Summary and Findings from the NREL/DOE Hydrogen Sensor Workshop (June 8, 2011)

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
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Executive Summary

On June 8, 2011, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) hosted a hydrogen sensor workshop attended by nearly 40 participants from private organizations, government agencies, and academic institutions. The participants represented a cross section of stakeholders in the hydrogen community, including sensor developers, end users, site safety officials, and code and standard developers. The goals were to identify critical applications for the emerging hydrogen infrastructure that require or would benefit from hydrogen sensors, to assign performance specifications for sensors deployed in each application, and to identify shortcomings or deficiencies (i.e., technical gaps) in the ability of current sensor technology to meet the assigned performance requirements. Current (e.g., on-board sensors for hydrogen forklifts) and emerging (e.g., residential) applications were included.

The workshop was structured into two parts. The morning session consisted of topical talks that provided background information about various emerging hydrogen energy applications, the certification and listing processes, and about strategies for sensor deployment. Several critical key application areas were specifically identified, and for each application, breakout groups were formed to identify critical performance metrics, assign values to specifications, and identify shortcomings or deficiencies in current sensors to meet these requirements. Three sequential breakout sessions were held, which allowed workshop attendees to participate and provide input into multiple topical areas. Several breakout groups met in parallel, which restricted the size of each group to eight or fewer participants and enabled open discussions. Each breakout group was chaired by a topic expert. The breakout topics and chairs were:

- Indoor Fueling and Operations (chaired by Albert (Snapper) Pouché Jr., Defense Logistics Agency Susquehanna)
    - Facility Monitoring
    - In-Dispenser Deployment of Sensors
- Storage (chaired by Robert Burgess, NREL)
- Production (chaired by Joe Cohen, Air Products)
- Residential (chaired by Carl Rivkin, NREL)
- Battery Backup (chaired by Curtis Ashton, CenturyLink)
    - Dedicated Controlled Environmental Vaults
    - Shared-Use Buildings
- Industrial Trucks (chaired by Aaron Harris, Nuvera Fuel Cells)
- Vehicles (William Buttner, NREL)

Sensor requirements for each application were defined based on feedback from the breakout groups. Although application specific, many requirement metrics overlap applications. For example, response time is a critical parameter for all applications; however, specifications vary. Sensors deployed as facility monitors (in warehouses, battery backup rooms, etc.) need a moderate response time (e.g., 30 seconds), whereas sensors deployed within enclosures surrounding pressurized hydrogen (i.e., in dispensers or on-board forklifts proximal to an enclosed storage tank) require a fast response time (e.g., 1 second). A 30-s response time is readily achieved with current technology, whereas the 1-s response time remains problematic; some newer sensor models have fast response times but compromised performance for other critical parameters (e.g., linear range, long-term stability). Other key sensor performance shortcomings were reviewed. Several of these parameters cross cut over multiple applications, but are not necessarily universal to all applications. Outstanding sensor shortcomings include:

- Analytical performance parameters
    - Response time (1 s)
    - Cross sensitivity/poisons
- Operational parameters
    - Cost of maintenance and calibrations
    - Alarm thresholds
- Deployment parameters
    - Code requirements
    - Placement
    - Point sensors versus wide area monitoring.

The workshop and findings represent a critical first step in defining the sensor requirements for the emerging hydrogen infrastructure. Recognizing that additional applications may be identified that were not addressed at the workshop, or that sensor requirements may evolve, a Hydrogen Sensor Task Group was organized by the Fuel Cell and Hydrogen Energy Association and NREL, and is open to all stakeholders in the hydrogen community. The task group meets regularly via a teleconference link and web conference format.

Abbreviations and Acronyms

AHJ	Authority Having Jurisdiction (typically for permitting)
ASIL	Automotive Safety Integrity Level
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CEV	Controlled Environment Vault
CSA	Formerly Canadian Standards Association, CSA is now the official name
CFD	Computational Fluid Dynamics
CGS	Combustible Gas Sensor
cm^3	Cubic Centimeter
CO	Carbon Monoxide
DOE	U.S. Department of Energy
DOT	Department of Transportation
FCV	Fuel Cell Vehicle
ft^2	Square Foot (Feet)
ft^3	Cubic Foot (Feet)
g	Gram
h	Hour
IEC	International Electric Code
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
kg	Kilogram
LDL	Lower Detection Limit
LEL	Lower Explosion Limit, defined for safety purposes to be equivalent to LFL
LFL	Lower Flammable Limit
MEM	Microelectromechanical System
min	Minute
MOX	Metal Oxide Sensor
MPa	Megapascal
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
OSHA	Occupational Safety and Health Administration
P	Pressure
ppm_v	Concentration unit of a component in a gas mixture, expressed as a fraction of the volume of the component to the total gas volume scaled by a factor of 10^6
psi	Pounds per square inch
RH	Relative Humidity

T	Temperature
TCD	Thermal Conductivity Detector
UE	Utility Enclosure
UL	Underwriters Laboratories
V_{DC}	Volts of direct current
vol%	Concentration unit of a component in a gas mixture, expressed as a volume percentage of the component to the total gas volume

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1 Background

Hydrogen has been recognized by the U.S. Department of Energy (DOE) Vehicle Technologies Program as one of six alternative and renewable fuels for advanced vehicles [1]. Its use as a fuel already has commercially viable markets, which include stationary power systems (e.g., backup power) and fuel cell-powered industrial trucks (e.g., forklifts). Both markets are expanding, and this growth is driving the development of hydrogen support systems that include transport and production capability, on-site storage, and on-site dispensers [2]. The use of hydrogen as an alternative fuel will continue to grow, especially with the pending deployment of light-duty road vehicles [3]. Automobile manufacturers in North America, Europe, and Asia project a 2015 release of commercial hydrogen fuel cell-powered road vehicles. These vehicles will be for general consumer applications, albeit initially in select markets but with much broader market penetration expected by 2025 [4]. The necessary support systems need to be developed to implement these vehicles. For the consumer market this includes not only expanded hydrogen production capacity, transport, on-site storage, and dispensing (fueling) infrastructure, but also other infrastructure elements unique to general public deployment such as parking garages compatible for hydrogen vehicles (residential as well as large public facilities) and maintenance facilities. It is critical that the hydrogen market and infrastructure develop safely and efficiently to ensure the successful deployment of hydrogen as an alternative fuel.

Safety is recognized as a critical factor for the successful implementation of hydrogen as a fuel, and numerous expert working groups have been organized to ensure hydrogen safety is properly addressed in the field [5, 6, 7]. A reliable safety system is composed of various elements that can include intrinsic design features (e.g., material specifications, pressure control systems, venting systems), engineering controls (e.g., sample size minimization, deployment location) and the use of hydrogen sensors to detect unexpected releases. Hydrogen gas is odorless and colorless; thus, its detection requires a sensing device with an audible alarm or other indication for personnel and property safety. Hydrogen safety sensors are typically separate from the main operational features of a system, such as part of a dispenser control system or an internal monitor of a storage facility, and thus can provide a critical independent assurance of safety. Sensors can also operate on backup power or batteries, and thus remain operational during power outages, which may not necessarily be the case for all other safety design elements. In addition to audible alarms or other indicators, hydrogen sensors may be used to activate site ventilation and initiate system shutdowns. Hydrogen sensors can thus be viewed as an enabling technology for the safe implementation of the emerging hydrogen infrastructure.

Furthermore, the use of hydrogen safety sensors in indoor hydrogen fueling operations was explicitly mandated by the National Fire Protection Association (NFPA 52), *Vehicular Gaseous Fuel Systems Code* and more recently by NFPA 2, *Hydrogen Technologies Code*. In addition to safety applications, hydrogen sensors will play a role in process control operations. Typically, process sensors would be deployed in highly enriched hydrogen atmospheres, possibly up to 100% hydrogen. Their signals could provide necessary feedback to improve the desired output. Applications may include monitoring of composition, purity, and metering. Process control sensors have relevance for production, dispensing, and controlling the fuel cell. Of the two applications, safety sensors have more short-term relevance for the implementation of the hydrogen infrastructure, and this was the focus of the 2011 Department of Energey/National Renewable Energy Laboratory (NREL) Hydrogen Sensor Workshop and this report.

Safety sensors are regularly used to indicate a potentially hazardous situation. The flammable range is 4–75 vol% hydrogen in air. Accordingly, sensors are normally set to alarm below the hydrogen lower flammable limit (LFL) of 4 vol% in air. Different risk levels can be associated with different ambient hydrogen concentrations, which can be qualitatively described as *trace* (0.1 vol% H_2 in air), *low* (0.4 vol% H_2 in air), *medium* (1 vol% H_2 in air), *elevated* (4 vol% H_2) and *high* (8 vol% H_2 in air), as summarized in the Table 1, where the hydrogen concentration is given as fraction of the LFL and in concentration units (percent by volume in air – vol% or parts per million by volume in air – ppm_v). This categorization, which can guide alarm thresholds for hydrogen sensors, indicates that for safety applications hydrogen at or above the LFL represents a serious risk, and that providing separate distinctions for higher hydrogen concentrations (such as the lower explosion limit [LEL] of 17 vol%) is unwarranted. Furthermore, safety regulations often treat LFL and LEL as synonymous, using the more conservative concentration (4 vol%) or fractions thereof as the action (alarm) level. Hydrogen safety sensor alarm levels are usually set below the LFL, typically at either the low (0.4 vol% H_2 in air, which is equivalent to 10% of the LFL) or medium (1 vol% H_2 in air, which is equivalent to 25% of the LFL) condition. However, to provide risk level data to site and emergency response personnel, it may be necessary to measure the hydrogen at concentrations above the LFL, especially if the concentration may either be increasing or remaining stagnant at or above the LFL.

Table 1. Risk Levels for Different Hydrogen Concentrations

Condition (risk)	% of LFL	$[H_2]$, vol% (in air)	$[H_2]$, ppm_v (in air)
Trace	2.5	0.1	1,000
Low	10	0.4	4,000
Medium	25	1.0	10,000
Elevated	100	4.0	40,000
High	>200	>8.0	>80,000

1.1. Hydrogen Safety Sensor Metrics

The selection of a sensor technology (or any other analytical system) will be based on several performance parameters (or metrics) as they pertain to a specific application. One can envision a large number of metrics, which for the most part can be divided into analytical and logistic parameters. The most important and obvious performance parameters pertain to the analytical characteristics of the device, which are those that are directly related to the ability of the chosen technology to perform the analytical measurements required by the application. The logistic needs of the application will impose additional parameters to the sensor requirements, which can be demarcated into deployment and operational metrics. The deployment and operational parameters do not pertain to a sensor's ability to accurately detect hydrogen, but rather to other factors that ultimately determine the suitability of a technology for a specific application. The deployment parameters pertain primarily to the installation or incorporation of the sensor technologies into a specific system and are typically one-time, upfront considerations. Alternatively, the operational parameters pertain to operation and maintenance of the sensors once they have been installed and are ongoing or recurring considerations. Analytical, deployment, and operational parameters identified as important criteria for hydrogen safety sensor specifications are as follows:

1.1.1. *Analytical*

- **Analytical parameters.** Selectivity, Lower Detection Limit (LDL), Analytical Resolution, Linear Range (and Dynamic Range), Accuracy, Response Time, Recovery Time, Repeatability, Drift, Environmental Effects (e.g., temperature [T], pressure [P], and relative humidity [RH]), Reversibility, Limits of Quantization (Limits of Determination), Saturation Stability, Sensitivity

1.1.2. *Logistical*

- **Deployment parameters.** Capital Cost, Installation Costs, Placement, Physical Size, Control Circuitry, Power Requirement, Electronic Interface, Pneumatic Design, Shelf Life, Maturity/Availability, Regulations (Codes), Alarm Set Points

- **Operational Parameters.** Operational Lifetime, Consumables, Calibration and Maintenance Requirements, Sample Size, Matrix Requirements, Signal Management, Orientation Effect, Device to Device Repeatability, Warm Up Time, Alarm Interface, Mechanical Stability

Definitions for and supplemental information about these parameters are provided in Appendix A. Typically a quantitative or numerical specification is assigned to each. For example, a 1-s response time refers to the performance metric "response time" having the specification of 1 s. Additional parameters may be identified and added to the list. Additional parameters may be incorporated, especially for unique applications with specialized requirements (e.g., sensor installed for crash test studies, which will need to withstand forces associated with sudden impacts [8]).

In all cases, the importance of each parameter and its assigned specification is application specific, and the relative importance of a specific parameter varies by application. Thus, a critical parameter for one application may have negligible importance for another. As an example, a process control sensor may be expected to precisely and accurately control hydrogen concentration and thus would have stringent analytical resolution requirements with minimal importance assigned to the LDL; in contrast, safety sensors deployed as area monitors must have an LDL at a fraction of the alarm threshold, but would not have severe requirements to quantitatively resolve small changes in hydrogen concentrations.

The application defines the sensor requirements, which thus must be explicity assessed for each application. Since not every parameter listed will necessarily have strong relevance for a specific application, the project engineer must determined the relative importance of all metrics for each application. Thus, a universal (short) list of critical sensor metrics with assigned specifications relevant for all applications is of limited value, and may be counterproductive; a 1-s response time may add cost and complexity to a sensor and yet be of limited value for a given application. Accordingly, the focus of the 2011 DOE/NREL hydrogen sensor workshop was to identify crucial applications (current and emerging) associated with the hydrogen infrastructure and then to define critical metrics and specification requirements for the various specific applications. The goal was not to define an all-encompassing set of metrics to cover every scenario.

Sensor cost factors are decoupled from the analytical parameters. Cost requirements – not analytical requirements – are deployment and operational issues. This decoupling is consistent with allowing the requirements of the application to define the necessary analytical performance metrics without influence from programmatic and administrative inputs (e.g., budget constraints). Nor does the list favor one technology over another, which is also consistent with allowing the application to define the critical requirements as opposed to refining the requirements by the capability or limitations of the detector. Of course, facility engineers must often compromise between needs and capability; for example, a maintenance-free sensor is a typical desire, but code and manufacturer recommendations will often mandate periodic calibration. Facility engineers must also have reasonable expectations about the specifications assigned to critical metrics. Thus, a low-cost sensor with minimal maintenance may be a reasonable requirement, but a maintenance-free sensor with zero operational costs is probably not realistic.

Sensitivity is a term commonly used to describe a sensor performance, and as such it is included in the list of possible analytical parameters. It can be a vague performance parameter, however, and other metrics (e.g., LDL, analytical sensitivity, and linear range/dynamic range) actually precisely define specific properties often associated with sensitivity. For example, s*ensitivity* is often misused as synonymous with the *LDL*. *Sensitivity* is the electronic response of a sensor to a given amount of an analyte and has units of concentration divided by electronic signal (e.g., the slope of a calibration curve). It can be misleading in that a sensor with a high sensitivity may have a noisy output and thus be less able to resolve analyte concentrations than a sensor with a lower sensitivity and less noise in its output (*analytical resolution* refers to the ability of a sensor to resolve analyte concentrations). An increased sensitivity means only a stronger electrical response for a given analyte concentration, and does not necessarily imply improved LDLs, analytical resolution, linear range, or other critical parameters.

Finally, as a point of clarification, *sensor* can have various meanings. Developers of sensing technology often use *sensor* to describe the sensing element. In this context, the *sensing element* is the electrochemical, thermal conductivity, or other component that reacts with or responds to the analyte gas (e.g., hydrogen) to generate an electrical response that then can be processed, directly or indirectly, into an electrical signal. The control circuitry and user interface allow practical use of this signal. In this report, *sensor* will refer to an instrumented system composed of a sensing element, control circuitry, and user interface that provides analytically useful information to the end user.

1.2. The 2007 and 2011 DOE/NREL Hydrogen Sensor Workshops

Numerous hydrogen sensor technologies are currently available and new model types are being developed and commercialized every year. In part, this is because hydrogen has been for many years a common chemical in the petroleum, food, glass, and other industries, and because of the projected market growth as hydrogen use as an alternative fuel increases. The availability of hydrogen safety sensors will be critical for the successful utilization of hydrogen as an alternative fuel. These sensors, however, must meet necessary requirements. Several broad-range applications for hydrogen sensors were previously identified in the 2007 DOE workshop, which were the Fuel Producer/Supplier Environment and the End-User Environment [9]. Accordingly, DOE has published a short list of performance parameters with target specifications for hydrogen safety sensors to provide sensor developers sufficient guidance to meet the hydrogen community needs as viewed in 2007 [10] (see Table 2). These targets were viewed as 5-year goals to meet the projected 2012 needs. Most hydrogen sensors are based on a few basic platform types, each of which has unique operating principles that will ultimately control its performance [11, 12].

Each technology type has its advantages and limitations, but none have been shown to simultaneously meet all of the target specifications prescribed by DOE in 2007.

Table 2. DOE Target Specifications for Hydrogen Safety Sensor R&D*

Parameter	Specification (Value)
Measurement range	0.1 to 10 vol%
Operating temperature	-30° to 80°C
Response time	<1 s
Accuracy	5% of full scale
Gas environment	Ambient air, 10% to 98% RH
Lifetime	10 years
Interference	Resistance (e.g., hydrocarbons)

*Table 3.8.2 in [10]

Since 2007, new markets have emerged and overtaken light-duty road vehicles as currently available and deployed commercial technologies; the most prominent are hydrogen-powered forklifts, and to a lesser extent, hydrogen-fueled stationary power systems. However, demonstration projects associated with road vehicles are ongoing and early demonstrations have been successfully completed. There is also extensive ongoing infrastructure implementation (e.g., installation of filling stations and associated support systems) to prepare for the 2015 commercial release of hydrogen fuel cell vehicles (FCVs). With this growth in infrastructure, applications and new requirements are emerging for hydrogen fuel. Independent reviews on the ability of commercial sensors to meet the needs of some markets (e.g., automotive sensors) have been performed.

A market survey of more than 50 commercial sensors provided an overview of their ability to meet the safety requirements for automotive and stationary applications [13] with a focus on a few analytical performance metrics. This survey relied primarily on vendor-supplied specification and performance data and did not include independent validation of sensor performance. Even so, some devices readily meet some – but not necessarily all – the application requirements.

Attempts to improve the specification of one parameter (e.g., response time) often compromise other metrics (e.g., linear range or device operational lifetime). It was therefore useful to revisit the 2007 sensor workshop to refine hydrogen sensor requirements for safety purposes for a range of *specific* hydrogen infrastructure applications. To achieve this, a second workshop, sponsored by DOE/NREL, was organized to provide an updated assessment of the hydrogen sensor requirements. This workshop was held on June 8, 2011 in Chicago (Rosemont), Illinois. The 2007 targets were developed for generalized applications and thus were consolidated into a single short list of desired metrics, but as indicated above and explicitly demonstrated in the following sections of this report, sensor metrics are dependent on the specific application. Thus, rather than producing generalized targets for sensor performance, application-specific requirements were explored. Nearly 40 participants attended the workshop, representing a range of stakeholders in the hydrogen community. They included representatives from private, government, and academic institutions. Sensor developers, end users, standard developing organizations, and site safety officials participated. A list of attendees and the workshop agenda is provided in Appendix B.

The workshop was structured to include a series of topical talks by invited speakers that covered selected aspects of hydrogen sensors. The following topical talks were presented at the 2011 DOE/NREL Hydrogen Sensor Workshop [14]

- DOE Fuel Cell and Hydrogen Program; Role of Sensors – *Scott McWhorter, Savannah River National Laboratory and DOE*
- 2007 Workshop – *Robert Burgess, NREL*
- 2011 Workshop Background and Objectives; Technology Update – *Robert Burgess, NREL*
- Codes and Standards Sensor Requirements – *Carl Rivkin, NREL*
- What a Battery User Needs from a Hydrogen Sensing Unit – *Curtis Ashton, CenturyLink*
- Wide Area Sensor Needs – *Nick Barilo, Pacific Northwest National Laboratory*
- Hydrogen Fuel Detection based on Smart Sensor Systems – *Gary Hunter, National Aeronautics and Space Administration – Glenn Research Center*
- Indoor Fueling – *Bob Skinner and Albert (Snapper) Pouché* Jr.*, LMI*
- Hydrogen Sensor Certification – *Michael Alexander, Underwriters Laboratories (UL) Project Engineer*
- H_2 Sensor in Industrial Truck Applications – Needs assessment from Field Experience – *Aaron Harris, Nuvera Fuel Cells*
- Sensor Metrics – *William Buttner, NREL*

More importantly, several critical key application areas were identified that will require hydrogen sensors for safe operations. For each application, breakout groups were formed to identify critical performance parameters requirements, assign values to specifications, and identify gaps or shortcomings in current technologies to meet these requirements. Three sequential breakout sessions were held. Typically, each breakout group met in multiple sessions, albeit with different participants. In each session, multiple breakout groups met in parallel, which restricted the size of each group to eight participants and enabled open discussions. Sequential sessions allowed workshop attendees to participate and provide input in three topical areas. Each breakout group was chaired by a topic expert. The breakout topics and chairs were:

- Indoor Fuel and Operations (chaired by Albert (Snapper) Pouché Jr., Defense Logistics Agency Susquehanna)
- Storage (chaired by Robert Burgess, NREL)
- Production (chaired by Joe Cohen, Air Products)

- Residential (chaired by Carl Rivkin, NREL)
- Battery Backup (chaired by Curtis Ashton, CenturyLink)
- Industrial Trucks (chaired by Aaron Harris, Nuvera Fuel Cells)
- Vehicles (William Buttner, NREL)

1.3. Report Format

Sections 2.1–2.7 summarize the outcomes of the breakout groups by major application. This assessment prioritizes the performance metrics by application and attempts to assign target specifications. Neither the workshop nor this report addresses specific sensor technology types, nor are the respective performance metrics among various sensor types covered. An assessment of the main sensor platform types has been presented elsewhere [10, 11]. Rather, the workshop organizers strived to specifically identify critical applications for the emerging hydrogen infrastructure that require or would benefit from hydrogen sensors, and, more importantly, to then assign performance specifications for sensors deployed in that application.

