

Hydrogen and Oxygen Gas Monitoring System Design and Operation

Safety and Technology of Nuclear Hydrogen Production, Control, and Management

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HYDROGEN AND OXYGEN GAS MONITORING SYSTEM DESIGN AND OPERATION

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This paper describes pertinent design practices for selecting types of gas sensors, placing sensor units, choosing set points, and maintaining gas monitor systems. Information from the literature about best practices is presented. This is followed by the actual practices used in a laboratory with experiments in support of the U.S. Department of Energy Nuclear Hydrogen Initiative (NHI).

I. INTRODUCTION

Whenever flammable or toxic gases are used, it is possible that a gas could be leaking into the room or contiguous areas. Monitoring for the presence and concentration of these gases is a prudent safety precaution. The National Electrical Code¹ recommends following ANSI/ISA-RP12.13.02, "Recommended Practice for the Installation, Operation, and Maintenance of Combustible Gas Detection Instruments, Section 6.2.1, which states²

A fixed gas detection system should be installed that is capable of monitoring those parts of a plant or other premises where flammable gas(es) accidentally accumulate and may create significant hazard. The system should be capable of giving an early audible or visual (or both) warning of both the presence and the general location of an accident accumulation of flammable gas(es), in order to initiate one or more of the following actions, either automatically or under manual control:

- a) safe evacuation of premises*
- b) appropriate fire-fighting procedures*
- c) shutdown of process or plant*
- d) ventilation control.*

Designing a gas monitoring system is a complex task, however, with many necessary decisions. This paper aids in effective design by discussing the four main steps of choosing, setting up, and using gas monitoring equipment:

- What types of gas sensors should be used?
- Where and how should the sensors be placed?
- What alarm thresholds should be used?
- How should the system be maintained?

The design of an actual gas monitoring system for an NHI laboratory room is given as an example.

II. SENSOR SELECTION

The initial step in sensor selection is to define the gases to be sensed. First, the system designer must list all of the gases to be used in the room or facility: process input gases, maintenance or cleaning gases, welding gases, background gases, and process product gases. With the list of gases established, the properties of the gases can be defined (chemical toxicity, chemical combustion, etc.). Table I gives an example list of gases and their properties.

Once the gases are defined, the type of sensor to detect those gases can be selected. Chou has reviewed all of the major types of gas sensors, including their operating temperature ranges, response times, accuracies, repeatabilities, drift in settings, and life expectancies.³ Table II gives some highlights from Chou's work. There are a few other parameters to review in the course of selecting a sensor. Temperature range in which the sensor must function, sensor power demand, sensor susceptibility to false alarms from infrequent intruding gases (e.g., forklift truck exhaust), and humidity expected in the location are all important to sensor functionality.

Chou states that gas sensors tend to be placed in two broad categories: toxic gas monitoring and combustible range monitoring.³ In general, toxic gas sensors measure very small concentrations for tracking human inhalation exposure. These sensors measure up to three to five times above the permissible exposure limits, usually in tens of

TABLE I. Parameters for Several Gases^a

Gas	Formula	Chemical Type	General Hazards	ACGIH TLV (ppm)	ACGIH STEL (ppm)	NIOSH IDLH (ppm)	LFL/UFL (%)	LDL/UDL (%)
Acetylene ^b MW=26	C ₂ H ₂	Flammable	Combustible, reactive	NA	NA	NA	2.5/100	6.7/21.4
Carbon dioxide MW=44	CO ₂	Non-flammable gas	Asphyxiant	5,000	30,000	40,000	NA	NA
Carbon monoxide MW=28	CO	Flammable	Toxic, combustible	25	None	1,200	12.5/74	Not available ^c
Hydrogen MW=2	H ₂	Flammable	Combustible, asphyxiant	Not listed	Not listed	NA	4/75	18/59
MAPP gas ^d MW=40.1	C ₃ H ₄	Hydrocarbon	Combustible, toxic	1,000	1,250	3,400	2/10.8	3/10
Methane MW=16	CH ₄	Hydrocarbon	Combustible, asphyxiant	1,000	None	None	5/15	6/13.5
Oxygen MW=32	O ₂	Oxidizer	Toxic	NA	NA	NA	NA	NA

a. Notes:

- ACGIH = American Conference of Governmental Industrial Hygienists
 - NIOSH = National Institute for Occupational Safety and Health
 - IDLH = immediately dangerous to life or health
 - LDL and UDL = lower detonation limit and upper detonation limit in air, respectively
 - MW = molecular weight
 - TLV = threshold limit value
 - STEL = short-term exposure limit
 - LFL and UFL = lower flammable limit and upper flammable limit in air, respectively
- Data sources for this table are Refs. 4–7.

b. For acetylene, NIOSH allows up to 2,500 ppm exposure as a ceiling limit. Acetylene can decompose explosively at 100% concentration (even though some texts list a UFL of 80%).

c. Kuchta states that CO-oxygen has detonation limits at 38 to 90%, but the detonation velocity at stoichiometric conditions is marginal at 1,264 m/s (normally detonations are > 1,500 m/s).⁸ CO may not truly detonate in air.

d. MAPP is a welding gas and is a mixture of methyl-acetylene, propane, and propadiene.

volume parts per million (ppm). Combustible range sensors generally measure much higher concentrations, up to 100% of the lower flammable limit (LFL) or a fraction of that, such as 50% LFL. The LFL levels for gases tend to be in the several percent of the atmosphere range, where 1% = 10,000 ppm.

