requires the manual push of a button to initiate testing
- Requires manual download to a USB device or directly to a computer equipped with a compatible software program
- Provides a USB connection to connect to a PC or printer to download or print calibration and bump test reports
- Requires manual check of calibration gas levels and expiration.

A docking station provides more functionality than the calibration station which includes:

- Preset bump and calibration frequencies and instrument settings are automatically initiated when the detector is docked
- Recognition of the battery type and charging as necessary
- Automatic capture and storage of all data when the detector is docked to include calibration data, alarm events, employee exposures, and unsafe behaviors such as ignoring or turning off a detector while in alarm or using it without calibration
- Allows parameters such as alarm and calibration gas settings to be uploaded to the detector, eliminating manual instrument configuration changes
- Information on sensor life, sensitivity to target gases or ambient conditions, date of last calibration, and next calibration due

2.6 Additional Considerations and Features

The sensitivity of a handheld multi-gas detector is an important consideration and refers to the lowest concentrations of chemicals in the air that are detectable. Another key consideration is the operating ranges of the sensors, which are the measurable ranges of concentrations that can be reported. The sensitivity and operating ranges will vary by sensor and thus by the type of hazard being monitored. Some multi-gas detectors can be configured to monitor one chemical or group of chemicals and ignore others. This is referred to as selectivity and permits the user to focus on particular hazards of concern with a greater degree of confidence. Some detectors are also capable of data logging and can therefore store information for transmission to a computer for further analysis. This capability allows the user to download key data to create reports, track calibration, sort and graph detection data, and archive information relative to a response.

3. COMMON APPLICATIONS

Handheld multi-gas detectors are used by public safety agencies such as fire and law enforcement for a multitude of incidents, responses, or calls where the hazard is either unknown or there is a need to confirm the presence of oxygen deficiency or enrichment, or the presence of a toxic or combustible gases. The multi-gas detector is a necessary piece of equipment to ensure the safety of the responder as well as to best understand the mitigation options for response environments where dangerous levels of gases exist. Below are a few examples of those types of environments and situations in which a handheld multi-gas detector is needed.

3.1 Hazardous Materials (HazMat) Response

HazMat teams must know in real-time exactly what chemical threats they face in order to determine which level of personal protective equipment (PPE) to wear, and when the area is safe. Multi-gas detectors are necessary tools for HazMat personnel for issues such as assessing PPE needs, detecting gas leaks, and establishing a perimeter. When approaching a potential HazMat incident, the responder must make a PPE decision. Some potential incidents may not require PPE at all, while others may require significant levels of PPE. Often, a gas leak is not readily apparent and it must first be located before it can be stopped. Many detectors utilize a PID to measure concentration gradients for many gases and vapors that would otherwise be undetectable. HazMat technicians assess the incident and set a perimeter based upon the toxicity of the gas or vapor, temperature, wind direction, and other factors. Many of these conditions tend to change during a response and would require effective monitoring to account for these changing conditions to adjust the perimeter. Multi-gas detectors can provide instantaneous alarms that warn personnel when it is necessary to retreat from an incident scene.

Fire departments often respond to calls concerning CO home alarms. Multi-gas detectors can detect the presence of CO upon arrival at call sites and determine if the premises are safe for habitation. In addition, the detectors can be used to locate the gas source (often garages or leaky furnace vents). Moreover, the multi-gas detectors can be used in response to calls for natural gas leaks or suspicious odors to measure concentrations of several gases simultaneously.

3.2 Confined Space Entry

Emergency responders may be called upon to perform services or rescues in confined spaces.

While often industrial in nature, a confined space is typically defined as any enclosed area not meant for human habitation. In the confined work spaces found in chemical plants, paper mills, refineries, underground mines, and utility passageways, the air may be contaminated with toxic or combustible gases or suffer from a lack of oxygen. Each person entering the confined space should carry a multi-gas

Figure 3-1. Confined Space

Image courtesy of SCI Analytical Laboratories detector where it can be checked easily and frequently.

Multi-gas detectors with four or five different sensors may be sufficient for many confined space applications. Some situations may require monitoring capabilities for other substances. Best practices indicate that a worker should sample the air in a confined space prior to entry, continuously during entry, and prior to re-entry. Because some gases are lighter than air and others are heavier than air, stratification can occur. Stratification is the extent to which the heavier gases rise to the top of an initially uniform gas mixture, in the absence of bulk air movement. Gas samples should be taken in 4-foot intervals in every direction of travel to address gas stratification. Sample time is also important to consider for detection in confined spaces. For most multi-gas detectors, the flow rate is between 0.25 and 0.50 liters per minute. When pulling a gas through a sample tubing, it is best to allow 2 seconds per foot of tubing for the sample to travel. Additionally, the detector will need time to react once the sample is read by the sensors, which is usually an additional 30 to 120 seconds.