A relative ranking of each identified performance metric was assigned and is presented by application in Tables 3 through 11. For each application, each metric was assigned a qualitative ranking of low, medium, or high importance, as indicated by a marker in the appropriate column. The position of the marker within the column refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment within the column. Specification requirements are also listed.

An identification of gaps and deficiencies in the ability of current sensor technology to meet these requirements is included in the accompanying discussion. Each of the following sections provides a brief description of a specific application, a prioritization of sensor performance metrics and assignment of desired specifications, an assessment of current technology to meet requirements, and finally, proposed recommendations to address the identified shortcomings and gaps in sensor performance. The discussion for each application is presented in separate sections, which are complete and structured to be independent of the other application discussions. A summary (Section 3) discusses similarities and differences between sensor requirements for the various applications. The following assessments were based primarily on the findings of the sensor workshop, and in general, each section was reviewed and updated by the corresponding breakout session participants and chairs.

The workshop and findings represent a critical first step in defining the sensor requirements for safety in the emerging hydrogen infrastructure. Recognizing that additional applications may be identified that were not addressed at the workshop, or that sensor requirements may evolve, a Hydrogen Sensor Task Group was organized by the Fuel Cell and Hydrogen Energy Association and NREL, and is open to all stakeholders in the hydrogen community. The Hydrogen Sensor Task Group is now chaired by NREL (for information see the NREL Sensor Test Laboratory home page [15]). The task group is to meet quarterly via a teleconference link and web conference format.

2 Applications

The 2011 hydrogen sensor workshop identified several distinct hydrogen applications and subtopics that require or would benefit from hydrogen sensors. Breakout groups were formed to review the sensor requirements for each application. The goals of the breakout groups were to formulate relative rankings of the importance of the various sensor performance parameters, assign specifications, and to review the ability of current sensor technology to meet these requirements. The following applications were specifically addressed in the workshop and are discussed in the following sections:

- Industrial Trucks
- Indoor Fuel and Operations
    - Facility Monitoring (area monitors)
    - Internal Dispenser Sensor Deployment
- Residential
- Production
    - Distributed Hydrogen Production
    - Centralized Hydrogen Production
- On-board Light Duty Road Vehicles
- Battery Backup
    - Building
    - Controlled Environment Vaults
- Storage

2.1 Industrial Trucks (Forklifts)

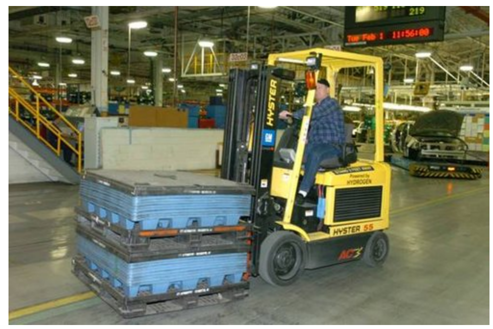
- Application
    - Deployment of hydrogen sensors to detect leaks in on-board forklift fuel storage and delivery systems.
- Applicable standards
    - NFPA 2, Hydrogen Technologies Code
    - Listing of sensor and sensor components
    - UL 60079-15, Electrical Apparatus for Explosive Gas Atmospheres or equivalent listing requirements for use in Class I, Division 2 hazardous locations
    - UL 2075, Gas and Vapor Detectors and Sensors or CSA C22.2, No. 152, Performance of Combustible Gas Detection Instruments or equivalent listing for sensor performance

- FM Global Class 6310 and 6320, Approval Standard for Combustible Gas Detectors
- UL 2267, Fuel Cell Power Systems for Installation in Industrial Electric Trucks

- Local Authority Having Jurisdiction (AHJ) invoking modified fire code

2.1.1 Background

Fuel cell-powered industrial trucks (forklifts) are an emerging, near-term market that uses hydrogen as a fuel [1]. These forklifts are already commercially available and are being deployed in numerous private industrial operations. The currently deployed fleet typically has on-board hydrogen sensors as part of its safety systems, and the use of sensors is likely to continue with future generations of hydrogen-powered forklifts. Thus, this application represents an existing and growing market for hydrogen sensors.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Forklift on-board hydrogen storage is approximately 1 kg, but this varies with forklift design. Although uncommon, system failures leading to a full release of hydrogen from the storage tank have occurred [16]. In one instance, hydrogen was released during the fill that followed a maintenance operation on an on-board solenoid valve. A malfunction in the solenoid valve led to the release of the hydrogen within the tank. It should be noted that the hydrogen was safely dissipated, and there was no report of a fire or other event. However, there is reason for concern. A release of 1 kg of hydrogen uniformly distributed in a 25,000-ft^3 facility would be only approximately 1.7% by volume, which is less than half of the hydrogen LFL (a 5000-ft^2 warehouse with a 25-ft ceiling would be 125,000 ft^3). However, uniform distribution is highly unlikely and such a release may not be instantaneously distributed. A release of stored hydrogen, even in quantities less than a full tank, could lead to a potentially dangerous situation in the event of containment, pockets, or entrapment that are caused, for example, by structural features or operation in an enclosed space such as a small room or unloading/loading a truck trailer. Although flow regulators, shutoff valves, and bypass valves are incorporated into the forklift safety system, hydrogen sensors, which are separate from operation, provide an increased independent assurance of safety.

Hydrogen sensors can be deployed on board the forklift to detect and quickly alert personnel to hydrogen leaks. Sensor placement should be proximal to the storage tank and fuel cell, which are usually enclosed in a metal housing. Although the housing is not sealed and allows for passive ventilation, exchange of the inside gas with outside air is to some extent impeded, which may cause hydrogen to build up internally. Thus, this deployment may be considered a contained environment. Currently, there are no mandatory sensor requirements for on-board deployment, but manufacturers recognize the importance of sensors and generally have voluntarily incorporated them into the forklift safety system. Local AHJs may impose locally modified fire code and thereby mandate sensor use. Sensors listed as compliant to national standards, especially Class I, Division 2 listings, would be useful, although such a listing is not currently required. A sensor not listed to an accepted safety standard may need to be shut down when it is in alarm because it is not approved for operation in a (potentially) combustible atmosphere. This in turn may require system (e.g., the forklift and all control elements) shutdown because of a lack of active detectors.

In addition to electrical and other safety standards, there are performance-based standards for combustible gas sensors (CGSs) (e.g., UL 2075, Gas and Vapor Detectors and Sensors and CSA C22.2, No. 152, Performance of Combustible Gas Detection Instruments). Although these standards are not specific to hydrogen detection, some jurisdictions have already mandated that hydrogen safety sensors be listed as compliant to UL 2075, and at some point this may be more universally required. Typically, hydrogen sensors deployed on forklifts are configured for a single alarm level. When hydrogen is detected at 10% of the LFL, an audible alarm is activated. Two levels of response could be of interest.

- A low-level response (e.g., 10% of the LFL or 0.4 vol% hydrogen) to activate the audible alarm and, if possible, to enhanced ventilation with a ventilation fan mounted around the storage tank.

- A medium-level risk corresponding to 25% of the LFL (1 vol% hydrogen), which would shut down the forklift operation and isolate the fuel delivery system bya activating the shutoff valves.

Telemetric communication for remote monitoring of the output is not required. The gas detector should have electronic outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. If an on-board control system monitors the state, operation, and performance of the forklift, the output of the sensor should interface with the control system. The interfacing would be performed by the forklift manufacturer.

Leaks in an enclosure, even with ventilation ports, may quickly lead to situations of concern (e.g., hydrogen concentrations approaching the LFL), so a fast response time for the sensor is necessary. Although unlikely, the sensor may experience a direct hit of hydrogen by a leak jet. Accordingly, a brief exposure to pure hydrogen should not impact its analytical capability. The sensor should also not be affected by chemical interferences, including, but not limited to, carbon monoxide (CO) and sulfur compounds. Because silicone compounds such as sealants, lubricants, and pneumatic elements are used extensively, the sensor should also be resistant to silicone; these compounds are known poisons of many sensing element platform types, especially combustible bead sensors or metal oxide sensors (MOXs).

Failure caused by dust buildup on the sensor or sensor inlet was reported in the workshop. This can lead to either a false positive, such as would occur with a catalytic bead sensor that heats up because of the thermal insulating effect of dust, or to false negatives because the active surface of the sensing elements is blocked. Thus, some means to control dust buildup on the sensing element or gas inlet to the sensing element may be necessary. Forklifts will often operate in warehouses with limited climate control or in freezer storage areas. Therefore, sensors ought to operate over a temperature range of -40–40°C and a humidity range of 5%–90%.

If the forklift will be operated in or around refrigerated facilities, the sensor should also not show cross sensitivity to common refrigerants, including ammonia or chlorofluorocarbon compounds such as Freon. Although significant pressure fluctuations are not expected, sensors must be calibrated to local prevailing pressure levels, as barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m). Routine maintenance, such as calibration, should be required perhaps once per year, although longer intervals are highly desirable. Sensors deployed for on-board operation will be subjected to mechanical stresses (e.g., vibrations). The target sensor cost has been set at $100, but lower costs are of course desired.

Table 3 summarizes the sensor requirements and specifications for on-board forklift deployment. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left-justified mark indicates a lower importance than a right or middle alignment.

Table 3. Hydrogen Sensor Metric Rankings for Industrial Truck Applications – On-Board Deployment

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity			X	Sulfur, silicone resistance, CO, dust
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		10 s
Recovery Time		X		30 s
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts		X		T and RH are more relevant than P
- T			X	0 to +40°C (or -40°C for freezer storage areas)
- P	X			Must be calibrated for deployment altitude
- RH		X		15%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability			X	Relevant for sensors mounted near tank
Deployment Parameters				
Capital Cost		X		<$100
Installation Cost	X			
Physical Size			X	Small size compatible with mounting around tank
Control Circuitry			X	
Electronic Interface		X		Output in engineering units (e.g.,% H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)	X			Not required for on-board, trace background is possible
- Low (low risk)			X	10% of the LFL, indicate adverse for single alarm level
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes		X		Possible local AHJs
Deployment Placement			X	Within enclosure proximal to the tank
Operational Parameters				

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Lifetime			X	5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Readout is not necessary
- Remote monitoring	X			Remote interrogation is not necessary
Device Repeatability		X		Plug in replacement is useful
Warm-Up Time		X		<1 h for initial installation, <1 min for all shutdowns
Alarm Interface				
- Number of set points		X		One mandatory, two useful shutdowns
- Audible			X	Activate alarm at lowest set point
- Ventilation	X			Activate at 1^{st} set point, if feasible
- Shutdown			X	Activate at 2^{nd} set point (25% of LFL)
- Remote	X			Not necessary
Mechanical Stability		X		Vibration tests, specification TBD
Power Requirements		X		Moderate power requirements preferred (<0.5 W)

2.1.1.1 Critical Gaps and Deficiencies

The operational requirements for sensors are a major limiting factor for on-board sensor deployment. Costs, especially maintenance costs, are a concern. The overall sensor cost encompasses several elements, including the actual capital cost of the device, the expense associated with on-board installation, and the operational expenses (e.g., recurring in-the-field calibration and maintenance). Because capital cost and factory installation are typically one-time upfront expenses (per truck), they are not viewed as detrimental to sensor acceptance as the ongoing and recurring operational costs. There is, of course, always a desire for lower capital cost and simplified installation requirements, providing sensor reliability is not compromised. Operational expenses are recurring costs and are a major concern. Operational activity, such as routine maintenance, calibrations (or validation of calibration), and sensor replacement are typically performed manually in the field, and are very expensive because they require forklift downtime and trained personnel must do the work.

Although the on-board hydrogen sensor is primarily in an indoor environment, it must operate in temperature and humidity extremes, especially when the sensor is co-deployed in an enclosure containing the fuel cell or storage tank. Some hydrogen forklift fleets operate outdoors, and thus would be subjected to more extreme temperature fluctuations. False alarms are caused by the physical operating environment, which can include temperature, pressure, and humidity fluctuations as well as interferents, poisons and dusts, so they remain major concerns. It is therefore unlikely that the calibration requirement will be eliminated for the sensor.

Another deployment consideration is that sensors often need to be certified (or listed) for deployment in a potentially combustible atmosphere. Some jurisdictions are requiring performance-based certification as well. Although a nonlisted sensor can be used to detect hydrogen, it would not necessarily be safe to operate as the hydrogen concentration approaches the LFL. In the event the sensor must shut down, it would also be advisable to shut down the forklift. Some sensors are compliant with Class I, Division 2 (e.g., UL 60079-15) operation, but no sensor is currently compliant with performance-based standards (e.g., UL 2075 or CSA C22.2).

Sensor deficiency areas and gaps impeding deployment can be summarized as follows. A major deficiency represents a current critical issue that has been problematic (e.g., occurring with an unacceptable frequency). A secondary issue is important but is either not critical or has not been reported as occurring (e.g., false negatives have not been reported).

- Major
    - Analytical performance in the on-board environment (high T and RH)
        - No false positives, due to environment-induced effects
        - Fast response/recovery times
    - Maintenance and calibration frequency
        - Long-life sensors (>5 years)
    - Calibrations no oftener than once per year
    - All other maintenance requirements less often than once per year
    - Robust performance, especially against contaminants, poisons, and dust
- Secondary
    - Capital cost for appropriate monitoring systems
        - Acceptable target: <$100/sensor)
    - Listed sensors
        - Performance-based approvals (e.g., UL 2075 or CSA C22.2, No. 152)
        - Approval for operation in a combustible environment (UL 60079)
    - Analytical performance
        - Recovery from high hydrogen exposure
        - No false negatives

2.1.1.2 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment is to simplify and economize the operational requirements. Every deployed sensor must be calibrated (or have the calibration of the instrument validated) prior to truck delivery. Following deployment, trained personnel will use on-site gas standards to perform or validate periodic calibrations. Robust sensors with long operational lifetimes would cut down replacement cost, and could, in principle, lower the cost of maintenance by increasing the time between calibrations. However, sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., dust, thermal stresses, and vibration), and electrical factors (e.g., power surges, shutdowns, and circuit failures). The extreme and fluctuating temperature and RH operating conditions are also contributing factors for sensor drift. Thus, even though robust sensor technology may reduce site maintenance, deployed sensors will still require periodic calibration. Manual calibration performed in the field is not a cost-effective solution. An automated, efficient sensor functionality test is required.

A limited number of hydrogen sensors are currently listed for Class I, Division 2 operation (e.g., UL 60079-15), but no sensors are currently listed as compliant to performance standards (UL 2075, for example). Sensors listed to safety standards could allow operation once alarm levels of hydrogen are detected, and listed components may eventually be required. A nonlisted sensor would have to shut down when it detects hydrogen near the LFL, probably at 25% of the LFL. When the sensor shuts down, other systems should also terminate operation. Listed sensors, which could continue monitoring at or beyond the alarm level, would facilitate operation by differentiating between a spurious response (e.g., a transient exposure of hydrogen from some internal source) and an internal system release of hydrogen. A listed sensor would also allow for continuous monitoring once a release is detected, thereby providing more reliable performance. Thus, listing of sensors should be supported and facilitated. Currently, the sensor of choice for on-board applications has been the catalytic bead sensors (also called CGSs and MOXs), although no specific technology has been explicitly endorsed. Both are high-temperature devices, and thus, less susceptible to adverse impact from high-temperature operation, but some platforms are highly susceptible to drift induced by moisture fluctuations.

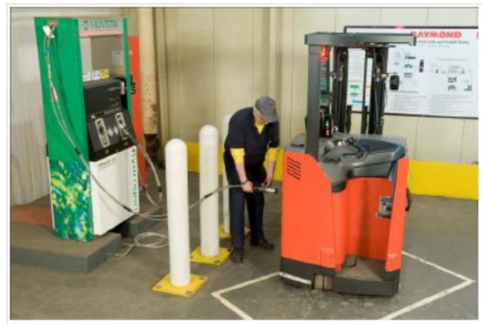
Sensor capital costs are likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted by economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, microelectromechanical systems [MEMs], and thin-film deposition protocols) could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements for range (e.g., multiple alarm levels) and robustness requirements (insensitive to poisons, interferences, and drift). Improved protection from dust and interferences via design changes should be pursued; this must be accomplished without compromise to the response/recovery time requirements.

2.2 Indoor Fueling Operations

- Applications
  - Facility (warehouse) monitoring around indoor fuel operations (area monitor)
  - Sensors installed inside dispensers (contained environment monitor)
- Applicable standards
  - NFPA 2, Hydrogen Technologies Code
  - Local AHJs invoking modified fire code
  - Listing of sensor and sensor components
  - UL 60079-15, Electrical Apparatus for Explosive Gas Atmospheres or equivalent listing requirements for use in Class I, Division 2 hazardous locations

- UL 2075, Gas and Vapor Detectors and Sensors or CSA C22.2, No. 152, “Performance of Combustible Gas Detection Instruments,” or equivalent listing for sensor performance
- FM Global Class 6310 and 6320, Approval Standard for Combustible Gas Detectors

2.2.1 Background



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Fuel cell-powered industrial trucks (forklifts) are already commercially available and deployed in numerous industrial and government facilities. Thus, the fundamental support technology is already available, although significant near-term infrastructure expansion can be expected as deployments increase. Forklift fueling requires support systems, including delivery of hydrogen or on-site hydrogen production, on-site storage (typically outdoors), transfer hardware, and hydrogen dispensers. Typically fill quantities for forklifts range from 0.25 kg to usually less than 1 kg. A 0.5 kg/min delivery rate corresponds to a flow rate of approximately 5,500 standard liters per minute. A 1 kg hydrogen release uniformly distributed in a large room (e.g., 25,000 ft^3) would be approximately 1.7% by volume, which is less than half of the LFL (a 5000-ft^2 warehouse with a 25-ft ceiling would have a volume of 125,000 ft^3). However, uniform distribution throughout the warehouse is highly unlikely and such a release may not be instantaneously distributed. Even a relativley small release during dispensing could lead to a dangerous situation in the event of containment or entrapment within the dispenser.

During fueling, the dispenser delivers hydrogen to the forklift for high-pressure storage in the on-board tank. The maximum nominal settled pressure of the forklift storage tank can be as high as 35 MPa. For comparison, light-duty road vehicle tanks will be filled to nominal settled pressures up to 70 MPa, although road vehicles will be fueled primarily with outdoor dispensers. Hydrogen is typically supplied to the dispensers via a transport system from outdoor storage tanks, which hold either liquid or gaseous hydrogen pressurized to 1.4–14 MPa (200–2000 psi). Thus, during a fill, the dispenser must pressurize hydrogen by up to a factor of 50. Within the dispenser are high-pressure hydrogen and the associated pneumatic elements (tubing, fittings, valves, compressors, etc.).

Facility managers overseeing hydrogen forklift deployments generally prefer indoor hydrogen dispensing. Indoor fueling allows for easier access to the dispenser, hence much quicker fill times relative to outdoor fueling. Indoor fueling operations have been safely performed throughout the DOE-funded demonstrations; this safety record has continued through the early market entry of commercial fleets [2]. Indoor dispensers are typically mounted at the wall adjacent to the outdoor storage facility to minimize the volume of the indoor transfer lines. Thus, the indoor hydrogen systems required for forklift fueling are primarily associated with the dispenser.

Although flow regulators, shutoff valves, and bypass valves are incorporated into the hydrogen dispenser, hydrogen sensors, which are independent of operation, provide increased assurance of safety. Further, sensors can operate on backup power or batteries and therefore can be independent of the site power. Thus, even though the dispenser and its internal safety system may shut down during power outages, the hydrogen safety sensor can remain active through backup power systems, analogous to battery backup designs used in residential smoke and CO detectors. Sensors thus play a critical role in hydrogen dispenser safety.