For our practical application in this discussion, we will use the NHI laboratory at the Idaho National Laboratory (INL). Four gases need to be monitored in this lab: CO, CO₂, H₂, and O₂. The monitoring system selected is manufactured by the Draeger Company. The CO and O₂ transmitters are Draeger Polytron 2 XP Tox explosion-proof gas detectors for continuous monitoring of toxic gases and oxygen in air. Toxic gas and oxygen ranges are user adjustable. The CO₂ transmitters are infrared CO₂ gas detectors for continuous monitoring.

They have adjustable ranges from 2,000 ppm to 30 vol%. The H₂ transmitters are Draeger Polytron 2 XP-Ex explosion-proof catalytic bead gas detector transmitters for continuous monitoring. They detect combustible gases and vapors in ambient air from 0 to 100% LFL.

The NHI gas monitoring system has relay outputs, display readout, visual and audible alarms, and an auto dialer. The relay outputs are used to automatically shut down the experiments and isolate hazardous gas flow if an evacuation alarm is activated. The relays also open valves to initiate safe gas flow to purge experimental systems as appropriate.

The gas monitoring system consists of eight hazardous gas sensor/transmitters that all feed into a master system controller. Each of the eight transmitters

Table II. Typical Sensor Specifications

Sensor type ^a	Temperature Range (C)	Response Time (s)	Accuracy (± %)	Drift (%/yr)	Life Expectancy (yr)	Comments
Electro-chemical (most widely recognized sensor)	-40 to +45	< 50	1-2	24 Can drift down by 2% per month	1-3 detector head is consumed and needs replacement	Temperature sensitive, can misread by 0.5 to 1% per °C away from calibration temperature. Humidity does not affect the sensor. Measures ppm ranges, well suited for toxic gas sensing. About 20 gases can be read by this type of sensor.
Diffusion catalytic bead	-40 to +60	10-15	5	5-10	≤ 3 detector head is consumed and requires replacement	Used for over 50 years for dozens of combustible gases. Note that the catalyst can be poisoned by other gases or particulates in the air. Well suited for use as portable sensors.
Solid state sensor	-20 to +50	20-90	3-10	— Little drift	10+ when used in clean applications	Used for more than 120 gases. Susceptible to background gases giving false alarms. Absorptive filters reduce background gas false alarms but require periodic filter replacement.
Infrared sensor	-40 to +60	<10	1	— Little drift	3 to 5 for light source, detector can operate > 10 years	High sensitivity, from a few ppm to 100% concentration. Suitable for toxic and combustible gases. Does not react well to sudden temperature variations in the room. Not corroded or reacted by gas. The most user friendly and least maintenance sensor available.
Photo-ionization detector	-20 to +50	3	1-10	Up to 30% humidity drift	< 1 for the UV lamp	Almost always used for detecting volatile organic compounds.

a. For toxic gases, electrochemical and solid-state sensors are the most widely used. For combustible gases, catalytic bead, solid-state, and infrared sensors are the most widely used. The information in this table came from Chou.³



Fig. 1. The NHI lab hazardous gas system controller.

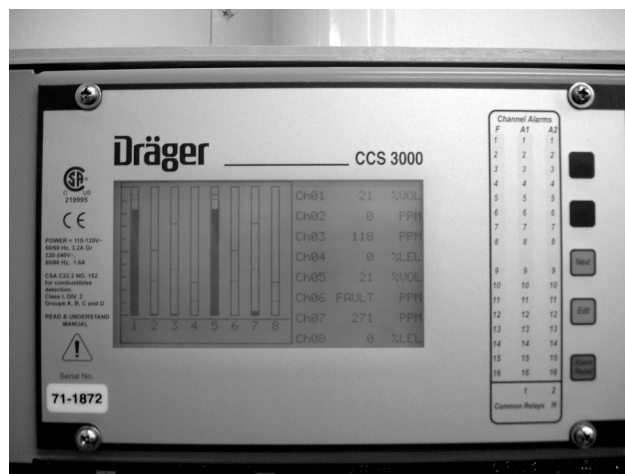


Fig. 2. The system controller readout screen showing normal gas concentrations in lab room air.

provides numerical readouts at the sensor along with alarm lights. The system controller is a Draegergard Alarm Controller (shown in Figure 1) and is located near the external personnel access door. A reinforced window was added to the door to allow personnel responding to an alarm to view the controller readout screen without opening the door. Figure 2 shows the controller readout screen with normal hazardous gas concentrations in the lab room. The lab has a standard ventilating system and approximately one air change per hour.

The system also features an auxiliary readout panel in the laboratory office area. Figure 3 shows the auxiliary readout panel. Note that it provides gas sensor levels for each channel and red indicator lights to indicate any channel with an alarm state.



Fig. 3. The auxiliary readout panel in the lab office area.