3.3 Fire Overhaul

Figure 3-2. Fire Overhaul

Image courtesy of Maumelle Fire Department

Fire overhaul includes searching for possible sources of re-ignition, and investigating the origin of the fire. This process includes sifting through smoldering ashes and partially burnt materials, where gases such as CO are formed due to incomplete gas combustion. Other chemicals and compounds found during fire overhaul operations include SO_2, NO, NO_2, and hydrogen cyanide (HCN). HCN and CO are invisible and cannot be detected by the color or amount of smoke present. Detection is critical in overhaul operations in order to ensure that responders are utilizing effective PPE when toxic gases are present. In some cases, firefighters will remove their self-contained breathing apparatus (SCBA) during overhaul operations, with the assumptions that there are no inhalational hazards present. Exposure to HCN can cause convulsions, unconsciousness, or death. CO can cause tissue hypoxia when inhaled, which prevents the blood from carrying sufficient oxygen leading to a variety of serious conditions including convulsions, tachycardia, or death. When inhaled together, HCN and CO can have a synergistic effect, causing a higher probability of serious complications for the firefighter. Multi-gas detectors can help determine which toxins are in the fireground and overhaul environment and provide the real-time information necessary to decide whether to treat the site as a HazMat situation, or whether it is safe to remove PPE. Since overhaul is often an extended operation, one best practice would be to utilize the multi-gas detectors in conjunction with area monitors to identify various concentrations of gases in given areas over time in the fireground, providing real-time situational awareness to on-scene or remote command staff.

3.4 Clandestine Laboratories

The number of clandestine laboratories has increased dramatically in recent years, chiefly due to the popularity of methamphetamine. Some methamphetamine production methods employ a menu of toxic and combustible substances, among them pseudoephedrine, lithium metal strips, hydrochloric acid, acetone, iodine, lye, hydriodic acid, red phosphorous, mercuric chloride, phosphine, and ammonia. Multi-gas detectors, particularly those with PIDs measure volatile organic compounds (VOCs) such as benzene, toluene, and acetone, which are all typical substances used in methamphetamine production. Multi-gas detectors with electrochemical sensors can detect other clandestine laboratory contaminants such as ammonia and phosphine in addition to detection of combustible and various toxic gases, and oxygen deficiency.

Figure 3-3. BHO Clandestine Laboratory

Image courtesy of County of Los Angeles Fire Department

In some instances, in clandestine laboratories, it has been found that some containers found may be mislabeled and contain other materials. One of the most common found at methamphetamine laboratory sites is propane tanks filled with anhydrous ammonia. A best practice would be for responders to monitor for a wide array of substances due to the unknown or misleading presence of hazards. Clandestine laboratories have also increased due to the rise of butane hash oil (BHO) extraction from marijuana. Recent incidents have indicated dangerous conditions in these laboratories through the unsafe storage and handling of large quantities of butane. First responders can be involved in situations where there are clandestine laboratory explosions, or they could be assigned the task of closing down these laboratories. As a result, first responders involved in the raid, shutdown, cleanup, or investigation of clandestine laboratories require multi-gas detection equipment that identifies the risks within these hazardous environments.

3.5 Urban Search and Rescue

When large-scale disaster strikes, urban search and rescue (USAR) teams can face unexpected exposure to toxic and combustible gases. These teams are tasked with responding rapidly to a variety of environments with toxic or combustible gases present. Handheld multi-gas detectors provide the data necessary to respond rapidly to save lives by enabling team members to obtain real-time detailed data on specific toxic gases. In addition, some USAR teams opt to include PID sensors to provide broad-based assessment for other VOCs that might be present due to leaks or fire. For many USAR teams best practices with the use of a multi-gas detector have been adopted to ensure the safety of responders prior to entering a home or building for search operations following a natural disaster.

4. CONCLUSION

In summary, this application note provides information regarding the capabilities, functionality, and use of handheld multi-gas detectors which may assist first responders in the management of multiple types of common hazards. Handheld multi-gas detectors are available from several manufacturers and have a wide variety of available features and components. While most come standard with O_2, LEL, CO, and H_2S detection capabilities, there are multiple options for toxic gas sensors to choose from. The main consideration one should make when selecting the right multi-gas detector is understanding the risks or hazards faced by a given response organization or jurisdiction. Proper maintenance and calibration of the instruments will ensure accuracy and reliability when they are utilized for a variety of responses. Lastly, responders will need to incorporate standard use of handheld multi-gas detectors for hazardous environments such as confined spaces and fireground operations as evidenced by their successful use in past response, lessons learned from past events (either if they were not used, or used incorrectly), and through evidence-based research. By gaining this understanding, one can determine the right kind of sensors and functionality necessary for protection of their first responders.

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APPENDIX B. ACRONYMS

AEL	Authorized Equipment List
BHO	Butane Hash Oil
Br	Bromine
C_3H_8	Propane
C_5H_{12}	Pentane
CH_2O	Formaldehyde
CH_4	Methane
Cl	Chlorine
CO	Carbon Monoxide
DHS	Department of Homeland Security
HazMat	Hazardous Materials
H_2S	Hydrogen Sulfide
HCN	Hydrogen Cyanide
IR	Infrared
LEL	Lower Explosive Limit
MOS	Metal Oxide Semiconductor
NH_3	Ammonia
NO	Nitrogen Oxide
O_2	Oxygen
O_3	Ozone
PID	Photoionization Detector
PPE	Personal Protective Equipment
SAVER	System Assessment and Validation for Emergency Responders
S&T	DHS Science and Technology Directorate
SCBA	Self-Contained Breathing Apparatus
SO_2	Sulfur Dioxide
SPE	Solid Polymer Electrolyte
USAR	Urban Search and Rescue
USB	Universal Serial Bus
VOC	Volatile Organic Compound