Indoor hydrogen dispensing is an established and accepted operation, and thus represents an existing and growing application for the use of hydrogen safety sensors. Two main sensor applications are associated with indoor hydrogen dispensing: facility monitoring for external releases (e.g., an area monitor) and deployment in the dispenser (e.g., a contained environment monitor). These applications are treated separately below.

2.2.2 Facility Monitoring (Area Monitors)

NFPA 2 mandates the use of chemical sensors around hydrogen operations, including indoor hydrogen fueling. Accordingly, hydrogen sensors are mounted proximal to the hydrogen dispenser (e.g., an area monitor). The sensor can be mounted either on the wall adjacent to and above the dispenser (the most common location) or from the ceiling above the dispenser. Typically a single sensor is used. Hydrogen sensors currently deployed proximal to indoor dispensers are typically configured for a single alarm level. If they detect hydrogen at 10% of the LFL (or 25%, depending on local requirements), an audible alarm is activated. This is the minimim requirement for the safety sensor deployed as an area monitor. Although currently multiple alarm levels are not typically used around indoor dispensers, two alarm levels could be of interest:

- A low-level threshold at 10% of the LFL (0.4 vol% hydrogen) would activate the audible alarm and enhanced ventilation.
- A medium-level response at 25% of the LFL (1 vol% hydrogen) would activate shutdown of the dispenser operation and isolate the fuel delivery system via activation of shutoff valves.

It may be useful and at some point mandated by AHJs for the sensor to interface with the building ventilation systems, which would be activated at the low alarm level. Relays would be useful in this circumstance.

Sensors that are compliant with national standards, especially Class I, Division 2 listings, are advisable, and most indoor fueling facilities conform to this. A sensor not certified to operate in a combustible environment would need to shut down when such a condition is indicated (e.g., when the sensor is in an alarm state). This in turn may require shutdown of the dispenser and associated support systems because of a lack of active area hydrogen detectors. Although system shutdown is a conservative action in response to the detection of hydrogen at the alarm level, it may be an overreaction. A depowered sensor would not be able to indicate whether the condition was either becoming more hazardous with increasing hydrogen levels, stable at a hydrogen concentration above the alarm threshold but below the LFL, or transitory such that all spurious hydrogen has dissipated.

Such uncertainty would mandate shutdown of the dispenser because the sensor indicates a potentially unsafe condition, which might be only a transitory event. Of course, system shutdown should occur whenever hydrogen continues to rise above at the medium action level (25% LFL).

In addition to electrical safety standards for Class I, Division 2 operation, there are performance-based standards (e.g., UL 2075 and CSA C22.2, No. 152). Some jurisdictions (e.g., the state of California) have already mandated that hydrogen safety sensors be listed as compliant to UL 2075, and at some point this may be more universally required.

The gas detector should have outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. Although not required, telemetric communication capability could be useful for convenient remote interrogation. Several factors contribute to the desired sensor response time. System leaks can quickly lead to situations of concern, so a reasonably fast response time is desirable. Alternatively, the sensor is likely to be mounted remotely from the source, so diffusion processes will dominate the sensor response. A facility sensor response time of 10–30 s seems adequate. It is possible, although highly unlikely, that a release jet may directly contact the sensor. Accordingly, the sensor should be immune to or recovery quickly from a brief exposure to a high hydrogen concentration. This is not, however, a critical requirement.

The sensor should not be affected by common interferants, including but not limited to CO and sulfur compounds. Because silicone compounds are used extensively as sealants, lubricants, and pneumatic elements, the sensor should also be resistant to poisoning by silicone, unless site operations can specifically ensure that such compounds will not be present. However, such guarantees are unlikely for most industries. If operated in or around refrigerated facilities, the sensor should also not show cross sensitivity to common refrigerants, including ammonia or chlorofluorocarbon compounds such as Freon. In fact, fuel cell-powered forklifts serve some refrigerated warehouses that store perishable items. Such facilities are an ideal market for these forklifts because they need emission-free vehicles around food products and, in contrast to batteries, fuel cells maintain their power at lower temperatures.

Most warehouses have some indoor climate control, but it may not be extensive. Thus, sensors ought to operate over broad temperature and humidity ranges. Working temperature ranges for the sensor should be consistent with the deployment facility, which can range from below -20°C for refrigerated facilities or unheated facilities in winter to +40°C for summer operation in a thermally unregulated facility. Of course, the selected sensor must be suitable to the prevailing condition and not necessarily for this temperature range. Although significant pressure fluctuations are not expected, sensors must be calibrated to prevailing pressure levels, because barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m elevation). Routine maintenance such as calibration should be once per year or sooner per manufacturer recommendations, but longer times between routine maintenance are highly desirable, as this significantly lowers operational costs. The target sensor cost, which would include all control elements and user interfaces, can be set at $500, but lower costs are of course desired.

Table 4 summarizes the sensor requirements and specifications for facilities with indoor fueling operations. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left-justified mark indicates a lower importance than a right or middle alignment.

Table 4. Hydrogen Sensor Metric Rankings for Indoor Fueling – Facility Monitoring

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO, dust, ammonia , chlorofluorocarbons
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		1 min
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts				T and RH are more relevant than P
- T			X	-20° to +40°C
- P		X		Must be calibrated for deployment altitude
- RH		X		5%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability	X			Unlikely to experience 100% H_2 (or very high H_2)
Deployment Parameters				
Capital Cost		X		<$500 for complete sensor system
Installation Cost		X		Part of capital cost
Physical Size	X			Size is not a significant issue for wall/ceiling mounting
Control Circuitry			X	Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)		X		Not required but useful in ventilation system or extractive
- Low (low risk)			X	10% of the LFL, to track intermediate or increasing levels
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes			X	NFPA 2. Class I, Division 2 operation
Deployment Placement			X	Guidance on placement is needed
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years, 10 years desired
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment, possible dust concern
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays		X		H_2 concentration readout could be useful
- Remote Monitoring		X		Remote interrogation is useful
Device Repeatability	X			Plug in replacement not required, but must be calibrated

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Warm-Up Time		X		<1 h for initial installation,15 min for all shutdowns
Alarm Interface			X	Must connect to control system
- Number of set points		X		One mandatory, two useful shutdowns
- Audible			X	Activate at lowest alarm set point
- Ventilation			X	Activate at 1st set point if feasible
- Shutdown	X			Activate at 2nd set point (25% of LFL)
- Remote			X	Option to external alarm, and remote transmitters
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

2.2.2.1 Critical Gaps and Deficiencies

The operational requirements for sensors are a major limiting factor for sensor utilization; overall costs are a dominant concern. Sensor costs encompass several elements, including the actual capital cost of the device, the expense associated with on-site installation, and the operational expenses (e.g., recurring in-the-field calibration and maintenance). Capital cost and site installation are typically one-time upfront expenses, so these costs do not impact as strongly as the ongoing operational costs. There is, of course, always a desire for lower capital costs and simplified installation requirements, providing the sensor reliability is not compromised. Operational activities, such as routine maintenance, calibrations (or validation of calibration), and sensor replacement are typically performed manually in the field, and are very expensive because trained personnel must do the work. A second concern pertains to actual deployment of the sensor.

There is little guidance for establishing optimal sensor location and distribution. Multiple sensors may be required for large facilities and some operations may have specific requirements for sensor networks in large facilities [17]. It is not clear if the monitoring requirements of a large facility, especially one with mobile hydrogen-powered forklifts, would be better served by an array of point sensors or wide area monitoring technologies [18]. Wide area monitors currently are primarily experimental systems. Technical questions remain about their performance, and logistical questions remain about their commercial maturity for real-world applications. Currently, a single point sensor with an alarm set point at 10% of the LFL is typically used around each indoor hydrogen dispenser. Sensors will be mounted on the wall or near the ceiling around the dispenser, so actual hydrogen detection will be remote from the hydrogen source. There is thus some uncertainty about the appropriate alarm levels because of potential impacts of dilution as the vapor migrates from the source; this is exasperated by sensor deployed in ventilation systems or extractive sensor designs with multiple sampling points (e.g., a sensor with active sample collection from a remote location or locations using internal sampling). Currently, alarm levels are typically set to 10% of the LFL (0.4 vol% hydrogen), although some jurisdictions may allow alarm thresholds at 25% of the LFL.

Another deployment consideration is the need for sensors that have been certified (or listed) for deployment in a potentially combustible atmosphere. Although a nonlisted sensor can be used to detect hydrogen, it would not be necessarily safe to operate as the hydrogen concentration approaches the LFL. In the event the sensor must shut down, it would be advisable to shut down the dispenser. Some sensors are compliant with Class I, Division 2 (e.g., sensors certified to UL

60079-15) operation, but no sensor is currently compliant to performance-based standards (e.g., UL 2075 or CSA C22.2).

Sensor deficiency areas and gaps inhibiting deployment can be summarized as follows. A major deficiency represents a current critical issue that has been problematic (e.g., occurring with an unacceptable frequency). A secondary issue is important but is either not critical or has not been reported as occurring.

- Major
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
        - Manual calibrations no oftener than once per year (less often than one year or no calibration requirement is preferable)
        - All other maintenance requirements oftener than once per year
        - Robustness against interferents, poisons, and dust
    - Acceptable target: <$500 per sensor
    - Deployment guidance
- Secondary
    - Capital cost for appropriate monitoring systems

2.2.2.2 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment is to simplify and economize the operational requirements. Currently, the sensor of choice for hydrogen monitoring around indoor dispensers has been the catalytic bead sensor (also called the CGS), although no specific technology has been explicitly endorsed by AHJs or facility engineers. Currently, manufacturers require periodic calibration to ensure sensor accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., stresses from vibration and thermal fluctuations), and electrical factors (e.g., power surges, shutdowns, and circuit failures).

Typically, calibrations are to be performed at least once per year, but could be more frequent based on local code requirements or manufacturer recommendations. Robust sensors with long operational lifetimes would reduce replacement cost, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most nonroutine maintenance requirements. However, because a broad range of factors can affect sensor performance, the sensor calibration requirement most likely will not be eliminated, especially because local regulations or codes often specifically require a minimal calibration cycle. Thus, an automated calibration system would significantly lower operational costs associated with wide-scale sensor deployment for area monitors. Acceptance of such a system would be facilitated if it were available at a reasonable cost (<$100 per sensor).

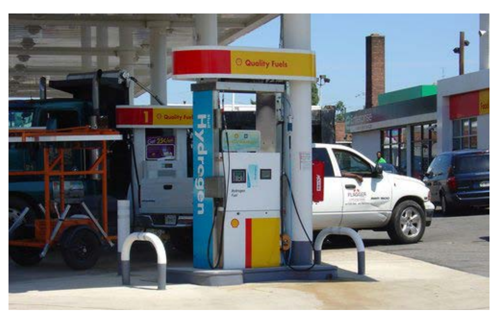
Sensor capital costs are likely to drop as demand increases with the emerging hydrogen infrastructure. However, certain platforms and designs will be better impacted with economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements including range (e.g., multiple alarm levels) and robustness requirements (insensitive to poisons, interferences, and drift). Commercial hydrogen sensor technologies are emerging for a number of thin-film and other microfabrication platform types. These show a fast response to hydrogen, but many tend to saturate at low concentrations and to exhibit a poor dynamic range. Their long-term stability and robustness to stresses (e.g., chemical, thermal, and moisture) should be more thoroughly studied.

Guidance about sensor deployment (e.g., ceiling, walls, or in ventilation systems) and their relationship to appropriate action levels is needed. Hydrogen may be released from a localized source (e.g., from the dispenser) or dispersed sources (forklifts). The sensor will likely be placed remote from the source, and the distance may vary depending on the specific source of the leak. Thus, the detected hydrogen gas concentration could be significantly attenuated. This is especially true for sensors deployed in ventilation systems, although sensors mounted on the wall adjacent to the dispenser are more common. Although mandated by code (e.g., NFPA 2), no specific guidance is provided about how to best position the sensor to detect a spurious hydrogen release. Nor is there rational guidance on the appropriate number of sensors to be installed in a facility.

Hydrogen can concentrate remotely from the dispenser via natural prevailing dispersion processes or from mobile source (e.g., from the forklift). It is thus necessary to established whether a single point sensor mounted on the wall adjacent to the dispenser would ensure that a hydrogen release is detected, and if multiple monitoring points are required, whether a distributed array of point sensors would be more advantageous and a better approach than wide area monitoring technologies. Cost, performance, and level of commercial maturity must be considered, and point source sensors are certainly more commercially mature than wide area monitoring technologies. Computational fluid dynamics (CFD) modeling of various release scenarios (for example, low and high release rates) and sensor deployment should be performed to provide such guidance about position and appropriate alarm levels. This guidance should ultimately be incorporated into or cited by NFPA 2.

2.2.3 Internal Dispenser Sensor Deployment (Contained Environment Monitor)

The hydrogen dispenser is the interface between the site hydrogen storage (typically outdoors) and the forklift. For facile fueling, forklift hydrogen fills are typically performed using indoor dispensers, although dispensers servicing the road vehicle fleet are typically outdoors. Once communication between the dispenser and the vehicle is established, the actual fill times are as fast as 2 min. The following discussion focuses primarily on sensors installed inside dispensers installed for indoor fueling, but it is also relevant for dispensers deployed for outdoor operations. Although flow regulators, shutoff valves, and bypass valves are incorporated into the dispenser safety system, hydrogen sensors, which are independent of operation, provide



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increased safety. Furthermore, sensors can also operate on backup power, and thus remain active even in the event of a power outage. Although not mandatory, hydrogen sensors are often installed within the dispenser, especially for systems that are used for indoor fueling.

Hydrogen concentrations can quickly build up within a contained environment. For example, less than 0.8 g of hydrogen uniformly distributed within a container having a free volume of 8 ft^3 would exceed the LFL. Without venting, this amount would be reached in less than 1 h with an average release rate of only 0.013 g/min (or approximately 2 cm^3/s), a rate sufficiently slow that it may not be detected by pressure sensors. There is typically a single alarm set point at 25% of the LFL for sensors installed within the dispenser. At 25% of the LFL the system shuts down and an audible alarm is activated. Although multiple alarm levels are not currently employed to internally monitor the dispenser, two alarm levels could be of interest:

- A low-level threshold at 10% of the LFL (0.4 vol% hydrogen) would activate the audible alarm and enhanced ventilation. Relays could be used to activate internal ventilation of the dispenser to facilitate the purge.

- A medium-level response at 25% of the LFL (1 vol% hydrogen) would shut down the dispenser and isolate the fuel delivery system via activation of shutoff valves.

Sensors listed as compliant to Class I, Division 2 operation (e.g., sensors certified to UL 60079-15) are required for deployment within dispensers and other contained environments. In addition to electrical safety standards for operation in potentially flammable environments, there are performance-based standards for gas sensors (UL 2075 and CSA C22.2, No. 152"). Some jurisdictions have already mandated that hydrogen safety sensors be listed as compliant to UL 2075, and at some point this may be more universally required. The sensor should have electronic outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. Although not required, telemetric communication capability could be useful. The sensor output may be interfaced to an internal communication system that is integral to the dispenser.

Many manufacturers monitor commercial dispensers remotely, but this may not always be the case. For now, internal control systems that allow the dispenser manufacturer remote access to system controls and sensors fulfill the telemetric communication requirement. System leaks within the dispenser can quickly lead to high hydrogen concentrations, and a fast response time (1 s) is desirable and recommended. Within a contained environment, especially one surrounding high-pressure hydrogen, there is an increased likelihood that a release jet would directly contact the sensor. The sensor should therefore be immune to or recover quickly from a brief exposure to high concentration of hydrogen. The sensor should not be affected by common interferences including but not limited to CO and sulfur compounds. Because silicone compounds are used extensively as sealants, lubricants and pneumatic elements, the sensor should also be resistant to poisoning by silicone. The dispenser, if installed inside warehouses or other buildings, will have some indoor climate control, but it may not be extensive. Thus, sensors ought to operate over broad temperature and humidity ranges.

Working temperature ranges for the sensor should be consistent with the deployment facility, which can range from 0° to +40°C operation in a facility with limited thermal regulation that includes some heating in winter but very limited air conditioning in summer. Lower temperatures may be encountered for dispensers in unheated (or refrigerated) environments. Of course, the selected sensor must be amenable to the prevailing condition and not for this whole range.

Although significant pressure fluctuations are unlikely, sensors must be calibrated to prevailing pressure levels, as barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m elevation). Routine maintenance, such as calibration, should be required once per year or sooner per manufacturer recommendations, but longer times between routine maintenance would significantly lower operational costs. The target sensor cost, which would include all control elements and user interfaces, can be set at $100, but lower costs are of course desired.

Table 5 summarizes the sensor requirements and specifications for in-dispenser sensor deployment. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment.

Table 5. Hydrogen Sensor Metric Rankings for Indoor Fueling – In-Dispenser Deployment

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time			X	1 s
Recovery Time		X		1 min
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts				T and RH are more relevant than P
- T			X	-10° to +40°C
- P		X		Must be calibrated for deployment altitude
- RH		X		5%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability			X	May be exposed to 100% H_2 (or very high H_2)
Deployment Parameters				
Capital Cost		X		<$100
Installation Cost		X		Part of capital cost
Physical Size			X	Must be physically compatible for in-dispenser deployment
Control Circuitry			X	Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)		X		Not required (trace background may be present)
- Low (low risk)			X	10% of the LFL, to track intermediate or increasing levels
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes			X	NFPA 2, Class I, Division 2 operation listing required
Deployment Placement		X		Guidance on placement is needed

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years, 10 YEARS desired
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Display not necessary
- Remote Monitoring		X		Remote interrogation is useful, output should be %H_2 units
Device Repeatability		X		Plug in replacement useful, but must be calibrated
Warm-Up Time		X		<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface			X	Must connect to control system
- Number of set points		X		One mandatory, two useful shutdowns
- Audible			X	Activate at lowest alarm set point
- Ventilation			X	Activate at 1st set point if feasible
- Shutdown	X			Activate at 2nd set point (25% of LFL)
- Remote			X	Option to external alarm, and remote transmitters
Mechanical Stability		X		Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

2.2.3.1 Critical Gaps and Deficiencies

The operational requirements are a major limiting factor for extensive sensor deployment. Acceptance is severely affected by cost of maintenance, especially calibration requirements. Capital costs for the sensors are also a factor impacting acceptance. This factor is typically a one-time upfront expense, so it does not impact as strongly as the ongoing operational costs. Nevertheless, there is always a need for lower cost systems, providing the sensor reliability is not compromised.

Sensor deficiency areas and gaps inhibiting deployment can be summarized as follows. A major deficiency represents a critical issue that has been problematic (e.g., occurring with an unacceptable frequency). A secondary issue is important but is either not critical or has not been reported as occurring.

- Major
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
        - Manual calibrations no oftener than once per year (less often than once per year or no calibration requirement is preferable)
        - All other maintenance requirements less often than once per year
        - Robustness against poisons and dust
        - Response time of 1 s

- Acceptable sensor target cost: <$100 per sensor)
    - Deployment guidance
- Secondary
    - Capital cost for appropriate monitoring systems

2.2.3.2 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment would be to simplify and economize the operational requirements. Robust sensors with long operational lifetimes would cut down replacement cost, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most nonroutine maintenance requirements, although sensor calibrations would still be required. Most manufacturers require periodic calibration to ensure sensor accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., thermal stresses and vibration), and electrical factors (e.g., power surges, shutdowns, and circuit failures). Underlying codes may specifically require a minimal calibration cycle. Usually calibrations are to be performed at least once per year, but could be more frequent based on either local requirements or manufacturer recommendations.

Because of the broad range of factors that can affect sensor performance, it is unlikely that the sensor calibration requirement will be totally eliminated. Thus, an automated calibration system would significantly lower operational costs associated with wide-scale sensor deployment for battery backup systems. Acceptance of such a system would be facilitated if it were available at a reasonable cost (<$100 per sensor per year, including initial capital cost). Currently, the sensor of choice for in-dispenser deployment has been the catalytic bead sensors (also called CGSs), but no specific technology has been explicitly endorsed. The CGS is a high-temperature sensor; a room temperature sensor may have safety advantages. Sensors listed to national standards will likely be required, especially to be compliant for Class I, Division 2 operation.

Sensor capital cost is likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted with economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements including range and robustness requirements (insensitive to poisons, interferences, and drift). Commercial hydrogen sensor technologies are emerging for a number of thin-film and other microfabrication platform types. Although these show a fast response to hydrogen, these devices tend to saturate at low concentrations and to exhibit a poor dynamic range. Their long-term stability and robustness to stresses (e.g., chemical, thermal, and moisture) should be more thoroughly studied.

Guidance about sensor deployment and the relationship to appropriate action levels is needed. The number of internal dispenser sensors will be kept to a minimum, mostly likely one. The sensor must be able to respond to internal leaks, and thus should be designed into the dispenser rather than treated as an add-on. The dispenser should also be designed so as to not trap hydrogen and to channel internal gas releases to the sensor.