III. SENSOR PLACEMENT

Fixed-point sensors, such as those chosen for the NHI lab, can only function if the intruding gas contacts the sensor. Therefore, sensor placement is vital to proper monitoring of the room or area. Factors in sensor location selection include whether it's an indoor or outdoor site, the location and nature of potential gas or vapor sources, chemical and physical data of the gases or vapors, volatility (liquids with volatility need sensors near the potential sources of release), nature and concentration of gas or vapor releases, natural and mechanical ventilation, vulnerability to mechanical or water damage from normal operations, and easy access for maintenance and calibration. The rationale for selecting sensor locations

should be recorded in permanent laboratory documentation.

Jessel states that there are three approaches to monitoring: spot, area, and fence monitoring.⁹ Spot or local monitoring is locating sensors near recognized sources of leakage (valves, nozzles, flanges, bellows, etc.). Spot monitoring makes judicious use of just a few sensors by identifying the most likely leak locations in the facility or system. For this reason, spot detectors are normally located adjacent to identifiable, single-spot, potential gas release locations having a significant risk of toxic or combustible gas leakage (e.g., pump and gas compressor seals or valves). Area or room monitoring means siting sensors at regular intervals throughout an area, similar to smoke detectors placed in grid patterns for fire protection. Area monitoring typically uses a larger number of sensors than spot monitoring. Jessel states that for area monitoring, 46–93 m² (500–1,000 ft²) per sensor head is often used as a rule of thumb.⁹ The Texas Analytical Control handbook (TAC) states a system design recommendation for at least one sensor per 84 m² (900 ft²).¹⁰ Anderson and Hadden state that some manufacturers give a design recommendation of one sensor per 37 m² (400 ft²).¹¹ Obviously, there is variability in sensor coverage and placement. The third monitoring approach, fence or perimeter monitoring, is the design where four or more sensors are placed at the facility periphery to alarm when hazardous gases leave the site and intrude into neighboring areas. Perimeter monitoring is used more for an industrial complex, such as a hydrogen production facility, than for a laboratory facility.

ANSI/ISA-RP12.13.02 gives this guidance on sensor placement:²

- Locate detectors above the level of ventilation openings and close to the ceiling for the detection of gases lighter than air
- If ceilings are compartmentalized by equipment or other obstructions, install sensors in each compartment
- Account for thermally induced flow (e.g., hot surfaces on equipment) that may affect the distribution of gas in air
- Place sensors in all areas where hazardous accumulations may occur; these areas may not be close to release points but may be in areas of restricted air movement
- Locate sensors close to potential areas of major release; to avoid nuisance alarms do not place

immediately adjacent to equipment known to produce small leaks (inconsequential leakage might include gas bottle racks where there are tiny releases during gas bottle changeout)

- Sensor orientation may be specified by the manufacturer.

Other authors offer these additional guidelines:

- Protect detectors from direct sprays of oil and other liquid¹²
- Do not place sensors in high vibration or high temperature areas; elevated levels of either vibration or temperature can reduce the sensor lifetime¹³
- Use dust covers in dirty areas and splashguards in areas that are washed down or in outdoor areas that experience high levels of annual rainfall¹³
- For combustible gases or vapors, position sensors between the leak source and any ignition sites if possible⁹
- If the sensor performs tasks such as de-energizing a process or starting ventilation fans, take the sensor reaction time and countermeasure timing into account.⁹

When gas leaks occur, a gas disperses according to its physical properties, especially vapor density. Vapor density is defined as the molecular weight of a gas divided by the molecular weight of air (molecular weight of air is 28.9). Using the molecular weight of the gas in question, as shown in Table I, system designers can determine whether a gas is lighter or heavier than dry air (i.e., whether a gas will rise or settle when released). Note that humid air has a slightly reduced molecular weight than dry air.

The diffusion rate of a gas is proportional to its density relative to that of air.¹⁴ Lighter-than-air gases rise toward the ceiling and are likely to accumulate in overhead spaces (such as above drop ceilings) and can form “gas nests” (such as gas pockets between beams). Alcoves, roof peaks, and dormers also tend to be poorly ventilated and can be accumulation areas for gases. Jessel states that only three combustible gases are significantly lighter than air: hydrogen, ammonia, and methane.⁹ Hydrogen is the lightest of these gases and diffuses rapidly. Room air that is 0 or 5°C hotter than ambient will not retard hydrogen diffusion to the same extent it would retard other gases, even ammonia or methane. For light gases, sensors should be placed above release points. In enclosed areas, sensors can be placed at or near the ceiling^{15,16} or near an exit fan or exit duct.^{3,11}

Vapors from combustible liquids are always heavier than air and tend to stay close to the ground.⁹ Heavier-than-air gases are likely to accumulate in pits, trenches, drains, and other low areas. In general, sensors for these gases should be located close to any potential sources of major gas release and close to the ground. To avoid nuisance alarms, however, do not place sensors immediately adjacent to equipment that may produce inconsequential leakage during normal operation. Also, to keep sensors free from dirt, water, and other contamination, place them slightly above ground level. The TAC handbook recommends heavier-than-air gas sensor placement at 50–66 cm (20–26 in.) above the low point or floor and no higher than 106–122 cm (42–48 in.).¹⁰ Anderson and Hadden suggest 30–46 cm (12–18 in.) height from the floor or low point and no higher than 91 cm (36 in.).¹¹ Gas sensor standards do not give specific distances. Gases that are heavier than air and in small concentrations (< 1% by volume) and gases with densities close to air do not diffuse much. These gases are moved by air currents and should be monitored at head height (i.e., monitoring in the breathing air zone). Sensor placement near ventilation exit fans or outlet ducts is also prudent for gases with vapor densities similar to air.^{3,11} Placing a combustible gas sensor between a gas source and any ignition source (e.g., a furnace or open flame equipment) can give a warning to de-energize the equipment.

Ventilation air currents are usually the largest motive force for gas movement in a room. Air currents can create anomalies in the expected gas movement and behavior. Ventilation needs change with seasons (e.g., air conditioning versus heating), so all seasons at a facility site must be taken into account when choosing sensor locations. Care should be taken not to place sensors where airflow will push or pull gases away from the sensor. Instead, take advantage of the airflow by placing centers upstream where the greatest concentrations will exist or near an area where air will be drawn to the sensor (e.g., next to a ventilation air return or exhaust fan). Never mount a gas detector near a fresh air inlet duct; the fresh air inflow will not allow gas to reach the detector and any inflowing particulate in the air flow will accumulate in the detector.

Air temperature is yet another factor to consider. Warm air near the ceiling has a lighter density than the room air (hot air rises). The warm air can delay the gas concentration buildup near the ceiling because less dense air diffuses gas more rapidly. Corsi calls this warm layer of air a “thermal barrier.”¹⁴ A thermal barrier can either delay or prevent an accurate gas concentration from reaching a sensor placed on the ceiling. If room

ventilation moves this hot air, however, churning the hot air layer into the rest of the room air, then the concern for sensor delay is small.

In some cases, gases are stored as compressed liquid or cold gases (perhaps a cryogenic gas). Anderson and Hadden¹¹ and Chou³ state that gases released into rooms are not predictable and are especially unpredictable when they are close to the density of air. When this type of gas is released, the gas may settle until it warms closer to room temperature; it will then mix with (dilute in) room air currents as it warms. This gives a time delay to the gas buoyancy in air and may present more of a safety concern because there is less stratification at the ceiling and more gas concentration throughout the air in the room.

For outdoor monitoring, perimeter sensors are common. In this setting, wind and weather must be accounted for. Prevailing winds warrant careful attention. Sensors should be directed down to prevent moisture and dust from entering the detector cell. Anderson and Hadden also note that electrochemical sensors are susceptible to freezing, so if perimeter sensors are exposed to freezing they must be heated to proper operating temperatures.¹¹

Perimeter sensors represent a significant investment for a large footprint facility in terms of equipment, installation, and periodic calibration costs. Such sensors are generally the only means of warning for any nearby community, however. The TAC handbook recommends perimeter sensors for combustible gases be placed on the order of 4.5 to 7.6 m (15 to 25 ft) apart along the perimeter of the facility.¹⁰ Anderson and Hadden suggest having sensors no farther than 15 m (50 ft) apart, and closer sensor spacing for toxic gases so that a wind shift does not steer a vapor cloud between sensors.¹¹

Wiring sensors in series is often performed because of cost savings in cabling and time, but such an approach results in cumulative outputs, difficulty in sensor calibration, and reduced safety. One open circuit results in a loss of all sensors. A safer method is to wire the sensors individually. The sensor will then give an accurate concentration reading and the location of the gas can be determined. Sensor wiring should be separate from alternating current wiring. Sensor wiring near high-power alternating current wires will need electrical shielding (it is a good engineering practice to always use shielded [braided] cable). The shielded cable will prevent radio interference (e.g., walkie-talkie radios used by security or maintenance personnel) and other interference with the sensor signals.

The INL NHI lab chose an area monitoring approach. Because of the room size (198 m²), two sets of monitors were used. The O₂, CO, and CO₂ sensors are located in two sets approximately 0.9 m (3 ft) off the floor. Figure 4 shows one of the sets. The two hydrogen sensors are mounted on the ceiling, as shown in Figure 5. These locations were chosen with the stated guidance in mind so the sensors are not near the air ducts and are above the two main experiment areas of the room. A schematic of the lab is shown in Figure 6.



Fig. 4. O₂, CO, and CO₂ sensors used in the NHI lab. The sensors are located on a wall near each experiment area.

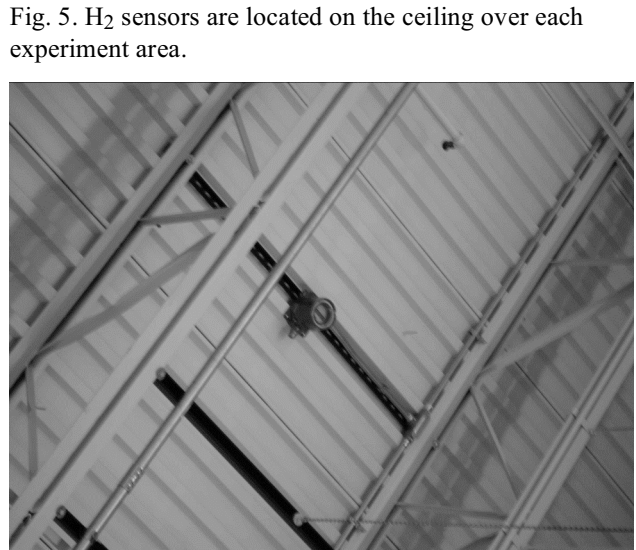


Fig. 5. H₂ sensors are located on the ceiling over each experiment area.