2.3 Residential

- Application
  - Safety sensors installed in private dwellings
- Applicable standards
  - Listed sensors
    - UL 60079-15 or equivalent listing requirements for use in Class I, Division 2 hazardous locations
    - UL 2075 or CSA C22.2, No. 152 or equivalent listing for sensor performance
  - NFPA 2, Hydrogen Technologies Code
  - Local AHJs invoking modified fire code
  - Society of Automotive Engineers standards for hydrogen vehicles (e.g., J2579)

2.3.1 Background

The target release date for commercial hydrogen light-duty road vehicles is set for 2015. It is projected that by 2025 there will be more than 1 million FCVs in the United States [4]. Thus, although there is as yet no market for residential hydrogen sensors, it is likely to be quite large within a few years. Hydrogen vehicles will be parked on private property, including inside residential garages. The design of on-board hydrogen storage systems, per SAE J2579, dictates performance-based requirements to limit worst-case leakage so that the LFL will not be reached in a minimum sized garage space. Although flow regulators, shutoff valves, and bypass valves will be incorporated into the vehicle fuel system to minimize released hydrogen volumes, hydrogen sensors in areas around the vehicle will increase safety. Safety sensors on board the FCV may be considered to provide indoor monitoring capability, but these sensors are designed to ensure passenger safety. Specifically, on-board sensors will monitor for hydrogen within the passenger and trunk compartments, and thus would not respond to hydrogen releases external to the vehicle. Because of safety concerns, it is preferred that hydrogen releases vent external to the vehicle rather than internally where they can quickly concentrate to hazardous levels; less than 1 g of hydrogen uniformly distributed in 8 ft^3 would exceed the LFL.

Sensors on board FCVs may also not be operational when the vehicle is turned off. Thus, if the vehicle is parked in a garage, the external venting of hydrogen would then be contained within the garage, and would most likely be undetectable with on-board vehicle sensors. These releases can best be detected with a dedicated sensor mounted inside the garage. Furthermore, ongoing NFPA 2 code development may require that hydrogen sensors be placed in garages that house hydrogen vehicles, although this is not yet the case. Even if not mandated by code, some homeowners may decide to install hydrogen sensors. The residential application thus represents an emerging and potentially very large market for hydrogen detectors. In many ways the need for residential hydrogen detector deployment is analogous to home CO detectors. There is a potentially large sales volume, but this market demands low-cost, low-maintenance technology with high reliability. Garage deployments can be more challenging because there is less environmental control and more potential exposures to chemicals than those encountered in residential living spaces.

At a minimum, a single alarm level that activates at 10% of the LFL (or possibly 25% of the LFL), would be required for residential hydrogen safety sensors. Two sensor alarm levels could be of interest for larger residential garages such as apartment building parking structures. These would be a low-level response (e.g., 10% of the LFL, 0.4 vol% H_2) that would enhance ventilation and a medium-level response (e.g., 25% of the LFL, 1 vol% H_2) that would activate an audible alarm. The second alarm level might also interface to the vehicle to shut down the fuel delivery system and isolate the bulk hydrogen from the release point. However, such multilevel alarms with active feedback to both home and vehicle control systems may be too complicated and expensive for general consumer use and acceptance.

Comparisons between residential hydrogen detectors and home CO detectors can be made. Residential CO detectors are priced well below $100. Home CO detectors certified to UL 2034, Single and Multiple Station Carbon Monoxide Alarms have multilevel scenarios to activate an audible alarm or other indication. These scenarios require faster response times for higher concentrations of CO [19]. Specifically, home CO detectors will alarm at a low CO concentration (70 ppm_v) providing it has been present for longer than 1 h and must alarm within 4 h; a midlevel CO concentration (150 ppm_v) must activate the alarm within 15–50 min, whereas a higher concentration of CO (400 ppm_v), must activate the alarm between 4 and 15 min. This multilevel alarm threshold is based on the known toxicity properties associated with CO exposure. There is generally more tolerance to low concentrations of CO, thus allowing longer exposure times. Allowable exposure times become correspondingly shorter with higher concentrations, thereby shortening the instrument alarm activation time. Typically, however, only a single alarm type (e.g., audible) is incorporated into the detector, and it is not possible to ascertain which scenario triggered the alarm.

Alternatively, hydrogen exposure has no known adverse health effects, providing that it does not displace oxygen below 19.5 vol% [20]. This requires approximately 7 vol% hydrogen. Hydrogen becomes immediately hazardous when its concentration exceeds the LFL of 4 vol% in air, regardless of time at this concentration. Thus, hydrogen alarm levels should be set to an acceptable fraction of the LFL. At a minimum, a medium-level alarm threshold of 25% of the LFL (1 vol% H_2 in air) is recommended as soon as hydrogen is detected at this concentration. Depending on jurisdiction, the alarm set point could be 0.4 vol% (10% of the LFL). Trace level detection (e.g., 1000 ppm_v or less) is not likely to be necessary, nor would it be advisable, because residual hydrogen levels are likely from releases associated with standard fuel cell purge cycles that could occur during vehicle startup or idling.

The basic consumer hydrogen detector would primarily provide an alarm and would not require interfacing to the ventilation control system (although this could be an option) or communicate with the vehicle fuel shutoff system. The audible alarm must, however, be detectable external to the garage, including (when appropriate) within the attached house (either audibly or by some other indication, such as flashing lights). It will be necessary to train FCV owners and their families to respond appropriately in the event of a hydrogen sensor alarm, which could include:

- Avoid entering the garage until it has been demonstrated that it is safe to do so.
- Evacuate the house if it is attached to the garage.
- Contact emergency response personnel.

The sensor response time should be fairly fast, allowing alarms within 30 s. This should be adequate, as concentration buildup in a garage is likely to be slow – most releases will be slow and the migration of hydrogen to the sensor will be controlled by diffusion processes. Displays or other readout systems are optional, but if present, the output should be in engineering units (e.g., vol% H_2). Exposures to higher hydrogen concentrations (e.g., 10 vol% or greater) should not adversely affect the analytical capability of the sensor, but exposure to pure hydrogen is unlikely. The sensor should not be affected by common interferences, including CO and sulfur compounds. Because silicone compounds are used extensively in consumer products such as sealants and lubricants, the sensor should also be resistant to poisoning by silicone vapors. Residential garages will have at best minimal climate control, so sensors ought to operate over a temperature range of -40 to +40°C and a humidity range of 10%– 95% RH. Less restricted ranges, especially for temperature, are allowed based on regional considerations. Although significant pressure fluctuations are not expected, sensors must be calibrated to prevailing pressure levels because barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m). Other than routine power checks to ensure battery backup, there should be no user-required maintenance procedures, including calibrations. Five-year reliability is necessary for the consumer market. The target sensor cost should be less than $100, but lower costs are of course desired.

Table 6 summarizes the sensor requirements and specifications for facilities with indoor fueling operations. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment.

Table 6. Hydrogen Sensor Metric Rankings for Residential Applications

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity			X	Sulfur, silicone resistance, CO, household solvents and paints
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±50% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		1 min
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts				T and RH are more relevant than P
- T			X	-40° to +40°C to cover both northern and desert climates
- P		X		Must be calibrated for deployment altitude
- RH		X		5%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability	X			Unlikely to be exposed to 100% H_2 (or very high H_2)
Deployment Parameters				
Capital Cost			X	<$100
Installation Cost			X	Easily mounted (no special requirements or costs)
Physical Size		X		Size not a significant issue for wall/ceiling mounting

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Control Circuitry			X	Simple, must be part of integrated system for deployment
Electronic Interface		X		Output in engineering units (e.g., % H_2)
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity		X		Currently not available, but must be off-the-shelf by 2015
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)	X			Not required (trace background may be present)
- Low (low risk)	X			10% of the LFL, activate alarm (or 25%)
- High (pending risk)			X	25% of the LFL, activate alarm
Regulations and Codes			X	NFPA 2, possible performance specification
Deployment Placement			X	Guidance on placement is needed
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years, 10 years desired
Consumables		X		None
Calibration Schedule			X	No calibration during operational lifetime
Maintenance			X	Maintenance free
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% or 25% of LFL, depending on AHJ)
- Displays		X		Display not necessary
- Remote Monitoring	X			Not required
Device Repeatability	X			Will be replaced as unit
Warm-Up Time		X		<1 h for initial installation, 15 min for all shutdowns
Alarm Interface				To activate audible alarm, which is part of system
- Number of set points		X		One mandatory
- Audible			X	Activate at alarm set point
- Ventilation	X			Not required
- Shutdown	X			Not relevant
- Remote			X	Perhaps useful to warn against entry
Mechanical Stability	X			No special requirements for fixed deployment
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

2.3.2 Critical Gaps and Deficiencies

Acceptance in a consumer market will be severely affected by the original capital cost of the hydrogen sensor. Using the home CO monitor as a model system, residential hydrogen sensors must cost less than \$100, and preferably less than \$50. Other costs, such as those associated with maintenance, especially calibration requirements, have to be negligible. The sensor must operate reliably (e.g., no false positives or false negatives) for several years. A 5-year deployment lifetime is a good target.

Sensor deficiency areas and gaps inhibiting deployment can be summarized as follows. A major deficiency represents a current critical issue that has been problematic (e.g., occurring with an unacceptable frequency). A secondary issue is important but is either not critical or has not been reported as occurring.

- Major
    - Maintenance and calibration are major shortcomings
        - (Long-life sensors (>5 years)
    - No calibrations for the life of the sensor (5 years)
    - All other maintenance requirements (e.g., backup batteries) >1 year
    - Robustness against poisons and dust
    - Controlling the human response when confronted with a hydrogen sensor in alarm
    - Availability of appropriate technology for the application (Level of maturity) for <$100
    - Listing and certification requirements
- Secondary
    - Deployment guidance

2.3.3 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

Presently, hydrogen detectors are designed for residential applications. Industrial monitors are of course available, but these will not directly transfer to consumer applications because of cost and possible complex operational issues. One means to ensure availability of residential detectors is to support product development through grants or other incentives. Alternatively, as the private FCV fleet grows, so will the residential market. This will provide incentive to home safety system manufacturers (e.g., manufacturers of home CO and smoke detectors) to expand into this market. Market forces will tend to ultimately keep overall cost reasonable, but this must occur without corrupting performance. Economical product development will take time, however, and the cost of the first versions of the residential hydrogen detector should not be so high as to induce impediments to their deployment or to FCV acquisition. Thus, capital cost may initially impede deployment, but should ultimately become less significant. A second deployment concern pertains to guidance on the location of the hydrogen detector. Fortunately, preliminary research on this topic has been performed [21]. Hydrogen distribution in a normal garage is sufficiently fast and the deployment location has minimal impact on sensor response time, providing that the sensor was mounted above the potential hydrogen source. This work did not address thermal entrapment zones that are formed because of warmer temperatures near the ceiling than in the bulk, which preclude recommending deployment of sensors directly at the ceiling. Formalized guidance on sensor deployment, however, must be developed.

It is not unlikely that home hydrogen detectors will require listing to performance-based standards, such as UL 2075, providing they are compatible for the residential market. Such listings have been imposed on home CO detectors (e.g., UL 2034). Certification is an expensive process, and, without inducements, will be pursued by sensor manufacturers only after the development of a sizable market associated with commercial release of FCVs. The current standard needs to be reviewed, and edited if necessary for the residential market. Personnel in the NREL sensor test laboratory are on the UL 2075 Standards Technical Panel.

Sensor capital cost is likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted by economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential, and commercial devices are being developed based on thermal conductivity devices (TCDs), MOX, CGSs, palladium thin films, and other platforms. However, some platforms are highly susceptible to drift induced by moisture fluctuations. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements lifetime and robustness requirements (insensitive to poisons, interferences, and drift). Home CO alarms could form the basis of the residential hydrogen detector, albeit with modification of the sensor element to optimize for hydrogen measurements. Home CO detectors use primarily MOXs and electrochemical sensors (for higher end models). Both platforms can be used for hydrogen detection. Improvements in cross-sensitivity may be necessary; a means to compensate for temperature fluctuations must also be developed. Sensor lifetime will have to be increased to ensure a reliable 5-year deployment.

Finally, an FCV owner should receive training about hydrogen safety, which should include the importance of hydrogen detectors and what to do when they go into alarm.

2.4 Production

- Applications
  - Distributed production (localized low to medium scale hydrogen production)
  - Centralized production (large scale, with hydrogen transported to utilization site)
- Applicable standards
  - NFPA 2 Hydrogen Technologies Code
  - Local AHJs invoking modified fire code
  - Listing of sensor and sensor components
  - UL 60079-15 or equivalent listing requirements for use in Class I, Division 2 hazardous locations
  - UL 2075 or CSA C22.2, No. 152 or equivalent listing for sensor performance
  - FM Global Class Number 6310 and 6320
  - U.S. Department of Transportation (DOT) transport of flammable material

2.4.1 Background

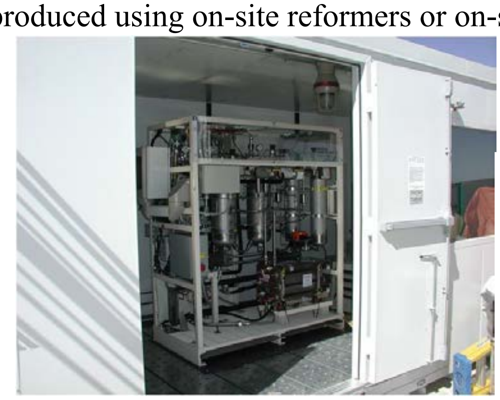
The hydrogen vehicle infrastructure requires several support systems and operations, including delivery or on-site production, on-site storage (typically outdoors), transfer hardware, and dispensing systems. In this section, issues pertaining to sensor requirements for hydrogen production are discussed. Two main methods of hydrogen production are reforming from methane (natural gas) and through water electrolysis; other experimental production methods (e.g., algae, biomass, and photoelectrolysis over specialized catalyst) are being explored. There are two broad categories of hydrogen production: centralized large-scale and distributed small- to medium-scale production. Centralized production facilities are well established and have been operating for many years to fulfill the traditional hydrogen markets, especially hydrogen for the petroleum industry. The distributed production would be for on-site use (e.g., fueling stations with on-site electrolyzes or reformers), and daily capacity at 5000 kg or less. Central production technology has been developed for established industries and may ultimately be the main supplier of hydrogen providing the transportation or transport infrastructure is established; this would require increased capacity for trucking and ultimately the establishment of a hydrogen pipeline network. Alternatively, distributed production with localized small- to medium-scale capacity is likely to play a significant role in the early phases of the developing hydrogen infrastructure. This role is necessary in part because of the needed support systems for centralized productions (e.g., pipelines, transport systems), which are less developed than the support systems required for distributed production (e.g., availability of water and/or natural gas, electricity). The two production types will be treated separately.

2.4.2 Distributed Hydrogen Production

Site reformers and electrolysis units are already commercially available and deployed in numerous industrial facilities and fueling stations. These systems produce hydrogen for stationary fuel cells deployed for backup power and for road vehicles and may, in the future, provide hydrogen for forklifts and other applications. Distributed (or localized) hydrogen production is typically performed within structures to protect expensive hardware from the weather. The hydrogen can be produced for on-demand use by a stationary fuel cell or stored on-site for future use. Two main sensor applications are associated with distributed hydrogen production: (1) facility monitoring for external releases (e.g., an area monitor); and (2) deployment within the production unit (e.g., a contained environment monitor). These applications are treated separately below.

2.4.2.1 Distributed Hydrogen Production – Facility Monitoring

Distributed (or localized) hydrogen is currently being produced using on-site reformers or on-site water electrolysis units. These operations are typically within structures to provide some protection of the hardware from the weather and proximal activity. Accordingly, the hazards and risks associated with indoor on-site production are analogous to other indoor operations (see Section 2.2.1). Although flow regulators, shutoff valves, and bypass valves are incorporated into hydrogen production, hydrogen sensors, which are independent of operation, provide increased safety.



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Hydrogen sensors can remain active in event of a power outage via battery backup systems. Sensors thus play a critical role in hydrogen production safety. Sensors are also mandated by code for indoor fueling (e.g., NFPA 2, Hydrogen Technologies Code, 2011 Edition). Local AHJs may impose locally modified fire codes and thereby regulate additional safety system designs for sensor deployment (e.g., nature of alarms, alarm levels, integration to facility ventilation systems). Accordingly, hydrogen sensors should be mounted proximal to the hydrogen production unit; the sensor can be mounted on the wall adjacent to the production unit or on or near the ceiling above the production unit. Most sensors deployed at distributed production sites are set to activate an audible alarm only. The alarm set point is typically 0.4 vol% hydrogen, which is 10% of the LFL. This is the most efficient and cost-effective use of sensors, but multiple alarm levels could be useful. For example, an audible alarm could be activated at 10% of the LFL, but at 25% of the LFL the system shuts down.

Sensors listed as compliant to national standards for instrument safety (e.g., Class I, Division 2 listings) are recommended for deployment around production facilities. Performance-based standards (UL 2075 and CSA C22.2, No. 152) would also be useful. Some jurisdictions have already mandated that hydrogen safety sensors be listed as compliant to UL 2075 for indoor operations, and at some point this may be more universally required. The gas detector should have electronic outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. Although not required, telemetric communication capability could be useful, especially to warn first responders and site engineers of a release before it becomes hazardous.

It may be useful and sometimes mandated by AHJs for the sensor to interface with ventilation systems. The ventilation system would be activated at the low alarm level for operations that have multiple alarm levels in the sensor. Therefore, relays would be useful to activate the alarm and to interface to the ventilation system. Several factors contribute to the desired sensor response time. System leaks can quickly lead to situations of concern, so a reasonably fast response time is desirable. Alternatively, however, because the sensor is likely to be mounted remotely from the source, diffusion processes will dominate its response. A response time of 30 s would seem adequate for a facility sensor. Herein, the response time can be defined as the time to reach 90% of the final indication that is achieved when the sensor is exposed to a steady flux of hydrogen at the designated alarm level (e.g., either 25% or 10% of the LFL if that is the alarm level). Although unlikely, the sensor may experience a direct hit of hydrogen by a leak jet. Accordingly, a brief exposure to pure hydrogen should not impact the analytical capability of the sensor.

The sensor should not be affected by common interferences, including but not limited to carbon monoxide and sulfur compounds. Reformer production units could also have methane, which will be an interferent on several sensor platform types (CGSs and MOXs, for example); on the other hand, the CGS could be used to monitor for both hydrogen and methane, although it would not be able to distinguish between these compounds. Water electrolysis units do not require methane or natural gas, although natural gas may be present for other purposes (e.g., facility heating). Because silicone compounds are used extensively as sealants, lubricants, and pneumatic elements, the sensor should also be resistant to silicone poisoning.

Structures housing production units will have some but not necessarily extensive indoor climate control, so deployed sensors ought to operate over broad temperature and humidity ranges. Working temperature ranges for the sensor should be consistent with the deployment facility, which can range from below -40°C for northern climates to +40°C for summer operation in a thermally unregulated facility. Of course, the selected sensor must be amenable to the prevailing condition and not for this whole temperature range. Although significant pressure fluctuations are not expected, sensors must be calibrated to prevailing pressure levels, as barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m elevation). Routine maintenance such as calibration should be once per year or sooner per manufacturer recommendations, but longer times between routine maintenance would significantly lower operational costs. The target sensor cost, which would include all control elements and user interfaces, can be set at $500, but lower costs are of course desired.

Table 7 summarizes the sensor requirements and specifications for facilities with indoor fueling operations. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment.

Table 7. Hydrogen Sensor Metric Rankings for Distributed Hydrogen Production – Facility (Area Monitors)

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity			X	Sulfur, silicone resistance, CO
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		60 s
Repeatability		X		Not critical
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts		X		T and RH are more relevant than P
- T			X	-40°C to +40°C
- P	X			ust be calibrated for deployment altitude
- RH		X		15%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability			X	Relevant for sensors mounted near tank
Deployment Parameters				
Capital Cost		X		<$500
Installation Cost		X		
Physical Size	X			Small size compatible with mounting around tank
Control Circuitry		X		Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)	X			Not required for on-board, trace background is possible
- Low (low risk)			X	10% of the LFL, indicate adverse for single alarm level
- High (pending risk)			X	25% of the LFL, shut down system for multiple alarm levels
Regulations and Codes			X	Possible local AHJs
Deployment Placement			X	Must avoid pockets
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		years
- Unit Replacement		X		5 years

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Readout is not necessary
- Remote Monitoring	X			Remote interrogation is not necessary
Device Repeatability		X		Plug in replacement is useful
Warm-Up Time		X		<1 h for initial installation,15 min for all shutdowns
Alarm Interface				
- Number of set points		X		One mandatory, two useful shutdowns
- Audible		X		Activate alarm at lowest set point
- Ventilation			X	Activate at 1st set point, if feasible
- Shutdown			X	Activate at 2nd set point (25% of LFL)
- Remote	X			Not necessary
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

2.4.2.1.1 Critical Gaps and Deficiencies

The operational requirements for sensors are a major limiting factor for extensive sensor deployment. Acceptance is severely affected by cost of maintenance, especially calibration requirements. Small drifts in the sensor background often lead to the need for on-site calibration. Capital costs for the sensors are also a factor impacting acceptance. This is typically a one-time upfront expense, so it does not impact as strongly as the ongoing operational costs. Nevertheless, there is always a need for lower cost systems, providing the sensor reliability is not compromised. A second operational concern pertains to actual deployment of the sensor. There is some ambiguity in defining optimal location of deployment and required distribution of the sensors; it is likely that multiple sensors will be required, depending on the size and complexity of the facilities. Although alarm levels were defined earlier in this section, actual detection will be remote from the hydrogen source. There is thus some uncertainty in the appropriate alarm levels because of potential impacts of dilution as the vapor migrates from the source. This is especially true for the mounting of sensors in ventilation systems in which gases are collected from multiple locations.