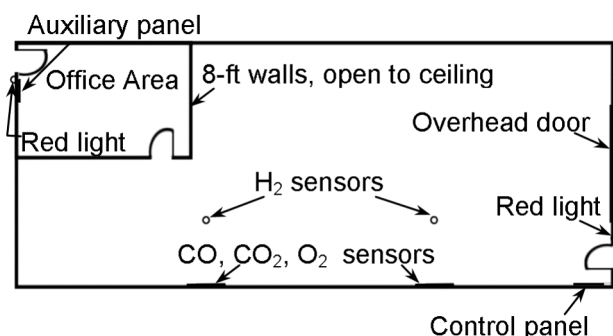


Fig. 6. A schematic of the NHI lab showing the locations of the sensors and control panels. The NHI lab is 21.5 m long by 9.2 m wide with a 6.4-m ceiling (70.4 × 30.1 × 21 ft).

IV. SENSOR SET POINTS

The third question to answer in designing a gas monitoring system is where to set the alarm thresholds. With the list of all gases to be used or created in the laboratory and their expected volumes, the designer can verify gas toxicity (i.e., any toxic chemical effects and the oxygen displacement or chemical asphyxia hazard) and the flammability or explosibility of each gas. One document that can give such information for a wide variety of gases is the National Institute for Occupational Safety and Health (NIOSH) *Pocket Guide to Hazardous Chemicals*.⁴ Other useful documents have been written by Rivkin,⁷ Kuchta,¹⁶ Zabetakis,¹⁷ and Patnaik.¹⁸ With the toxicity and flammability known, sensor set points can be chosen. Some definitions must be given here.

Combustible gases have a lower and upper flammable limit (LFL and UFL). Below the LFL, the mixture of gas and air lacks sufficient fuel to burn. Above the UFL, the mixture is too rich in fuel (deficient in oxygen) to burn. Any concentration between these limits can burn. These limits are also called lower and upper explosive limits. “Flammable” and “explosive” are used interchangeably because a deflagration in air is an explosion.^{19–21} These gases also have lower and upper detonation limits (LDL and UDL). Detonations are intense explosions whose combustion waves travel at supersonic speeds relative to the unburned gas immediately ahead of the explosion (deflagrations travel at subsonic speeds). Note that some gases in Table I have a detonation range within the flammable range.

Other terms needing explanation are the different exposure limits. Threshold limit values (TLVs) and permissible exposure limits (PELs) are limits set by the American Conference of Governmental Industrial Hygienists (ACGIH)²² and the U.S. Occupational Safety

and Health Administration (OSHA),²³ respectively. These limits are comparable and are the average airborne concentrations of chemicals to which most people can be exposed and show no ill effect. The short-term exposure limit (STEL) is the maximum continuous concentration allowed for 15-minute intervals (4 exposures per day with 60 minutes between exposures with the daily TLV not exceeded). The ceiling value is the exposure level that must never be exceeded.

With these definitions in mind, consider the standards and regulations for alarm set points. National Fire Protection Association (NFPA) Standard 55 states that a gas detection system shall alert persons on-site and a responsible person off-site when a gas concentration in a storage or use area reaches the PEL, ceiling limit, or STEL.²⁴ Gas detection systems must have a sensing interval not exceeding 5 minutes and provide a local alarm. The gas detection system must monitor the exhaust system at the point of discharge from the gas cabinet, exhausted enclosure, or gas room. For gases used in unattended operation, an automatic valve must close if the concentration of the gas reaches one-half of the NIOSH immediately dangerous to life or health (IDLH) value for that gas.

In the Code of Federal Regulations (CFR), the U.S. Department of Energy (DOE) states that when TLVs of respirable substances in air are lower (that is, more protective) than OSHA values, ACGIH values will be used.²⁵ Table I gives values for some representative gases. For example, in the case of carbon monoxide, the more protective ACGIH value of 25 ppm should be used as a toxic gas sensor alarm set point.

Another alarm set point to determine is the fraction of LFL to use. Guidance from the Instrumentation, Systems, and Automation Society (ISA) states that a combustible gas sensor indicating up to the LFL should be set as low as possible commensurate with the need to avoid nuisance alarm signals.² The NFPA suggests that to prevent deflagrations, the combustible concentration limit should be maintained at less than 25% LFL for the combustible gas, vapor, or mixture of gases.^{24,26–29} ISA-TR12.24.01-1998, “Recommended Practice for Classification of Locations for Electrical Installations Classified as Class I, Zone 0, Zone 1, or Zone 2,” Appendix D, states³⁰

- *An adequate number of sensors are installed to ensure the sensing of flammable gas or vapor in the building in all areas where such gas might accumulate*

- *Sensing a gas concentration at 20% LFL or less should activate a local alarm (audible or visual or both, whatever is appropriate for the location)*
- *Sensing a gas concentration of 40% LFL or less should activate a local alarm (audible or visual or both, whatever is appropriate for the location) and initiate automatic disconnection of power from all electrical devices in the area that are not rated for the gas environment*
- *Calibrate gas detectors at least once every three months*
- *Bypass for calibration is allowed*
- *The building should not have any electrically heated parts or components outside of explosion-proof enclosures that may operate at a temperature equal to or above 80% of the ignition temperature of the gas or vapor.*

The traditional set points for warning alarm and evacuation alarm have been 20% LFL and 40% LFL, respectively.^{10,11,31} White³² pointed out that for many years, the Uniform Fire Code and building codes required flammable gas detection systems and alarms at 20% LFL. A recent industrial trend is to add a warning alarm at a lower level, usually 10% LFL, to allow the staff to mitigate an event early. OSHA defines a hazardous atmosphere as >10% LFL in confined spaces, so room monitors are sometimes also set at 10% LFL.^{33,34} Some chemical facilities also set a special alarm at 50% LFL. If the gas concentration reaches 50% LFL, the alarm actuates facility shut down and de-powers equipment to preclude any deflagration damage.³⁵

Three gases warrant special attention here: hydrogen, oxygen, and carbon monoxide. The ACGIH lists hydrogen gas as a simple asphyxiant. A simple asphyxiant gas displaces air to cause a lack-of-oxygen asphyxiation with no other health effects. A chemical asphyxiant takes the place of oxygen in blood or prevents oxygen from its proper interaction in the lungs or bloodstream. The typical O₂ level in air is 20.9%. For simple asphyxiant gases, OSHA states that an oxygen-deficient atmosphere is below 19.5% O₂ by volume, and that all oxygen deficient atmospheres shall be considered IDLH.³⁶ To obtain an oxygen decrease from the usual 20.9% to 19.5%, a simple mole fraction of typical air (78% N₂, 20.9% O₂, 1% Ar, and traces of other gases) in a non-ventilated room would need an added 6.7% of hydrogen by volume (resulting in 72.8% N₂, 19.5% O₂, 0.93% Ar, and 6.7% H₂) to reach IDLH oxygen levels. Note, however, that the hydrogen gas LFL is 4% by volume so flammability is a larger

safety concern than asphyxiation. Therefore, a hydrogen detector should be set to alarm at a fraction of the LFL.

Next, let's turn our attention to oxygen-enriched atmospheres. Oxygen-enriched concentrations are not particularly hazardous to breathe for short periods of time. Klaasen states that short residence times of approximately 3 hours in 100% oxygen atmospheres are not debilitating or life threatening to healthy adults.³⁷ The issue of importance for oxygen enrichment is that some materials, notably hydrocarbons such as oil, grease, and hydraulic fluids, are more highly flammable in high oxygen concentrations, some to the point of spontaneous flammability.³⁸ Even "non-flammable" textiles used in protective clothing will burn fiercely in as little as 30% oxygen concentration by volume.³⁹ With an oxygen oxidizer present, flames burn much hotter than in normal air and propagate at much greater speed; such fires often require extra water for extinguishment. OSHA defines oxygen-enriched atmospheres as those containing more than 23.5% oxygen by volume.³³ Rivkin also states that flammability of hydrocarbons and other materials begins to increase at 23.5%.⁷ The Compressed Gas Association also defines an oxygen-enriched hazardous atmospheres as 23.5% oxygen in air by volume.⁴⁰

CO is the third gas from Table I to examine. CO is a flammable gas but has the highest LFL value in the table, with a LFL in air of 12.5% by volume.¹⁶ This 12.5% is equivalent to 125,000 ppm. Using the 10% warning level gives us a set point of 12,500 ppm. Looking at CO toxicity, however, we see a TLV of 25 ppm, which is a much greater hazard than the flammability of the gas and should be the alarm set point.

One final factor to consider for alarm set points is nuisance alarms. Nuisance alarms occur when no abnormal condition exists or when no operator invention is required. For example, small inconsequential leaks may cause nuisance alarms. These alarms are somewhat dangerous because they tend to desensitize the operator to alarms in general. Pham states that the lower the sensor set point, the more likely that a power surge, background electronic noise, or some other interference would trigger an alarm.⁴¹ Keeping the alarm set points at or above 10% of transmitter full scale will reduce nuisance alarms. If more sensitivity (lower set point) is needed for personnel protection, then select a sensor with a small range (such as 50 ppm full range versus 200 ppm full range).

Let's use CO again as an example. Of the gases listed in Table I, CO has the lowest TLV and may be the most sensitive sensor to nuisance alarms. The Environmental Protection Agency (EPA) states that the national primary

ambient air quality standard for carbon monoxide is 9 ppm for an 8-hour average concentration (not to be exceeded more than once per year).⁴² Generally, most office buildings are below that level. If the air quality typically remains below 9 ppm of CO, then a 25 ppm alarm level (almost three times the ambient concentration) should not result in nuisance alarms.