The major gaps inhibiting optimal sensor utilization in on-site hydrogen production facilities can be summarized as:

- Major
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
    - Manual calibrations no oftener than once per year (less often than once per year or no calibration requirement is preferable)
    - All other maintenance requirements less often than once per year

    - Robustness against poisons and dust
    - Unacceptable sensor drift (necessitating recalibration or system shutdowns)
- Secondary
    - Capital cost for appropriate monitoring systems
    - Acceptable target: <$500 per sensor

2.4.2.1.2 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment is to simplify and economize the operational requirements. Robust sensors with long operational lifetimes would cut down replacement cost, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most nonroutine maintenance requirements, although sensor calibrations would still be required. Many manufacturers require periodic calibration to ensure sensor accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., thermal stresses and vibration), and electrical factors (e.g., power surges, shutdowns, and circuit failures). Underlying codes may specifically require a minimal calibration cycle. Usually calibrations are to be performed at least once per year, but could be more frequent based on manufacturer recommendations. Because of the broad range of factors that can affect sensor performance, it is unlikely that the sensor calibration requirement will be eliminated. Thus, the development of automated calibration system would significantly lower operational costs associated with wide-scale sensor deployment for battery backup systems. Acceptance of such a system would be facilitated if it were available at a reasonable cost (<$100 per sensor).

Sensor capital costs are likely to decrease as demand increases as the hydrogen infrastructure develops. Currently, the sensor of choice for indoor monitoring has been the catalytic bead sensor, although no specific technology has been endorsed. However, certain platforms and designs will be better impacted with economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements including range (e.g., multiple alarm levels) and robustness requirements (insensitive to poisons, interferences, and drift). Commercial hydrogen sensor technologies based on thin-film and other microfabricated platforms are emerging. Although these devices show a fast response to hydrogen, they tend to saturate at low concentrations and to exhibit a poor dynamic range. Their long-term stability and robustness to stresses (e.g., chemical, thermal, and moisture) should be more thoroughly studied.

Guidance about sensor deployment (e.g., ceiling, walls, or in ventilation systems) and the relationship to appropriate action levels is needed. The sensor will likely be placed remote from the source, and the distance may vary depending on the specific source of the leak. Because the sensor will be remote, the detected hydrogen gas concentration could be significantly attenuated. This trend is especially true for sensors deployed in ventilation systems, although sensors mounted on the wall adjacent to the dispenser are more common. Although mandated by code (e.g., NFPA 2), no specific guidance on the means to best position the sensor to capture a hydrogen generation event is provided. Nor is there rational guidance on the appropriate number of sensors to be installed in a facility. For example, will a single point sensor mounted on the wall adjacent to the dispenser provide adequate assurance of detecting a hydrogen release? Hydrogen can concentrate remote from the dispenser via natural prevailing dispersion processes or from mobile source (e.g., from the forklift). Would a distributed array of point sensors be more advantageous and a better approach than wide area monitoring technologies? Cost, performance, and level of commercial maturity must be considered. CFD modeling of various generation rates (low and high) and sensor deployment should be performed to specifically provide such guidance on position and appropriate alarm levels [22]. This guidance should ultimately be incorporated into or cited by NFPA 2.

2.4.2.2 Distributed Hydrogen Production – In-Unit Sensor Deployment

Distributed (or localized) hydrogen production is currently being performed using on-site reformers or on-site water electrolysis units. In addition to area monitors, hydrogen safety sensors may be installed in the enclosure surrounding the production unit. A sensor within the enclosure represents a contained environmental application. A small hydrogen release could quickly lead to a dangerous situation. Although flow regulators, shutoff valves, and bypass valves are incorporated into the dispenser safety system, hydrogen sensors, which are independent of operation, increase safety. Furthermore, the sensor can also operate on backup power, and thus remain active even in the event of a power outage. Although not mandatory by national standards, local jurisdictions and customers have chosen to have hydrogen sensors installed in production units. To avoid buildup of dangerous gases, the enclosures are oftens purged with ambient air, although this is more common with reformers. If a sensor is deployed, it will typically monitor for hydrogen in this air purge. The internal environment differs between reformers and electrolysis units, so sensors are subjected to different stresses (environmental, chemical, and physical). Enclosures for both technologies will tend to be at elevated temperature and humidity levels than ambient. High humidity is especially true for electrolysis units. Because oxygen is an unused by-product coproduced with hydrogen, enclosures around electrolysis units may also have an enriched oxygen atmosphere relative to ambient. Reformers may have CO, carbon dioxide, and the feed gas within the enclosure.

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Sensors listed as compliant to national standards (e.g., Class I, Division 2 listings) are required for deployment within production units and other contained environments. In addition to electrical safety standards for Class I, Division 2 operation, there are sensor performance-based standards (UL 2075 and CSA C22.2, No. 152). Some jurisdictions have already mandated that hydrogen safety sensors be listed as compliant to UL 2075 for indoor operations, and at some point this may be more universally required. The sensor should have electronic outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. Many end users require telemetric communication capability (or interface to a control system that can be accessed remotely).

Many manufacturers monitor their commercial production units (especially those providing hydrogen to stationary fuel cells). Internal control systems that allow the manufacturer remote access to system controls and sensors fulfill the telemetric communication requirement, but this may not always be the case. System leaks in the production unit can quickly lead to high hydrogen concentrations, and a fast response time is desirable. Accordingly, a response time of 1 s is recommended. In a contained environment there is an increased likelihood that a release jet would directly contact the sensor. The sensor should therefore be immune to or recover quickly from a brief exposure to a high concentration of hydrogen.

The sensor should not be affected by common interferences including but not limited to CO and sulfur compounds (this requirement is less critical for electrolysis units). Carbon dioxide levels will be elevated in reformer units; in electrolysis units, the oxygen level will be elevated. Thus, depending on deployment, the sensors should be immune to higher levels of these two gases. Because silicone compounds are used extensively as sealants, lubricants, and pneumatic elements, the sensor should also be resistant to poisoning by silicone. Working temperature ranges for the sensor should be consistent with the production unit environment, which can range up to +60°C or hotter. Although significant pressure fluctuations are unlikely, sensors must be calibrated to prevailing pressure levels, as barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2000 m elevation). Routine maintenance, such as calibration, should be no more frequent than once per year. Longer times between routine maintenance would significantly lower operational costs. Calibration, as with other service activities on the production units, is performed by trained personnel. To minimize costs, nonroutine maintenance activity must be eliminated.

A reformer developer reported that sensors currently deployed in reformers tend to show unacceptable drift and thus require significantly more frequent calibration than that specified by the manufacturer. This often results in unscheduled sensor maintenance. One reformer developer has set the maximum allowable baseline drift between calibration cycles to a signal corresponding to <10% of the lower alarm level (that is, the drift in the sensor output should correspond to <0.25 vol% hydrogen). Because baseline drift cannot be differentiated from a response due to hydrogen, physical inspection and on-site calibration have been required once a minimal drift threshold has been detected. Often such drifts are due to a change in the sensor baseline as opposed to actual hydrogen, and thus can be classified as false positives. Accordingly, deployed sensors are being perceived as not reliably meeting an acceptable stability requirement, so there has been significant resistance to their use in production units. The occurrence of false positives leads to a loss of confidence in sensor technology. The target sensor cost, which would include all control elements and user interfaces, can be set at $500, but lower costs are of course desired.

Table 8 summarizes the sensor requirements and specifications for in-dispenser sensor deployment. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment.

Table 8. Hydrogen Sensor Metric Rankings for Distributed Hydrogen Production – In-Production Unit

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO
LDL		X		0.04 vol% (1% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time			X	1 s
Recovery Time		X		1 min
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts				T and RH are more relevant than P
- T			X	-10° to +40°C
- P		X		Must be calibrated for deployment altitude
- RH		X		5%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability			X	May be exposed to 100% H_2 (or very high H_2)
Deployment Parameters				
Capital Cost		X		<$500 (complete sensor system); <$100 if part of controls
Installation Cost		X		Part of capital cost
Physical Size			X	Must be physically compatible for in-dispenser deployment
Control Circuitry			X	Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)		X		Not required (trace background may be present)
- Low (low risk)			X	10% of the LFL, to track intermediate or increasing levels
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes			X	NFPA 2. Class I, Division 2 operation listing required
Deployment Placement		X		Guidance on placement is needed
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years, 10 years desired
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Display not necessary
- Remote Monitoring		X		Remote interrogation is useful, output should be vol% H_2 units

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Device Repeatability		X		Plug in replacement useful, but must be calibrated
Warm-Up Time		X		<1 h for initial installation,15 min for all shutdowns
Alarm Interface			X	Must connect to control system
- Number of set points		X		One mandatory, two useful shutdowns
- Audible			X	Activate at lowest alarm set point
- Ventilation			X	Activate at 1st set point if feasible
- Shutdown	X			Activate at 2nd set point (25% of LFL)
- Remote			X	Option to external alarm, and remote transmitters
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

2.4.2.2.1 Critical Gaps and Deficiencies

The operational requirements and capital cost are major limiting factors for extensive sensor deployment. Acceptance is severely affected by cost of maintenance, especially calibration requirements. Capital cost is typically a one-time upfront expense, so it does not impact as strongly as the ongoing operational costs. Nevertheless, there is always a need for lower cost systems, providing reliability is not compromised.

Sensor deficiency areas and gaps inhibiting deployment can be summarized as follows. A majo" deficiency represents a current critical issue that has been problematic (e.g., occurring with an unacceptable frequency). A secondary issue is important but is either not critical or has not been reported as occurring.

- Major
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
    - Manual calibrations no oftener than once per year (less often than once per year or no calibration requirement is preferable)
    - All other maintenance requirements less often than once per year
    - Robustness against poisons and dust
    - Drift
    - Acceptable target: <$100 per sensor.
- Secondary
    - Capital cost for appropriate monitoring systems

2.4.2.2.2 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment is to simplify and economize the operational requirements. Robust sensors with long operational lifetimes would reduce replacement cost, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most nonroutine maintenance requirements, although sensor calibrations would still be required. Many manufacturers require periodic calibration to ensure accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., thermal stresses and vibration), and electrical factors (e.g., power surges, shutdowns, and circuit failures). Underlying codes may specifically require a minimal calibration cycle. Usually calibrations are to be performed at least once per year, but could be more frequent based on manufacturer recommendations.

Because of the broad range of factors that can affect sensor performance, it is unlikely that the sensor calibration requirement will be eliminated. Thus, automated calibration systems would significantly lower operational costs associated with wide-scale sensor deployment for battery backup systems. Acceptance of such a system would be facilitated if it were available at a reasonable cost (<$100 per sensor). Currently, the sensor of choice for in-dispenser deployment has been the catalytic bead sensors (also called CGSs), but no specific technology has been explicitly endorsed. This is a high-temperature sensor; a room temperature sensor may have safety advantages. It is likely that sensors listed to national standards, both for electrical safety (e.g., Class I, Division 2) and performance will be required.

Sensor capital cost is likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted by economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential, and commercial devices are being developed based on TCDs, MOXs, CGSs, palladium thin films, and other platforms. However, some platforms are highly susceptible to drift induced by moisture fluctuations. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements lifetime and robustness requirements (insensitive to poisons, interferences, and drift). In addition, their long-term stability and robustness to stresses (e.g., chemical, thermal, and moisture) should be more thoroughly studied, especially for the production unit environment, which is significantly harsher (higher T, RH, and enriched levels of potential interferents) than typical ambient environments.

Guidance about sensor deployment and the relationship to appropriate action levels is needed. The number of internal dispenser sensors will be kept to a minimum, mostly likely one. The sensor must be able to respond to internal leaks, and thus should be designed into the dispenser rather than treated as an add-on. The dispenser should also be designed so as to not trap hydrogen and to channel internal gas releases to the sensor.

2.4.3 Centralized Hydrogen Production

Centralized (or localized) hydrogen production is typically being performed using on-site reformers, and is noted for high throughput production (>1,000 kg/day capacity, typically larger). Centralized production is an established process serving the petroleum and other markets. As such, centralized production has its own safety design requirements. Sensors have been included in these operations for many years. Appropriate safety systems have been developed by private industry; the centralized production of hydrogen has an excellent safety record. It is beyond the scope of this document to induce changes in established safety programs with excellent safety records. No further discussions about hydrogen safety sensors for centralized production are warranted at this time.

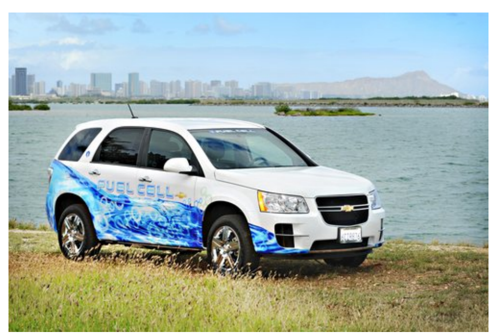
Centralized production does have other concerns as it is applied to the emergence of the hydrogen infrastructure. Namely, transport of hydrogen from production site to the filling stations (or other end users) needs development. Trucks can be used to transport pressurized or liquefied hydrogen, or it can be moved via a pipeline network. Trucking (road or rail) is ongoing and meets current needs. Ultimately, a hydrogen pipeline network will be implemented, much as the natural gas pipeline system. DOT oversees domestic regulations for trucking and piping of gaseous compounds. Sensors could be deployed for both categories of transport. However, the trucking application is currently well served, and the pipeline application is nearly nonexistent. This topic was not covered in the DOE/NREL workshop, and thus would best be addressed in the NREL-Fuel Cell and Hydrogen Energy Association sensor user group.

2.5 On-Board Light-Duty Road Vehicles

- Application
    - (Primary) hydrogen sensors to measure hydrogen in compartments (trunk, passenger, engine)
    - (Secondary) exhaust and internal controls
- Applicable standards
    - Automotive Safety Integrity Levels (ASIL) Safety requirements are set in International Organization for Standardization (ISO) Standards
    - ISO 26262 for automotive
    - IEC 61508 for demonstration of safety level integrity
    - DOT regulations for hydrogen vehicles

2.5.1 Background

The target release date for commercial hydrogen fuel cell-powered light-duty road vehicles (automobiles) is set for 2015. This would be the first large-scale commercial introduction of hydrogen fuel technology for consumer applications. The automotive fuel cell market is emerging in Asia, Europe, and North America. Compliance to international standards (or international harmonization of national standards) is highly desirable, as product profitability will be predicated on market size, especially in the initial years of release. An international market would be considerably larger than the expected U.S. domestic market. Thus, although there is as yet no consumer market, it is likely to be quite large within a few years.



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The hydrogen sensor may be viewed as a safety-critical item for first production vehicles, so it must be reliable. Numerous strategies, including redundancymay be used to ensure reliability. Although flow regulators, shutoff valves, and bypass valves will be incorporated into the vehicle fuel system to minimize the risks associated with hydrogen releases, hydrogen sensors around and inside the vehicle will increase safety. Hydrogen sensors may also have relevance as part of a process control system (fuel cell operation) and emission monitors. Safety sensors are, however, the most critical application for on-board sensor deployment, and will be focus of this discussion. To ensure safety, and to facilitate consumer acceptance, hydrogen safety sensors are being deployed on board hydrogen FCVs. The primary application will be to verify the absence of hazardous levels of hydrogen in the enclosed compartments, which include the passenger compartment, the trunk area (or the area proximal to the on-board storage tanks), and the front (engine) compartment. Sensors will likely be deployed in each identified compartment of the first generation of commercial hydrogen-powered road vehicles.

Unlike stationary applications, a range of deployment environments is likely for mobile applications. The sensor must thus accommodate extreme cold weather conditions associated with northern climates, dry, hot areas associated with the Southwest, and hot humid climates of the Southeast. Although passenger compartments may have regulated temperatures and humidity, such controls do not operate in other compartments, nor would such controls operate when the vehicle is off. In-vehicle temperatures will range from very low (-40°C) to extremely high (+40°C or higher) temperatures. The internal temperature of a car parked in the exposed sun is likely to exceed +40°C, especially in the southwestern United States.

Humidity fluctuations will be at least as great as those of ambient conditions and thus will likely range from dry to near condensing. Sensors deployed near or in line with exhaust vents will be subjected to high humidity levels, because water is produced by the fuel cell. Barometric pressure changes will also be encountered with variations in altitude. Although alarm levels (e.g., the LFL) are reported as the fraction of the total gas composition (a relative gas concentration), many sensor technologies are sensitive to the partial pressure of the target analyte (an absolute concentration).

Typically sensors are assumed to operate at 1 bar pressure, and the conversion from fractional units (e.g., 4 vol%) to absolute units (e.g., partial pressure of 0.04 bar for 4 vol% hydrogen at an ambient pressure of 1 bar) is straightforward. It is also typical to calibrate sensors at 1 bar. However, operation at a pressure of 0.8 bar, 4 vol% hydrogen would have a partial pressure of 0.032 bar, which could lead to an attenuated sensor response. Barometric changes of 0.3 bar would be encountered when driving from sea level (1 bar) to 10,000 feet (0.7 bar), the altitude of Leadville, Colorado. In the United States, it is also possible to drive on public highways at altitudes higher than 14,000 feet (0.6 bar). Thus, pressure fluctuations may be encountered, and in absence of compensation, these *may* impact sensor accuracy and performance.

Hydrogen sensors deployed on board light-duty road vehicles will need to monitor for and quickly respond to hydrogen leaks. A response time of less than 30 s would be adequate. The range of the sensor should be at least up to the LFL of hydrogen of 4 vol%, and the sensor should be able to distinguish to 25% accuracy the hydrogen concentration throughout this range. The ability to exceed the range (to 10 vol% hydrogen) would be useful. The sensor should output an audible alarm in the event of a hazardous condition. A single alarm threshold of 1 vol% hydrogen (25% of the LFL) would be adequate.

Although a direct hit by a hydrogen jet is unlikely, it is a possibility, so exposure to a high hydrogen concentration should not adversely affect the analytical capability of the sensor; its output may saturate during exposure to high hydrogen levels, but it should recover quickly (<1 min) to produce analytically accurate signals once the hydrogen concentration comes back into range. Nor should the sensor be affected by common chemical interferences, including CO and sulfur compounds. Because of silicone compounds are used extensively as sealants, lubricants, and pneumatic elements, the sensor should also be resistant to poisoning by silicone. The sensor will interface to the vehicle‘s on-board computer system, and may be used to implement a shutdown procedure in the event of a detected hydrogen release. On-board applications also have some restrictions on thesensor‘s size. Analogous to other automotive chemical sensors (e.g., the oxygen sensor), routine maintenance such as calibration should not be required for the expected life of the sensor, which should be at least 5 years. The target sensor cost can be set at $25 and would include required control circuitry and output interfaces. Lower costs are of course desired.

Table 9 summarizes the sensor requirements and specifications for on-board vehicle deployment. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment. For safety applications, ASIL requirements will guide the sensor deployment. For a lower rating (Level A), ASIL requirements can be met with redundancy or other means to ensure operability, but for the higher rating (B), an extremely small failure/hour must be demonstrated via a thorough engineering design review and risk analysis of the whole sensor system. On-board compartment monitors must meet ASIL Level A requirements.

Table 9. Hydrogen Sensor Metric Rankings for Automotive Fuel Cells – On-Board Safety Sensors

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO
LDL		X		0.1 vol%, which is 10% of proposed alarm set point)
Analytical Resolution		X		Differentiation is not important other than alarm set points
Linear Range/Dynamic		X		0 to 4 vol% H_2, may be extended to 10% hydrogen
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time			X	30 s
Recovery Time		X		60 s
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives for >5 years
Environmental Impacts				T and RH are more relevant than P
- T			X	-40 to +40°C
- P			X	0.6 to 1.1 bar (to account for altitude changes during drive)
- RH			X	5%–95% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability		X		Relevant for sensors mounted near tank
Deployment Parameters				
Capital Cost			X	<$25, including control circuitry
Installation Cost			X	Must be compatible with automotive requirements
Physical Size		X		Small size compatible with mounting in vehicle cabins
Control Circuitry			X	Compatible with commercial control systems
Electronic Interface			X	Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections		X		Passive (no power) sampling system
Shelf Life			X	>5 years

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Commercial Maturity			X	Must be off-the-shelf; does not exist at desired cost
Alarm Thresholds		X		
- Trace (1,000 ppm_v)	X			NA
- Low (low risk)			X	10% of the LFL, indicate adverse for single alarm level
- High (pending risk)				25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes		X		ASIL, SAE
Deployment Placement			X	Desire for one sensor to meet all in-vehicle requirements
Operational Parameters				
Lifetime			X	5 year minimum, 10 year desired
- Sensing Element			X	5 years
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	No routine calibrations
Maintenance			X	No routine maintenance
Sample Size		X		No critical restriction
Matrix Requirements		X		Normal air environment
Signal Management		X		
- Alarm (audible, lights)		X		Alarm set at 10% of LFL
- Displays	X			Readout is not necessary
- Remote monitoring	X			Remote interrogation is not necessary
Device Repeatability			X	Plug in replacement is useful
Warm-Up Time			X	<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface				
- Number of set points		X		One mandatory
- Audible			X	Activate alarm at lowest set point
- Ventilation	X			Not necessary
- Shutdown	X			Not necessary
- Remote	X			Not necessary
Mechanical Stability		X		Vibration tests, specification TBD
Power Requirements			X	Moderate power requirements preferred (<0.01 W)

2.5.2 Critical Gaps and Deficiencies

The on-board sensor has several critical analytical requirements. Sensor technology must operate over wide temperature and humidity ranges. The vehicle will also likely be subjected to variations in barometric pressure. A deployed sensor must be immune to changes in environmental parameters, but it must meet these analytical requirements without faulting on the necessary operational and deployment requirements. The operational requirements of a 5-year, maintenance-free deployment for sensors are major limiting factors for on-board sensors. False alarms caused by the physical operating environment (interferents, dusts) will be a concern. Deployment requirements remain an issue. Multiple sensors may be initially required, but the goal is to minimize the number of sensors to a single unit. This will be achieved, in part, through engineering enhancements and risk analysis as historical deployment data are accumulated. Capital costs of the sensors are also a concern; a target price of $25 (or less) for sensor and electronics can be achieved only through economy-of-scale manufacturing. Sensor reliability cannot be compromised. Another possible deployment consideration is the need for sensors that are safe for deployment in an atmosphere that may contain hazardous levels of hydrogen.

Although a nonlisted sensor can be used to detect hydrogen, it would not necessarily be safe to operate as the hydrogen concentration approaches the LFL.

- Major
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
    - No calibrations for the life of the sensor (5 years)
    - All other maintenance requirements less often than once per year
    - Robustness against poisons and dust
    - Acceptable target: <$25 per sensor)
    - Availability of appropriate technology for the application (level of maturity)
- Secondary
    - Capital cost for appropriate monitoring systems
    - Deployment (multiple sensors to meet current requirements)

2.5.3 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

Hydrogen detectors designed for automotive applications are available, but have not yet been totally demonstrated in all environmental regimes. Currently, the sensor of choice for on-board applications has been the TCD sensor, and to a lesser extent the MOX sensor, although no specific technology has been endorsed. However, many models of these platform types are susceptible to drift induced by moisture fluctuations and, to a lesser extent, by temperature. Smart sensor systems are under development. These show promise to compensate for temperature and humidity fluctuations. This development should be supported, and may need to expand to include robustness to pressure variations. As the FCV fleet grows, so will the market. This will provide an incentive to manufacturers to expand into this market and increase production capabilities. Market forces will tend to keep overall costs reasonable, but this must occur without corrupting performance. Sensor capital cost is likely to decrease with demand as the hydrogen vehicle market develops. However, certain platforms and designs will be better impacted by economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements lifetime and robustness requirements (insensitive to poisons, interferences, and drift).

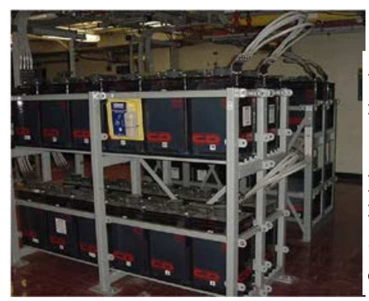
2.6 Battery Backup

- Application
    - (Primary) Hydrogen sensors for use in CEVs with battery backup
    - (Secondary) Supplemental safety system for battery backup systems deployed in multiple use buildings
- Applicable Standards

- Institute of Electrical and Electronics Engineers/American Society of Heating, Refrigerating and Air-Conditioning Engineers (IEEE/ASHRAE) Draft Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications
- OSHA 1910.146 *Permit Required Confined Spaces-General Environmental Controls*
- Local AHJs invoking modified fire code (NFPA, International Fire Code)
- Listing of sensor and sensor components
  - UL 60079-15 or equivalent listing requirements for use in Class I, Division 2 hazardous locations
  - UL 2075 or CSA C22.2, No. 152 or equivalent listing for sensor performance
  - FM Global Class Number 6310 and 6320

2.6.1 Background

Battery backup systems are deployed to ensure continuity of power during electrical outages. Many large- and small-scale industries and operations, from leaders in the telecommunications industry to startups, rely on battery backup. Accordingly, various levels of safety designs are necessary, although these should be based on IEEE/ASHRAE *Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications* and local AHJ requirements. Backup applications primarily use lead acid batteries, which can generate hydrogen as a by-product. Power backup systems can be quite large, encompassing several thousand battery units. Backup systems are routinely deployed, often in multiuse buildings. In addition, distributed, unmanned CEVs equipped with battery backup systems are extensively deployed in the telecommunications industry. Backup power systems in CEVs and multiuse buildings represent two distinct applications for hydrogen safety and hydrogen sensor requirements.


CenturyLink Image, Used with permission

The IEEE/ASHRAE *Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications* does not require hydrogen sensors for battery backup systems installed in buildings. Accordingly, sensors are not extensively deployed. Maintenance costs, especially those associated with calibrations, are a main reason the industry does not mandate their use. However, sensors are an optional supplement to the safety system, and AHJs may impose locally modified fire codes to mandate hydrogen sensors around battery backups. Nevertheless, the primary code does not mandate use of hydrogen sensors because the normal charging process does not produce significant levels of hydrogen. Only when the system is overcharged do relatively high and potentially dangerous levels of hydrogen occur. Hydrogen generation can be prevented by intelligent charging systems.

Further safeguards may include monitoring the integrity of select cells in a bank of batteries. A high or low cell voltage during charging may indicate a failed cell (e.g., partially shorted) in a bank of cells. Engineering controls such as active ventilation minimize the probability of hydrogen gas buildup. Typically six equivalent air changes per hour meet human occupancy needs. These are much more than the minimum air changes per hour in most instances to prevent excessive hydrogen buildup) and are implemented to preclude mandatory sensor deployment. There have been, however, situations where supplemental measures were overridden (e.g., the ventilation system was turned off as a cost-saving measure) that led to deleterious hydrogen events.

Hydrogen sensors could supplement safety designs for battery backup systems deployed in buildings. Guidance about deployment (e.g., where the sensor should be placed) would facilitate this. For example, guidelines about placement (e.g., on or near the ceiling versus in the air intake of the ventilation system) is needed. The corresponding alarm levels associated with the deployment design needs to be considered. For example, a lower alarm level may be advisable for sensor deployment in a ventilation system because of hydrogen dilution by air flow.

The telecommunications industry also has a network of battery backup systems deployed in distributed CEVs. CEVs are semisealed, mostly subsurface enclosures, and are considered confined spaces. Thus, they are regulated by OSHA 1910.146, Permit-Required Confined Space, which requires verifiable assurance that oxygen and combustible gases are at safe levels prior to human entry. Protocols to ensure appropriate oxygen levels and the absence of combustible gases may include one or more of the following: (1) active ventilation; (2) use of chemical detectors just prior to entry; and (3) continuous monitoring using deployed sensors. The telecommunications industry often continuously monitors the internal CEV atmosphere. CEVs may be partially below ground level. For CEVs, with battery backup systems, both methane and hydrogen are combustible gases of concern. A single sensor for methane and hydrogen is desired, which indicates that CGSs – and possibly TCDs or MOXs – are the technologies of choice.

As with all chemical sensors, periodic calibration is required (at least once per year, perhaps more frequently as dictated by local codes and sensor specifications); the mandatory calibration is a major expense associated with sensor deployment. The design and operation of CEVs define other requirements for hydrogen sensors. CEVs in the telecommunications industry may have thermal regulation, but typically minimal humidity control, so although major temperature changes are unlikely, the sensor should not be impacted by humidity fluctuations. Although significant pressure fluctuations are not expected, sensors must be calibrated to prevailing pressure levels, as barometric pressure depends on the installed elevation (from approximately 1 bar at sea level to 0.8 bar at 2,000 m). The CEV environment (temperature, ventilation, signal management, etc.) is managed by commercial control systems, such as but not limited to designs by Quest Controls, Sierra Monitor, or Honeywell. These systems have an estimated target cost of $2500. The hydrogen sensor is only one component of the overall system. Thus, target sensor costs can be set at $100, which would include control interface circuitry.

Because hydrogen buildup will occur only via side reactions with battery backup systems, which would be a slow process, fast response and recovery times are not essential. For most CEVs, a single point source hydrogen sensor is adequate because normal thermal equilibration processes will ensure near uniform distribution of hydrogen at or near the ceiling at a rate faster than any expected generation rate, and CEVs are relatively small structures. The main requirement of a sensor would be to alert personnel to a buildup of hydrogen toward the LFL. Typically two levels of response are of interest. Both response levels are well below any hydrogen concentration that poses danger, and may be defined as a low-level response (e.g., 10% of the

LFL) to activate enhanced ventilation and a medium-level response (e.g., 25% of the LFL) that would warrant manual inspection.

The telecommunications industry guarantees service, and thus strongly avoids unnecessary shutdowns, even at the medium level (manual inspection of the CEV will be promptly performed). Thus, the automated deactivation or shutdown of the CEV operation based solely on the readout of a hydrogen sensor is not desired. Of course, a disconnect of a CEV battery backup system remains an option if multiple safety systems indicate a potentially dangerous situation (e.g., a high differential between ambient CEV aisle temperature and battery post temperature could indicate thermal runaway of the batteries). Low-level detection (<1000 ppm_v or 0.1 vol%) is not required. The gas detector should have electronic outputs that are in engineering units (e.g., vol% H_2) or easily converted to engineering units. However, direct telemetric communication of the output is not a required sensor instrument option, as this is a core capability of the telecommunications industry. Although remote monitoring of the control system is routine in the telecommunications industry, other industries utilizing battery backup systems may not have extensive telecommunications expertise. Thus, remote monitoring capability might be a useful option.

Walk-in cabinets (sometimes known as utility enclosures or UEs in the telecommunications industry) are a cross between a CEV and an aboveground hut. These UEs are approximately half-buried. They are thus not considered confined spaces; however, they are commonly equipped with similar environmental control systems to CEVs, including combustible gas monitoring.

2.6.2 Critical Gaps and Deficiencies

The operational requirements and capital costs for sensors are major limiting factors for extensive deployment. Acceptance is severely affected by cost of maintenance, especially calibration requirements. Capital cost is typically a one-time upfront expense, so it does not impact as strongly as the ongoing operational costs. Nevertheless, there is always a need for lower cost systems, providing reliability is not compromised. A second operational concern pertains to actual deployment. There is some ambiguity in defining optimal deployment location and corresponding alarm levels.

Tables 10 and 11 summarize the sensor requirements and specifications for sensors around battery backup systems deployed in buildings and in CEVs, respectively. A relative ranking of each identified performance metric is presented and assigned a qualitative ranking of low, medium, or high importance, as indicated by the marker in the appropriate column. The position of the marker refines the assessment; a left justified mark indicates a lower importance than a right or middle alignment.

Table 10. Hydrogen Sensor Metric Rankings for Battery Backup Applications – Building Deployment

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO
LDL		X		0.4 vol% (10% of the LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	0.1–4 vol% H_2

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		60 s
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives for >5 years
Environmental Impacts				
- T	X			15°C to 30°C for indoor building applications
- P		X		Must be calibrated for deployment altitude
- RH	X			5 to 65% RH
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability	X			Highly unlikely to experience 100% H_2 (or high H_2)
Deployment Parameters				
Capital Cost		X		<$1,000
Installation Cost		X		<$1,000, should not be excessive
Physical Size			X	Moderate size restriction if deployed in ventilation system
Control Circuitry		X		Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds				
- Trace (1,000 ppm_v)		X		Possible for operation in ventilation system (dilution effects)
- Low (low risk)			X	0.4 vol% H_2 (10% of the LFL) to track intermediate levels
- High (pending risk)			X	25% of the LFL, audible alarm
Regulations and Codes		X		Local AHJs, possible update on IEEE/ASHRAE
Deployment Placement			X	Improved guidance needed
Operational Parameters				
Lifetime				5 year minimum, 10 year desired
- Sensing Element		X		5 years, 10 years desired
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	>once per year, lower calibration requirements the better
Maintenance			X	No routine maintenance other than calibrations
Sample Size	X			No critical restriction
Matrix Requirements	X			Normal air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Readout is useful
- Remote monitoring	X			Remote interrogation may be useful
Device Repeatability		X		Plug in replacement not required if recalibrated
Warm-Up Time		X		<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface			X	Must connect to control system
- Number of set points		X		1: 10% LFL to activate ventilation; 2: 25% LFL alarm
- Audible			X	Activate alarm at lowest set point (25% of LFL)
- Ventilation			X	Activate alarm at lowest set point (10% of LFL)
- Shutdown		X		Charging system shutdown (50% LFL) until inspected
- Remote			X	To external alarms, possible to remote transmitters

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.1 W)

Table 11. Hydrogen Sensor Metric Rankings for Battery Backup Applications – Telecommunications CEVs

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Sulfur, silicone resistance, CO; methane detection useful
LDL		X		0.4 vol% (10% of the LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	0.1–4 vol% H_2
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		60 s
Repeatability		X		
Signal Drift			X	To avoid false positives and negatives for >5 years
Environmental Impacts				
- T			X	10°C to 40°C for indoor building applications
- P		X		Must be calibrated for deployment altitude
- RH		X		5 to 65% RH; some RH regulation exists at high end
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability	X			Highly unlikely to experience 100% H_2 (or high H_2)
Deployment Parameters				
Capital Cost		X		<$100; sensors are part of (commercial) control system
Installation Cost	X			As part of capital cost; sensors are part of control system
Physical Size			X	Moderate size restriction if deployed in ventilation system
Control Circuitry			X	Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf, existing market
Alarm Thresholds			X	
- Trace (1,000 ppm_v)	X			Probably not necessary, small background is likely
- Low (low risk)			X	0.4 vol% H_2 (10% of the LFL) to track intermediate levels
- High (pending risk)			X	25% of the LFL, audible alarm
Regulations and Codes		X		Local AHJs, OSH Confined space entry, possibly IEEE/ASHRAE
Deployment Placement			X	Improved guidance needed
Operational Parameters				
Lifetime			X	5 year minimum, 10 year desired
- Sensing Element		X		5 years, 10 years desired
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	>once per year, lower calibration requirements the better
Maintenance			X	No routine maintenance other than calibrations
Sample Size	X			No critical restriction

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Matrix Requirements		X		Possible depressed oxygen level (confined space)
Signal Management				
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			vol% H_2 readout is useful but not critical
- Remote monitoring	X			Remote interrogation may be useful, but core with industry
Device Repeatability		X		Plug in replacement not required if recalibrated
Warm-Up Time		X		<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface			X	Must connect to control system
- Number of set points		X		1: 10% LFL to activate ventilation; 2: 25% LFL alarm
- Audible			X	Activate alarm at lowest set point (25% of LFL)
- Ventilation			X	Activate alarm at lowest set point (10% of LFL)
- Shutdown	X			Charging system shutdown possible, not system shutdown
- Remote			X	To external alarms, possible to remote transmitters
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.01 W)

The major gaps inhibiting sensor deployment can be summarized as:

- Major
  - Maintenance and calibration are major shortcomings
    - Long-life sensors (>5 years)
  - Calibrations no oftener than 1 year
    - Auto-Cal or an automated calibration system (acceptable target: <$100/sensor)
  - All other maintenance requirements less often than once per year
  - Deployment Guidance for Building applications
    - In ventilation system versus on upper walls or on the ceiling
    - Sensor placement density (number of sensors per area)
    - Area monitors
- Secondary
  - Capital cost for appropriate monitoring systems
  - Listing requirements

2.6.3 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment is to simplify and economize the operational requirements. Robust sensors with long operational lifetimes would reduce replacement costs, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most nonroutine maintenance requirements, although sensor calibrations would still be required. Many manufacturers require periodic calibration to ensure accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., thermal stresses and vibration), and electrical factors (e.g., power surges, shutdowns, and circuit failures – the electrical factors can be mitigated by powering from the highly stable, power-surge protected 48 V_{DC} bus, typically available in telecommunications CEVs).

Underlying codes may specifically require a minimal calibration cycle. This is usually at least once per year, but could be more frequent based on manufacturer recommendations. Because of the broad range of factors that can affect sensor performance, it is unlikely that the sensor calibration requirement will be eliminated. Thus,automated calibration system would significantly lower operational costs associated with wide-scale sensor deployment for battery backup systems. Members of the group discussing the application Hydrogen Sensors for Battery Backup asserted that if such a system were to become available at a reasonable cost (<$100 per sensor), the resistance to the use of hydrogen sensors monitoring building battery systems would be appeased to the extent that IEEE/ASHRAE *Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications* could strongly suggest their use. Currently, the sensor of choice for battery backup applications has been the CGS, although no specific technology has been endorsed.

Sensor capital cost is likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted with economies of scale, especially those that are amenable to high-scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response; a 1-s response time is feasible. However, the sensor must also still meet the analytical requirements including range (e.g., multiple alarm levels) and robustness requirements (insensitive to poisons, interferences, and drift).

Guidance on sensor deployment (e.g., ceiling, walls, or in ventilation systems) and the relationship to appropriate action levels is needed. Hydrogen will be produced and released from a localized source or, in the case of a bank of batteries, a series of sources. The sensor will be placed remote from the source. Thus, the detected hydrogen gas concentration could be significantly attenuated. This is especially true for sensors deployed in ventilation systems, which may be required for recirculation ventilation designs. Guidance on the means to best position the sensor to capture a hydrogen generation event is needed. CFD modeling of various generation rates (low and high) and sensor deployment should be performed to specifically provide such guidance on position and appropriate alarm levels.

2.7 Storage

- Application
  - Hydrogen sensors installed near on-site bulk compressed or liquid storage systems
- Applicable standards
  - NFPA 2 Hydrogen Technologies Code
  - Local AHJs invoking modified fire code
  - Listing of sensor and sensor components

- UL 60079-15 or equivalent listing requirements for use in Class I, Division 2 hazardous locations
- UL 2075 or CSA C22.2, No. 152 or equivalent listing for sensor performance
- FM Global Class Number 6310 and 6320
- DOT transport of flammable material

2.7.1 Background

The hydrogen infrastructure requires several support systems and operations, including delivery of hydrogen or on-site production, on-site storage, transfer hardware, and hydrogen dispensing systems. Two storage-related applications covered in the workshop were indoor and outdoor storage (see Table 12 and Table 13). Also, large-scale storage is associated with site operations and small-scale storage with on-board vehicle storage. The pertinent sensor requirements associated with on-board storage were discussed in Sections 2.2 and 2.5.

DLA, Susquehanna Image, Used with permission

This section discusses issues pertaining to sensor requirements for on-site bulk hydrogen storage. Two approaches are compressed hydrogen gas and cryogenic liquid hydrogen. Bulk storage capacity can vary significantly, ranging from less than 100 kg to thousands of kilograms for large facilities. For example, 9000 gallons (2400 kg) of hydrogen is stored at the Defense Distribution Depot in Susquehanna, Pennsylvania, to power its forklift fleet [2]. Storage vessels containing this amount of hydrogen are routinely transported by truck and railroad to the deployment site. Bulk storage thus requires a transfer of large quantities of hydrogen or changeout operations in which the depleted storage vessel is replaced. Such activities increase the possibility of hydrogen releases and leaks.