At the INL, the hazardous gas monitoring system allows two alarm settings for each of the eight sensors. A warning alarm is set at a level that is higher than typical gas concentrations but still safe to allow laboratory personnel to diagnose and correct problems early. The warning alarm is an alternating tone and amber light on the controller. The evacuation alarm, the second setting, is set to a maximum level for each gas. The evacuation alarm is a steady tone and red light at the controller and outside each personnel access door as shown in Figure 7. Figure 1 shows the red and amber cylindrical lights on top of the controller.



Fig. 7. The exterior and interior entrances to the NHI lab.

As discussed above, hydrogen alarm set points should depend on the LFL. When designing the INL monitoring system, designers followed the latest NFPA direction for hydrogen (25% LFL). Following recent trends, they also set a 10% LFL warning alarm. The hydrogen LFL is 4% so one-quarter of the LFL is a 1% concentration of hydrogen by volume, or 10,000 ppm for the evacuation alarm. The warning alarm level (10% LFL) is set at 0.4% or 4,000 ppm. The average hydrogen level in the lab is 0 ppm, so the warning level should be amply high to preclude nuisance alarms.

For CO and CO₂, the INL has in-house requirements to use 50% TLV as a warning alarm set point for gases that have listed TLVs. These values were used for the warning alarms; evacuation alarms are set at 100% TLV. One additional concern is the instrument accuracy given in Table II for CO because of its low set point and potential for nuisance alarms. The accuracies are up to plus or minus 10%. A 13 ppm warning level was chosen over 12.5 ppm to give a slightly higher difference from the suggested 9 ppm typical CO value in air. At 13 ppm, the accuracy range is ± 1.3 ppm. Because typical air quality is below 9 ppm of CO, even a 10% accuracy deviation should not create a high number of nuisance alarms.

All of the INL lab set points are shown in Table III. Thus far, the sensors have proven to be very sensitive. Typical readings in the lab room are 0 ppm for hydrogen, 20.9% for oxygen, 0 ppm for carbon monoxide, and 210 ppm for carbon dioxide. When construction activities were under way in an adjacent lab room, the CO sensors sensed the exhaust of the forklift trucks being operated in that room and issued a warning alarm to personnel working in the NHI laboratory.

Table III. Alarm Set points for Industrial Gases in the INL NHI Laboratory

Gas of Interest	Basis for Set Point Values ^a	Initial Warning Alarm Set Point (ppm)	Evacuation Alarm Set Point (ppm)
Hydrogen	Flammability 10% and 25% of LFL	4,000	10,000
Carbon dioxide	Toxicity 50% and 100% of TLV	2,500	5,000
Carbon monoxide	Toxicity 50% and 100% of TLV	13	25
Oxygen	Flammability OSHA enriched O ₂ value of 23.5%	225,000	235,000

a. LFL = lower flammable limit
 TLV = threshold limit value
 OSHA = Occupational Safety and Health Administration

V. MONITOR SYSTEM OPERATION AND MAINTENANCE

A gas sensor, like other measuring equipment, measures an amount and then compares it to a known quantity. Therefore, the quality of the measurements depends in large part on the quality of the calibration. In addition, detectors are susceptible to blockages from dust, particulate from the air, water condensation, etc. Catalyst units can be susceptible to compounds of silicon,⁴³ phosphorous, chlorine, lead, and other elements. Routine inspection and re-calibration are necessary to keep the sensors operating correctly.

Gas sensors require reasonably frequent recalibration. Most of the literature examined for this task indicates that the manufacturer's recommendations should be followed. Anderson and Hadden state that the calibration frequency varies with the manufacturer, sensor type, and particular installation.¹¹ Several authors state that gas sensors should be calibrated at a frequency in accordance with manufacturer's recommendations but at least once every 3 months.^{30,31,41} For chemical process industry applications (sensors exposed to temperature extremes, outdoor weather, hydrocarbon emission fouling, etc.) the 3-month interval is a wise precaution. Instruments should be calibrated when commissioned and recalibrated at defined intervals thereafter.²

Chou states that typically two calibrations are performed: one on the zero point and another on the sensor span.³ There is no established standard to define a practical zero value (that is, a zero concentration of the gas to be sensed). Many procedures call for use of dry nitrogen from gas cylinders, but dry nitrogen is not the same as typical room air. Dry gas will cause the zero point to be set lower than actual and the sensor will appear to drift in moist air when no instrument drift has occurred. The best approach suggested by Chou is to zero the sensor using ambient, typical-humidity air, provided the air is guaranteed clean by portable sensors. This is the most realistic zero reference and the water vapor in air will give a true zero point for sensors.

Span calibration is the second calibration. Chou states that the best accuracy comes from mixing target gas in background environmental air and using that as the calibration gas.³ However, this approach is complicated and expensive. The most popular method of span calibration is to use a premixed, dry calibration gas that is commercially available with a fixed concentration value of the target gas mixed into another bulk gas. (Some calibration gases can be mixed with air, others can only be mixed with nitrogen or other inert gases.) The

calibration gas bottle is fitted with a regulator and flow restrictor. Flow rates of 600–1,000 cc/minute at just 108.2 to 115.1 kPa (1–2 psig) are common, with flows lasting a minute or more. The gas sensor reads from zero concentration and gives periodic readings up to the “span gas” or calibration gas concentration; thus, the gas sensor reads through a span of concentrations. If the sensor gives an inaccurate reading during the calibration activity, this adjustment should be recorded. The span calibration is not a full range span, such as 0–100% LFL of a combustible gas in air. It is just the range up to the fixed concentration level of the calibration gas, typically 50% LFL for most combustible gases with the balance of the gas being dry nitrogen. Calibration gas bottle shelf life must be verified with the vendor because many of these gas mixtures have short lifetimes in the bottles (gas reacts with bottle walls, etc.).