A large quantity of hydrogen in a single location presents obvious hazards, and many systems are in place to keep the area safe, including outdoor deployment, setback distances, and safety systems. Although the equipment used to store compressed gas and liquid hydrogen are quite different, the sensor requirements are comparable. Unique to liquid storage facilities, however, is the controlled venting of "evaporated" hydrogen, so sensor deployment must take into account the presence of ambient hydrogen via controlled releases. Although flow regulators, shutoff valves, and bypass valves will be incorporated into the fuel system safety design to minimize released hydrogen volumes, the use of hydrogen sensors in areas around the storage vessel will increase safety. The sensors must respond to leaks before the release becomes dangerous.

Safety systems around large storage facilities typically include flame detectors designed to alarm in the event of hydrogen combustion. Flame detectors are beyond the scope of this report and were not explicitly included in the sensor workshop. Furthermore, they respond only during a combustion event and do not provide early warning capability.

Chemical sensors near storage areas are typically installed outdoors and need to be able to handle temperature and humidity fluctuations. Humidity will reach condensing levels, so the sensor must be able to handle water condensate. Water condensate can be handled by intrinsic sensor design, by adding a cover that will keep water away from the sensor, or other deployment designs. Temperature extremes will vary by location, but will range from below freezing to very hot in direct sunlight. Pressure will vary by location, so the sensor should be calibrated to the specific pressure when installed. The sensor signal should not vary significantly with local pressure fluctuations. The storage area may be near loading docks and parking areas, so the sensor needs to be selective against exhaust gases and other flammable gases.

Being outdoors, the hydrogen will be able to dissipate quickly, but design features of the storage facility and surrounding structures may provide entrapment zones. Sensor placement is an important consideration in this situation. More studies need to be done in this area, but in general, the sensor should be placed above the storage apparatus and away from any piping that normally vents hydrogen. Alarm levels should be at 10% of the LFL and safety action should take place at 25% of the LFL. The sensor should respond within 30 s of reaching these conditions. Indoor storage of hydrogen may include the use of approved cylinders stored in a safe area. Special requirements for indoor storage may include explosion proof or intrinsically safe electrical certification, added ventilation or the use of ventilated enclosures, and possibly added calibration requirements. The Idaho National Laboratory has developed guidance for the indoor storage of hydrogen and oxygen [17]. The guide includes recommendations for sensor placement based on the square footage of laboratory space. It suggests that these guidelines define an area of 400–900 ft^2 for each installed sensor.

2.7.2 Critical Gaps and Deficiencies

There is some debate about the optimal type and deployment of hydrogen sensor technology. As an outdoor facility, hydrogen released from storage facilities will dissipate into the atmosphere and could be transitory. However, sensors and flame detectors are often deployed to ensure site safety. Sensor placement remains a major gap for outdoor storage areas. An improperly placed sensor could result in not detecting a dangerous situation. Alternatively, placement of a sensor too close to a normal ventilation pipe, such as that required for liquid storage tanks, may cause spurious false alarms. Many of the issues with outdoor sensor placement and rapid dispersion of released hydrogen could be alleviated using wide area monitors [19] with rapid real-time response (<1 s), but such technology is not currently readily available commercially and significant development is still required for cost-effective, reliable wide area monitoring. Thus point sensors distributed at or around the storage facility are still necessary to detect hydrogen releases prior to adverse events.

When designing a hydrogen safety system for outdoor storage, one of the first things to consider is pressure holds and flow continuity checks to determine if the system is pressure tight. When employing sensors as part of a safety system, there are special considerations that should be considered. Boots can be added to valves and fittings that will trap hydrogen leaks and improve the capability of detecting external leaks. Other considerations include using hydrogen sensitive paint, wireless communication or odorants. Each safety system should be engineered to provide the level of safety required for the specific application.

The "operational requirements" for sensors is a major limiting factor for extensive sensor deployment. Acceptance is severely affected by cost of maintenance, especially calibration requirements. Small drifts in the sensor background oftentimes leads to the need for on-site calibration. Capital costs for the sensors are also a factor impacting acceptance. Since this factor is typically a one-time upfront expense, it does not impact as strongly as the ongoing operational costs. Nevertheless, there is always a need for lower cost systems, providing the sensor reliability is not compromised.

- Major
    - Sensor placement requires much more research
    - Maintenance and calibration are major shortcomings
        - Long-life sensors (>5 years)
    - Manual calibrations no more than once per year (>1 year or no calibration requirement is preferable)
    - All other maintenance requirements >1year
    - Robustness against poisons and dust
    - Unacceptable sensor drift (necessitating recalibration or system shutdowns).
- Secondary
    - Capital cost for appropriate monitoring systems
    - Acceptable target: <$500 per sensor

2.7.3 Alleviating Gaps and Deficiencies To Facilitate Sensor Utilization

One proposed strategy to facilitate sensor deployment would be to simplify and economize the operational requirements. Robust sensors with long operational lifetimes would cut down replacement cost, and could in principle lower the cost of maintenance by increasing the time between calibrations. Robust sensors should eliminate most non-routine maintenance requirements, although sensor calibrations would still be required. Currently, many if not all manufacturers require periodic calibration to assure both sensor accuracy and functionality. Sensor performance can be affected by a variety of stresses, including chemical (e.g., exposure to poisons), mechanical (e.g., thermal stresses and vibration), and electrical (e.g., power surges, shutdowns, and circuit failures) factors. Underlying codes may specifically require a minimal calibration cycle. Usually calibrations are to be performed a minimum of once per year, but could be more frequent based upon manufacturer recommendations. Because of the broad range of factors that can affect sensor performance, it is unlikely that the sensor calibration requirement will be eliminated. Thus, the development of "automated calibration system" would significantly lower operation costs associated with wide-scale sensor deployment. Acceptance of such a system would be facilitated if it were available at a reasonable cost (<$100 per sensor). Currently, the sensor of choice for deployment around storage tanks has been the catalytic bead sensors (also called combustible gas sensors, CGS), but no specific technology has been explicitly endorsed. Guidance on sensor deployment and the relationship to appropriate action levels is needed. The number of sensors placed around storage facilities will be kept to a minimum, mostly likely one or two. The deployed sensors must be able to respond to releases that are dispersing quickly.

Sensor capital cost is likely to decrease with demand as the hydrogen infrastructure develops. However, certain platforms and designs will be better impacted by economy of scale, especially those platforms which are amenable to high scale manufacturing afforded by technology developed by the microelectronics industry. Miniaturized, thin-film devices show particular potential. Miniaturized devices show particular potential. Miniaturized sensors, mass-produced using methods developed for the electronics industry (e.g., microfabrication, MEMs, or thin-film deposition protocols), could provide low-cost, low-power devices, coupled with a rapid response, with a 1-s response time being very feasible. However, the sensor must also still meet the analytical requirements including range (e.g., multiple alarm levels) and robustness requirements (insensitive to poisons, interferences, and drift). Commercial hydrogen sensors based on thin-film and other microfabrication platforms are emerging. While these show a fast response to hydrogen, there is a tendency for many of these devices to saturate at low concentrations and to exhibit a poor dynamic range. In addition, the long-term stability of these devices and robustness to stresses (e.g., chemical, thermal, and moisture) should be more thoroughly studied.

Table 12. Hydrogen Sensor Metric Rankings for Hydrogen Storage – Outdoor

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity			X	Exhaust gases
LDL		X		0.4 vol% (10% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		60 s
Repeatability		X		Not critical
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts		X		T and RH are more relevant than P
- T			X	-40°C to +40°C
- P	X			Must be calibrated for deployment altitude
- RH			X	15%–100% RH – Must be able to handle condensing
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability		X		Relevant for sensors mounted near tank
Deployment Parameters				
Capital Cost		X		<$500
Installation Cost		X		
Physical Size	X			Size not a significant issue
Control Circuitry		X		Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)	X			Not required for outdoor
- Low (low risk)			X	10% of the LFL, indicate adverse for single alarm level
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes			X	Possible local AHJs
Deployment Placement			X	Must be above system
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	>once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Outdoor air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Readout is not necessary
- Remote Monitoring	X			Remote interrogation is not necessary
Device Repeatability		X		Plug in replacement is useful
Warm-Up Time		X		<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface				
- Number of set points		X		Low-level mandatory for alarm, a second useful to shutdown
- Audible		X		Activate alarm at lowest set point
- Ventilation			X	Activate at 1st set point, if feasible
- Shutdown			X	Activate at 2nd set point (25% of LFL)
- Remote	X			Not necessary
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

Table 13. Hydrogen Sensor Metric Rankings for Hydrogen Storage – Indoor

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Analytical Parameters				
Selectivity		X		Exhaust gases
LDL		X		0.4 vol% (10% of LFL)
Analytical Resolution	X			Differentiation is not important other than alarm set points
Linear Range/Dynamic			X	To LFL (0.1–4 vol% H_2)
Accuracy		X		Within ±20% of reading for all working (T,P, RH) conditions
Response Time		X		30 s
Recovery Time		X		60 s
Repeatability		X		Not critical
Signal Drift			X	To avoid false positives and negatives at all alarm levels
Environmental Impacts		X		T and RH are more relevant than P
- Temperature			X	-40°C to +40°C
- Pressure	X			Must be calibrated for deployment altitude
- Relative Humidity		X		15%–100% RH – Must be able to handle condensing
Reversibility		X		Postexposure recovery should be >95%
Limits of Quantization	X			Quantization of trace hydrogen is not as critical as LDL
Saturation Stability		X		Relevant for sensors mounted near tank
Deployment Parameters				
Capital Cost		X		<$500
Installation Cost		X		
Physical Size	X			Size not a significant issue
Control Circuitry		X		Compatible with commercial control systems
Electronic Interface		X		Output in engineering units (e.g., % H_2) or easily converted

Parameters	Importance			Specifications and Notes
	Low	Medium	High	
Pneumatic Connections	X			Passive (no power) sampling system
Shelf Life		X		>5 years
Commercial Maturity			X	Must be off-the-shelf
Alarm Thresholds			X	Must indicate adverse condition
- Trace (1,000 ppm_v)		X		Not required but useful in ventilation system or extractive
- Low (low risk)			X	10% of the LFL, indicate adverse for single alarm level
- High (pending risk)			X	25% of the LFL, shutdown system for multiple alarm levels
Regulations and Codes			X	Possible local AHJs
Deployment Placement			X	Must be above system
Operational Parameters				
Lifetime		X		5 year minimum, 10 year desired
- Sensing Element		X		5 years
- Unit Replacement		X		5 years
Consumables		X		None
Calibration Schedule			X	once per year; longer time between calibrations is desired
Maintenance			X	Maintenance free except calibration
Sample Size	X			No critical restriction
Matrix Requirements	X			Indoor air environment
Signal Management		X		
- Alarm (audible, lights)			X	Alarm set at 10% of LFL
- Displays	X			Readout is not necessary
- Remote Monitoring	X			Remote interrogation is not necessary
Device Repeatability		X		Plug in replacement is useful
Warm-Up Time		X		<1 hour for initial installation,15 minutes for all shutdowns
Alarm Interface				
- Number of Set Points		X		One mandatory, two useful shutdown
- Audible		X		Activate alarm at lowest set point
- Ventilation			X	Activate at 1st set point, if feasible
- Shutdown			X	Activate at 2nd set point (25% of LFL)
- Remote	X			Not necessary
Mechanical Stability	X			Vibration tests, specification TBD
Power Requirements	X			Moderate power requirements preferred (<0.5 W)

3 Summary

The 2007 DOE/NREL Hydrogen Sensor Workshop resulted in a short list of technical targets (primarily Analytical Performance Metrics) for hydrogen sensors. These targets are presented in Table 1. The metrics listed in Table 1 were identified as critical sensor performance parameters and specifications, and as such, were viewed as necessary targets to meet 2012 requirements as envisioned in 2007. The 2011 workshop, however, approached the task of assigning metrics differently. Rather than developing generalized sensor technology performance requirements, specific applications were identified and the corresponding sensor requirements were thoroughly reviewed. It was recognized that different applications can have significantly different requirements. For example, the residential consumer market requires low-cost technology. In this application the target price to the end user (the consumer) would be low (e.g., $100). This contrasts to deployment of hydrogen dispensers in multimillion dollar warehouse facilities.

Facility protection is highly critical, such that capital cost concerns are less restrictive and a \$500–\$1000 capital cost is not prohibitive. Of course, industrial or commercial applications would have higher expectations and higher cost systems would have additional features such as certification to safety and performance standards, multiple (and adjustable) alarm levels, interface capability to control the system, remote interrogation, and hopefully, high reliability. In commercial applications, hydrogen levels are often continually monitored, and a small drift in the sensor background results in either a false alarm or a recalibration of the sensor, or both. Trained personnel calibrate sensors in the field, which is quite costly. For residential applications, drift in the sensor response would ultimately lead to a false positive (for a positive drift) or a possibility of a false negative (for a negative drift).

In the 2011 sensor workshop, breakout groups were organized by a variety of applications. Three sequential breakout sessions were held to allow attendees to participate in up to three topical areas. The preceding sections were based on the findings of these breakout groups, and comprehensive sensor requirements were developed for each specific application. Clearly, each application had its unique needs. Table 14 through Table 24 contain short lists of application-specific critical sensor performance metrics.

Table 14. Critical Sensor Requirements for Industrial Truck Applications – On-Board Deployment

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point of 1%) between calibrations; no false positive or negative
Temperature Stability	No on-board thermal regulation, except ventilation, 0° to +50°
Relative Humidity	Minimal on-board humidity regulation; 0 to 90% RH at prevailing T; RH drift should be <0.25 vol% H_2
Selectivity	Inert to silicone compounds, dust, no cross sensitivity to CO, H_2S, other application specific chemicals
Saturation Stability	No adverse effect or quick (<5 min) recovery
Response Time	1 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Physical Size	Must fit on-board in enclosure around tank
Regulation and Codes	Possible UL 2075 or equivalent
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 15. Critical Sensor Requirements for Indoor Fueling – Facility Monitoring

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10 vol% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point of 1%) between calibrations; no false positive or negative
Temperature Stability	Depends on location; 0° to 40°C for most, but -25° to +40°C for refrigerated facilities
Relative Humidity	25 to 90% RH at prevailing T in unregulated facility; RH drift should be <0.25 vol% H_2 equivalent response
Selectivity	Inert to silicone compounds, no cross sensitivity to CO, H_2S, or other application specific chemicals
Response Time	30 s at 1 vol% H_2 (or the alarm level)
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	NFPA 2, Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Required by NFPA2 but no guidance on placement is given
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 16. Critical Sensor Requirements for Indoor Fueling – In-Dispenser Deployment

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point of 1%) between calibrations; no false positive or negative
Temperature Stability	No on-board thermal regulation, except ventilation, 0° to +50°
Relative Humidity	Minimal on-board humidity regulation; 0 to 90% RH at prevailing T; RH drift should be <0.25 vol% H_2
Saturation Stability	No adverse effect or quick (<5 min) recovery
Response Time	1 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Physical Size	Must fit on-board in enclosure around tank
Regulation and Codes	Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 17. Critical Sensor Requirements for Residential Applications

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point of 1%) between calibrations; no false positive or negative
Temperature Stability	Little thermal regulation likely (garages) -40° to +40°C
Relative Humidity	Little RH regulations; 25%–95% at prevailing T, RH drift should be <0.25 vol% H_2 equivalent response
Selectivity	Inert to silicone compounds, no cross sensitivity to CO, H_2S, or other application specific chemicals
Response Time	30 s at 1 vol% H_2 (or the alarm level)
Deployment Parameters	
Commercial Maturity	Does not currently exist
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	NFPA 2, Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Plug and go type of installation; no electrical interfaces other than power
Capital cost	<$100
Operational Parameters	
Operational Lifetime	>5 years
Calibration	No calibration requirements during deployment lifetime,
Maintenance	No routine maintenance other than periodic battery (backup power system) check
Audible Alarm	Minimal requirement, must be heard external to garage

Table 18. Critical Sensor Requirements for Production – Facility Monitoring

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point of 1%) between calibrations; no false positive or negative
Temperature Stability	Depends on location; 0° to 40°C for most, but -25° to +40°C for refrigerated facilities
Relative Humidity	25 to 90% RH at prevailing T in unregulated facility; RH drift should be <0.25% H_2 equivalent response
Selectivity	Inert to silicone compounds, no cross sensitivity to CO, H_2S, or other application specific chemicals
Response Time	30 s at 1 vol% H_2 (or the alarm level)
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	NFPA 2, Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Required by NFPA2 but no guidance on placement is given
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 19. Critical Sensor Requirements for Production – In-Dispenser Deployment

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and mayb e required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	No on-board thermal regulation, except ventilation, 0° to +50°
Relative Humidity	Minimal on-board humidity regulation; 0 to 90% RH at prevailing T; RH drift should be <0.25 vol% H_2
Saturation Stability	No adverse effect or quick (<5 min) recovery
Response Time	1 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Physical Size	Must fit on-board in enclosure around tank
Regulation and Codes	Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 20.Critical Sensor Requirements for On-Board Light-Duty Road Vehicles

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and may be required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	No on-board thermal regulation, except ventilation, 0° to +50°
Relative Humidity	Minimal on-board humidity regulation; 0 to 90% RH at prevailing T; RH drift should be <0.25 vol% H_2
Saturation Stability	No adverse effect or quick (<5 min) recovery
Response Time	1 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf, technology exists, but needs advancement (cost and reliability)
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Physical Size	Must fit on-board in enclosures in vehicle (passenger and trunk compartments
Cost (to manufacturer)	<$15, including basic electronics (output signals in engineering units of vol% H_2, alarm set points)
Regulation and Codes	SAE, ASIL regulations
Operational Parameters	
Operational Lifetime	>5 years
Calibration	No calibration during lifetime
Maintenance	No routine maintenance
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 21. Critical Sensor Requirements for Battery Backup – Dedicated CEVs

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	Minimal facility thermal regulation, -10° to +50°
Relative Humidity	Minimal humidity regulation; 65 to 90% RH at prevailing T; RH drift should be <0.25 vol% H_2
Response Time	30 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm; connects to remote monitoring system

Table 22. Critical Sensor Requirements for Battery Backup – Multiple-Use Buildings

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and may be required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	Depends on location; 0° to 40°C for most, but -25° to +40°C for refrigerated facilities
Selectivity	Inert to silicone compounds, no cross sensitivity to CO, H_2S, or other application specific chemicals
Response Time	30 s at 1 vol% H_2 (or the alarm level)
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	NFPA 2, Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Required by NFPA2 but no guidance on placement is given
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

Table 23. Critical Sensor Requirements for Hydrogen Storage – Outdoor

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and maybe required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	Outdoor environment temperature extremes
Relative Humidity	Outdoor environment humidity extremes
Response Time	30 s at 1 vol% H_2
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Required by NFPA2 but no guidance on placement is given
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm; connects to remote monitoring system

Table 24. Critical Sensor Requirements for Hydrogen Storage – Indoor

Parameters	Comments and Specifications
Analytical Parameters	
Linear Range	0–4 vol% H_2, but extended to 10% may be useful (and may be required by local AHJ)
Signal Drift	<10% of alarm (<0.1 vol% H_2 drift for a alarm set point o 1%) between calibrations; no false positive or negative
Temperature Stability	Depends on location; 0° to 40°C for most, but -25° to +40°C for refrigerated facilities
Relative Humidity	25 to 90% RH at prevailing T in unregulated facility; RH drift should be <0.25 vol% H_2 equivalent response
Selectivity	Inert to silicone compounds, no cross sensitivity to CO, H_2S, or other application specific chemicals
Response Time	30 s at 1 vol% H_2 (or the alarm level)
Deployment Parameters	
Commercial Maturity	Must be off-the-shelf
Alarm Set Points	25% of LFL (or 10% depending upon local AHJ); multiple set points may be required
Regulation and Codes	NFPA 2, Class I Division 2 (UL 60079 or equivalent); possible UL 2075 or equivalent
Deployment Placement	Required by NFPA2 but no guidance on placement is given
Operational Parameters	
Operational Lifetime	>5 years
Calibration	Minimal manual calibration, no more than annual
Maintenance	No routine maintenance other than calibrations
Audible Alarm	Minimal (and current) requirements call for an audible alarm

3.1 Review of Gaps and Deficiencies

Several sensor performance gaps and deficiencies cut across multiple applications. These include:

- Analytical performance gaps
    - Response time (and to a lesser extent, recovery time)
    - Cross sensitivity/poisons
    - Signal drift
- Operational gaps
    - Calibration frequency
    - Cost of maintenance and calibrations
- Deployment gaps
    - Code requirements
    - Placement
    - Distributed point sensors versus wide area monitoring

In terms of analytical performance, avoidance of false positives (e.g., a positive drift in the sensor output misinterpreted as hydrogen present at or above the alarm level) remains a consistent concern. False positives, perceived or real, cause stakeholders to lose confidence. False positives can occur by a variety of mechanisms, including impact of fluctuations in environmental parameters, aging of the sensor, and chemical environment (e.g., exposure to interferents or poisons). An interferent induces a reversible response that could be incorrectly interpreted as having hydrogen present, whereas a poison permanently affects the response of the sensor. A poison will usually decrease the sensitivity of the sensor to hydrogen (e.g., sensor electrical response divided by concentration); however, a sensitivity increase is possible. Thus, robustness to interferents and poisons is critical. Common interferents include CO, methane, and other combustible gases; however, not all platform types are equally susceptible to these gases. Common poisons include sulfur and silicone compounds, but again some platforms are more susceptible than other. There is also the potential of application-specific interferents (e.g., in a warehouse storing large quantities of a product-specific industrial or residential chemical, such as a specific solvent).