For combustible gases, the calibration process is to attach a gas line to the sensor and send gas of known concentration from the calibration gas bottle to the sensor and determine the time the sensor takes to read the elevated gas levels. This calibration process works well for combustible gases mixed to some percentage (such as the typical 50% LFL) in nitrogen or air. For a catalytic bead-type sensor, a safe calibration interval can be chosen based on the changes in span and zero from the initial calibration, so recording these data and keeping them available for inspection are important.

Toxic gases pose more difficult calibration issues. Anderson and Hadden state that two means are typically used for toxic gas sensor calibration.¹¹ The first means is using toxic gas ampoules. This approach may not be very accurate, however, because ampoules are fragile and can leak and the glass ampoule walls have been known to react with toxic gas. The ampoules are heated during the sealing process, which can release contaminants from the glass and allow contaminants to react later with the toxic gas after sealing has been completed. The second toxic gas calibration means is the same approach used for combustible gases, delivering a known (but usually very small) concentration of the toxic gas or a similar toxic gas in a calibration gas from a cylinder to the sensor unit and taking a span reading.

Regular inspections of the control panel and sensors are another important maintenance activity. ISA-RP-12-13.02 suggests a regular inspection of the control panel, such as once per shift.² Inspections should also occur after malfunctions, damage, or deterioration. Inspections should verify the function of the lights, audible alarms, and electronics by using test switches. Records should be kept for each sensor head. Also, many sensors give a

readout of the percentage of remaining life for the sensor head. This number should also be recorded. When the remaining life of a sensor head is low, 10 or 20% remaining, it should be replaced and the new head given an initial calibration. Table IV lists some suggestions for routine maintenance given by Zdankiewicz.⁴⁴

At the INL NHI lab, a vendor representative performed the initial calibrations. This required over one day because of two unforeseen events: some wiring not responding as expected and the initial heat-up period of 4 hours on the oxygen sensors before they could be calibrated. The other sensor heat-up times were much shorter. The manufacturer's recommendations for calibration are 180 days for hydrogen sensors and 6 to 12 months for carbon dioxide sensors.^{45,46} All of the NHI sensors are recalibrated every 6 months. An electric-powered manlift was brought in to the facility to access the hydrogen sensors on the ceiling, and the aisles are kept clear for periodic manlift entry.

VI. CONCLUSIONS

In summary, an accurate fixed-point gas monitoring system is important to safety in any research area using flammable or toxic gases. To design such a system, the gases present in the lab need to be identified along with their properties. Next, sensors need to be placed, considering variables like the physical characteristics of the lab, the location and nature of potential vapor or gas sources, chemical and physical properties of the gases or vapors, and characteristics of the local ventilation system or weather conditions. Alarm set points are usually set at

an exposure limit set by a regulating agency, such as OSHA or ACGIH, or at some percentage of those limits. 10% LFL is typical for a combustible gas warning alarm, and 25, 40, or 50% for evacuation. Finally, calibration and routine inspections must be performed on a regular basis. These intervals are often set according to manufacturers' guidelines. Records concerning design decisions, sensor placement, and alarm set point determinations, as well as calibration results should be kept in a central location.

The gas monitoring system installed at the INL NHI laboratory provides protection in case of any process or input gas released into the room. Gas safety is an important concern to the researchers despite the large size of the room, and funds were spent to provide a very good monitoring system. Since the system became operational in December 2006, the INL NHI researchers have had favorable experiences with their H₂, O₂, CO, and CO₂ detection equipment. The monitoring system is robust and can accommodate any near-term future needs for the room, such as higher throughput experiments or additional experiments. A contract with the sensor vendor is in place to handle all repair needs. Calibrations are performed by INL personnel, and the results are shared with the vendor and the vendor's local representative company. For CO and CO₂, the set points are 50% TLV for the initial gas warning and 100% TLV for evacuation. The enriched oxygen atmosphere alarm is set at 22.5% for warning and 23.5% for evacuation. The hydrogen warning alarm is set at 10% LFL and the evacuation alarm at 25% LFL.

Table IV. Gas Detector Head Routine Inspection and Maintenance

Assembly or Function	Frequency	Procedure
Sample connection	Daily	Tighten probe or tube fitting as needed
Moisture trap	Daily	Drain and clean bowl
Flow meter	Daily	Check, adjust, replace dust filter as needed
Pump	Daily	Confirm operation and suction
Alarm test	Daily	Check with test switch
Detector output	Daily	Check for excessive output level
Batteries (portable)	Daily	Check remaining life and replace as needed
Alarm calibration	Monthly	Check with prepared gas sample
Span adjustment	Quarterly	Check and adjust with prepared gas sample
Zero calibration	Quarterly	Set with only clean air present
Filter elements	Twice/year	Clean or replace as needed
Sensor	Twice/year	Calibrate or replace

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