Environmental factors can also induce false positives. Temperature and humidity effects on sensor responses are common. Some sensing element platforms are particularly sensitive to temperature changes, but methodologies to compensate for the temperature dependence have been developed and incorporated into the sensor control circuitry. It is important that sensor stability be validated throughout the temperature and humidity ranges that are likely to be encountered, and such tests are incorporated into national (e.g., UL 2075 and CSA C22.2, No. 152) and international (e.g., ISO 26142) sensor performance standards. A third factor affecting false positives is sensor drift caused by aging, which affects the active sensing element. Overall sensor drift is typically addressed through periodic calibrations, which are critical for most sensor deployments. There are, however, reports from end users of unacceptable drift in sensor response in excess of manufacturer specifications, including the magnitude of the drift and the time frame in which it occurred.

Currently, most commercial sensors have response times on the order of 10–60 s. This is adequate for sensors deployed as area monitors, such as those mounted on the wall or ceiling around the dispenser, garages, or other facilities. Point sensors deployed as area monitors will typically operate remotely from the system; thus, the buildup of hydrogen to the alarm level will typically dominate the detection process. For these applications, a 30-s response time is adequate and readily accomplished by many commercial devices. However, sensor response time remains an important issue for applications where high concentrations of hydrogen may rapidly form in the event of small leaks, specifically leaks that occur in a contained environment or enclosure, such as within the dispenser or monitoring for on-board forklifts to monitor for leaks around an enclosed tank. Hydrogen concentrations can rapidly build up in a contained environment, so this application requires fast-responding sensors, preferably 1 second.

Even slow leaks, which may not be readily detectable by other means (e.g., pressure transducers installed in the pneumatic lines), can rapidly lead to dangerous situations. For example, <0.75 g of hydrogen uniformly distributed within an 8-ft^3 enclosure would exceed the LFL (a miniscule leak rate of 0.21 mg/s could reach this level within 1 h). Since the 2007 workshop, sensor response times have improved. Sensing elements (e.g., MOXs and CGSs) developed around microfabrication designs have shown improved response times relative to their conventional counterparts. Typically, however, the response times of these sensors are still around 5 s, and the 1-s response time remains a gap. Further, many thin-film devices are more adversely affected by environmental, chemical, and aging effects than are their conventional counterparts.

Gaps in deployment metrics also cut across the range of applications. Although NFPA 2 requires the use of hydrogen sensors around indoor operations, no guidance about sensor placement and recommended number of sensors for a facility is provided. This placement guidance has to be developed using CFD modeling with empirical validation, and should include assessments within a range of likely scenarios (e.g., relationship among leak rates, volumes versus facility designs).

There is also the need to have sensor technologies listed to national standards. Current building codes may require that the sensor be certified for combustible environments (e.g., Class I, Division 2). It is common practice in the petroleum industry to require Class I, Division 2 listing (or more rigorous certifications), so Class I, Division 2 certified hydrogen sensors are commercially available, albeit the number of platform types is limited. The certification requirement for hydrogen sensors is increasing, and some jurisdictions already require that sensors be listed to performance standards (e.g., UL 2075) for indoor operations. However, as of the publication of this report no hydrogen sensors are currently listed as certified for UL 2075. The lack of certified sensors slows the permitting process.

Capital costs associated with sensor purchases may be envisioned as a third deployment concern. However, current capital cost of sensors was not a major issue among the stakeholders attending the DOE/NREL workshop. Of course, lower costs are always desired, but certainly not if they come about through the loss of performance. Cost does remain an issue for the emerging applications of residential hydrogen sensors, including sensors deployed on-board light-duty road vehicles. Currently no technology is available that meets the cost requirements for the consumer market.

By far the most critical gap associated with sensor technologies pertains to maintenance. Every identified application requires more robust sensor technologies. In all indoor/enclosed applications (buildings, CEVs), the costs associated with routine calibrations are the major expense. Sensor deployment will be facilitated by either a fully reliable sensor with minimal calibration requirements or a means for autocalibration, providing the automated calibration system would be sufficiently low cost, simple to use, reliable, and accepted by AHJs.

3.2 Sensor Specification and Gap Level by Application

The relationship between a sensor specification for the various performance metrics and its relevance to each identified application is represented in Table 25. Rankings are given as high (■) for a critical metric, medium (■) for an important metric, low (■) for a metric that may be useful but not critical for the application, and not applicable (■). A comparable ranking of high, medium, or low provides an assessment of current commercially available technology to meet the indicated specification. The table provides a visualization of the relationship among sensor requirements for the various applications. Rankings typically vary with applications, but there are some trends. Area monitor applications, such as sensors deployed in residential garages, warehouses, battery backup rooms, have similar requirements. Sensors deployed within contained environments, such as in-dispenser or in-production unit (e.g., within an enclosure surround a reformer or electrolysis unit) also have similar requirements.

Table 25. Sensor Metric Rankings by Application and Sensor Gap Level

Parameters		Industrial Trucks	Indoor Fueling (Area Monitor)	Indoor Fueling (In-Dispenser)	Residential	Production (Area Monitor)	Production (In-Unit)	Road Vehicles	Battery Backup (Building)	Battery Backup (CEV)	Storage (outdoor)	Storage (indoor)	Performance
Analytical Parameters													**Gap Level**
Metric	**Spec.**												
Selectivity	Std. Mix	Red	Red	Green	Red	Red	Red	Green	Green	Red	Red	Green	**Medium**
	Poisons	Red	Red	Green	Green	Green	Green	Cyan	Green	Green	Red	Green	**High**
LDL	<0.1%	Yellow	Cyan	Yellow	Yellow	Yellow	Cyan	Cyan	Yellow	Yellow	Yellow	Yellow	**Low**
	0.4%–1%	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	**Low**
Analytical Resolution	<0.2% H_2	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	**Low**
Linear Range	0–0.1%	Yellow	Yellow	Yellow	Yellow	Yellow	Cyan	Yellow	Yellow	Yellow	Cyan	Cyan	**Low**
	0–>4%	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Red	**Low**
Response Time	1 s	Yellow	Yellow	Red	Yellow	Yellow	Red	Red	Yellow	Yellow	Yellow	Yellow	**High**
	10–30 s	Green	Green	Yellow	Green	Green	Yellow	Yellow	Green	Green	Green	Green	**Low**
Recovery Time	1–10 s	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	**Medium**
	30–60 s	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	**Low**
Repeatability	±20%	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	**Low**
Signal Drift	<0.2% H_2/cal	Red	Red	Red	Yellow	Red	Red	Yellow	Green	Green	Red	Red	**Medium-High**
	<1% H_2 5 years	Cyan	Cyan	Cyan	Red	Cyan	Cyan	Red	Cyan	Cyan	Cyan	Cyan	**High**
Temperature	-40° to +40°C	Yellow	Red	Yellow	Green	Yellow	Yellow	Green	Green	Yellow	Red	Cyan	**Medium**
	0° to +40°C	Red	Yellow	Red	Yellow	Green	Green	Yellow	Red	Cyan	Cyan	Red	**Medium**
Pressure (fixed	0.6–1.0 Bar	Green	Green	Green	Green	Green	Green	Green	Green	Cyan	Cyan	Cyan	**Low**
Pressure (var.	0.6–1.0 Bar	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	**Medium**
Relative Humidity	0%–95%	Green	Green	Green	Green	Green	Red	Red	Green	Cyan	Red	Green	**Low**
Reversibility	>95% in 5 min	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	**Low**
Limits of Quantization		Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	**Low**
Saturation Stability	<1–5 min	Red	Green	Red	Green	Green	Red	Green	Cyan	Cyan	Green	Green	**unknown**
Deployment Parameters													
Metric	**Spec.**												**Gap Level**
Capital Cost	<$100	Red	Cyan	Cyan	Red	Cyan	Cyan	Red	Cyan	Cyan	Cyan	Cyan	**High**
	<$1,000–	Yellow	Red	Red	Cyan	Red	Red	Cyan	Red	Red	Green	Green	**Low**
Physical Size		Red	Yellow	Red	Yellow	Yellow	Yellow	Red	Cyan	Cyan	Cyan	Cyan	**Medium**
Level of Maturity	COTS	Red	Red	Green	Green	Red	Red	Red	Red	Red	Red	Red	**Medium**
Codes and Standards	compliance	Green	Red	Red	Green	Red	Red	Green	Green	Red	Red	Red	**High**
Alarm Set Points	<0/1%	Yellow	Yellow	Green	Yellow	Yellow	Cyan	Cyan	Yellow	Yellow	Yellow	Yellow	**Low**
	10%–25% LFL	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	**Low**
Deployment Placement	Guidance	Green	Red	Green	Red	Red	Cyan	Cyan	Red	Green	Red	Red	**High**
Operational Parameters													
Metric	**Spec.**												**Gap Level**
Lifetime (deployment)	>5 years	Red	Red	Green	Red	Red	Red	Red	Red	Red	Red	Red	**Unknown**
Calibration Cycle	>1 year	Red	Red	Red	Yellow	Red	Red	Yellow	Red	Red	Red	Red	**High**
	>5 year	Cyan	Cyan	Cyan	Red	Cyan	Cyan	Red	Cyan	Cyan	Cyan	Cyan	**High**
Interchangeable		Green	Cyan	Cyan	Cyan	Cyan	Cyan	Red	Cyan	Cyan	Cyan	Cyan	**High**
Mechanical Stability	Vibration/Shock	Red	Cyan	Cyan	Cyan	Cyan	Cyan	Red	Cyan	Cyan	Cyan	Cyan	**Unknown**

Legend	
High importance	Red
Medium importance	Green
Low importance	Cyan
Not applicable	Yellow

A "high" importance coupled with a high gap rating represents a significant gap between application requirements and sensor capability and identifies specific areas for improvement. Examples include selectivity to poisons (indoor fueling area monitors and on-board sensors), 1-s response time (for contained environments including the on-board sensor and internal to production units), signal drift (all, except backup battery systems), saturation stability, regulation codes and standards, deployment guidance, and especially calibration requirements. These represent specific areas in sensor technology in which additional research and development is necessary.

References

1. Energy Efficiency & Renewable Energy, Alternative Fuels & Advanced Vehicles Data Center www.afdc.energy.gov/afdc/, accessed September 27, 2011. *Codes and Standards Requirements for Deployment of Emerging Fuel Cell Technologies*, R. Burgess, W. Buttner, and C. Rivkin, NREL/TP-5600-52641 (December 2011) www.nrel.gov/docs/fy12osti/52641.pdf)

2. "Codes and Standards Requirements for Deployment of Emerging Fuel Cell Technologies", R. Burgess, W. Buttner, and C. Rivkin, NREL/TP-5600-52641, (December, 2011) (www.nrel.gov/docs/fy12osti/52641.pdf)

3. "2011 Toyota FCV-R Concept Unveiled, Previews Fuel-Cell Production Car in 2015" www.autoevolution.com/news/2011-toyota-fcv-r-concept-unveiled-previews-fuel-cell-production-car-in-2015–40402.html, accessed December 1, 2011.

4. The Department of Energy Hydrogen and Fuel Cells Program Plan – An Integrated Strategic Plan for the Research, Development, and Demonstration of Hydrogen and Fuel Cell Technologies (September 2011) see https://www1.eere.energy.gov or http://search.nrel.gov/query.html?qp=&style=eere&qs=&qc=eren&ws=0&qm=0&st=1&nh=10&lk=1&rf=0&oq=&col=eren&qt=2010_market_report.pdf&x=8&y=12)

5. NREL Safety Codes & Standards Web Page: www.nrel.gov/hydrogen/proj_safety_codes_standards.html

6. H2 Incident Reporting and Lessons Learned Database (see www.h2incidents.org/)

7. International Association for Hydrogen Safety (see www.hysafe.org/IAHySafe)

8. Agreement concerning the establishing of global technical regulations for wheeled vehicles, equipment, and parts which can be fitted and/or be used on wheeled vehicles, Draft GTR, Hydrogen Fueled Vehicle, (ECE/TRANS/132 and Corr.1); draft document (September 19, 2011)

9. Hydrogen Sensor Workshop, Department of Energy, April 4, 2007. See www.lanl.gov/orgs/mpa/mpa11/sensors.html, accessed October 13, 2011.

10. See http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/safety.pdf, accessed October 13, 2011.

11. "Hydrogen Sensors – A review," T. Hübert, L. Boon-Brett, G. Black, U. Banach, *Sensors and Actuators* (B) 157 (2011) 329–352.

12. "Identifying performance gaps in hydrogen safety sensor technology for automotive and stationary applications," L. Boon-Bret, J. Bousek, G. Black, P. Moretto, P. Castello, T. Hübert, U. Banach, *International Journal of Hydrogen Energy* 35 (2010) 373–384.

13. "An overview of hydrogen safety sensors and requirements", W. J. Buttner, M. B. Post, R. Burgess, C. Rivkin, *International Journal of Hydrogen Energy* 36 (2011) 2462-2470. www.eiseverywhere.com/ehome/2011DOEHydrogenSensorWorkshop/presentations

14. https://www.eiseverywhere.com/ehome/2011DOEHydrogenSensorWorkshop/presentations, accessed December 2, 2011.

15. The NREL Sensor Testing Laboratory home page: www.nrel.gov/hydrogen/facilities_hsl.html, accessed April 1, 2012.

16. "Hydrogen Leak from Onboard Storage System of a Fuel Cell-Powered Lift Truck" in http://www.h2incidents.org/incident.asp?inc=298, accessed October 13, 2011.

17. "Hydrogen and Oxygen Gas Monitoring System Design and Operation Safety and Technology of Nuclear Hydrogen Production, Control, and Management," L.E. Cadwallader, K.G. Dewall, J.S. Herring, Idaho National Laboratory INL/CON-07-12079, June 2007. www.inl.gov/technicalpublications/Documents/3772047.pdf.

18. "Wide Area and Distributed Hydrogen Sensors," R. Zalosh; N. Barilo, 3rd International Conference on Hydrogen Safety, Paper 186, September 2009. http://conference.ing.unipi.it/ichs2009/images/stories/papers/186.pdf

19. UL 2034 "Single and Multiple Station Carbon Monoxide Alarms," 3rd Edition 2008.

20. OSHA minimal oxygen requirement www.osha.gov/pls/oshaweb/owadisp.show_document?p_id=9801&p_table=STANDARDS

21. "A Numerical Study of the Release and Dispersion of a Bouyant Ggas in Partially Confined Spaces," K. Prasad, W.M. Pitts, M. J.C. Yang, , *International Journal of Hydrogen Energy* 36(8) (2011) 5200.5210.

22. "Numerical Analysis of Accidental Hydrogen Release in a Laboratory," M. Heitsch, D. Baraldi, P. Moretto, *International Journal of Hydrogen Energy* 35(9) (2010) 4409–4419.

Appendix A Definitions

Analytical, Deployment, and Operational Parameters

Analytical Parameters

Accuracy	The relationship between the sensor indication and the nominal (accepted) concentration of the analyte, typically expressed as a percentage (Sensor Readout/Actual*100).
Analytical Resolution	The minimum change of concentration that a sensor can accurately resolve. It has been defined as the slope of a linear calibration curve divided by the standard deviation of the measurement, which includes the noise contributions from the baseline and the response due to analyte exposure (also called analytical sensitivity).
Cross Sensitivity	See selectivity
Drift	Slow change in the response of the sensor due to various changes in electrical components, temperature, and aging. Drift can be defined as an apparent change in concentration per unit time for a fixed input concentration that can be due to a change in baseline or degree of response to the desired analyte.
Dynamic Range	The range of analyte concentration above which a change in concentration gives a change in detector response, but not necessarily a linear change.
Environmental Effect	The effect of changes in Pressure (barometric pressure), Temperature, and Relative Humidity / Moisture to induce a change in sensor electrical response. If uncompensated, such changes may be mis-read as a change in analyte concentration.
Interferent	A chemical which produces a *reversible* response on the analytical detector. The impact of the interferent may be an apparent positive response, a negative response, or an attenuation of the response of the detector to the target analyte. *Reversible* implies that the detector will return to its normal behavior upon removal of the interferent; this recovery should be on the order of the stated response time of the detector. (see *Poison*)
Limit of Quantization	The smallest signal above background noise an instrument can reliably assign quantitative information; frequently calculated as 10 times the standard deviation of the background signal
Linear Range	The concentration range above which the change in detector (sensor) response is proportional to the change in analyte concentration. The output can be represented by the equation: $Concentration = Signal_{out} \times Gain$.

Lower Detection Limit	The smallest signal above background noise an instrument can reliably detect; frequently calculated as 3 times (or 2 times) the standard deviation of the background signal
Poison:	A chemical which produces a permanent or slowly recovering response on the analytical detector. The impact of the interferent may be an apparent positive response, a negative response, or an attenuation of the response of the detector to the target analyte. (see *Interferent*)
Recovery Time	The time for the sensor to recover to baseline following exposure to vapor.
Response Time	The time for a sensor signal to adjust during exposure to the analyte. For sensors that reach well-defined steady-state signals it is calculated as the time to reach a certain fraction of the response. Herein, the sensor response time can be defined as the time to reach 90% of the final indication that is achieved when the sensor is exposed to a constant flux of hydrogen at 10% of the LFL; 10% of the hydrogen LFL corresponds to the typical required alarm set point. T, P, RH, test gas flow rates and other parameters may be set by the manufacturer, but they must be consistent with the likely deployment conditions.
Repeatability	The degree of consistency in response time and signal range between sensor responses induced by identical sequential vapor exposures.
Recovery	See *Reversibility*.
Reversibility	The ability of the sensor to recover to baseline following an analyte exposure. (also called “Recovery”)
Saturation Stability	The ability of the sensor to provide quantitative information regarding the analyte within the specified concentration range of the device following a brief exposure to the analyte of concentrations in excess of the specified range including pure analyte exposure. The Saturation Stability can be defined as the time required for a sensor to be able to measure, within the instrument’s specified accuracy, hydrogen at the LFL or user-defined alarm threshold following a brief exposure to pure hydrogen.
Selectivity	A measure of the relative response of the sensor to two different analytes. For example to measure 100 ppm_v CO_2 in nearly 100% oxygen, the CO_2 detector must have a minimal CO_2/O_2 selectivity factor of at least 10^4. See *Interferent* and *Poison*.
Sensitivity	The electronic response of a sensor or instrument to a given amount of an analyte and has units of **Concentration/Electronic-signal.** It is set by the electronic gain of the sensor and associated electronic circuitry. In a linear system the sensitivity is a constant equal to the slope of the calibration curve. Frequently used, improperly, synonymously for LDL.

Deployment Parameters

Capital Costs	The actual cost of the sensor and required hardware (control circuitry) for general applications
Control Circuitry	Required electronic circuitry to control and obtain the electronic output signal from a sensing element. Control circuitry can be trivial (a resistor for a chemiresistor), simple (a fixed potential potentiostat with I-V converter for EC sensor), or complex (frequency analyzers).
Electronic Interface	Requirements to electrically connect the sensor to Instrument system and includes both power input requirements and signal output connections
Installation Costs	The costs associated with installation associated with the specific instrument, and includes custom pneumatic interfaces, mounts, fixtures, etc.
Maturity	Availability of the sensor technology for current deployment, including ability to meet market requirements.
Placement	Location selection of the deployed sensor
Physical Size	Basic dimensions of the sensor and of the required circuit board
Power Requirement	Voltage and current requirements to operate sensor and control circuitry
Pneumatic design	Requirements to make the gas-sensor interface
Regulations	Codes, standards and other government regulations which may mandate use of or properties of the sensor
Shelf life	Effective time that a sensor can be stored prior to installation.

Operational Parameters

Alarm Set Points	Analyte concentration(s) that activates an audible alarm or relay connected to an alarm system or other systems (e.g., ventilation system, shutdown system, remote monitoring systems). Although somewhat arbitrary, alarm levels for a hydrogen sensor can be described as trace (e.g., 1% of the LFL), low (10% of the LFL), medium (25% of the LFL) or high (LFL or higher).
Calibration	(**Cal**) Protocol and frequency for calibrating the sensor to assure accuracy and/or compliance to regulations.
Consumables	(**Con**) Required and depletable supplemental material requirements. For example, hydrogen in an FID; calibration and validation gases

Device Repeatability	Similarity of response characteristics between multiple samples of the same sensor type or model.
Maintenance	(**Mtc**) Required procedures to assure accuracy, includes replacement
Matrix requirements	(**Mtx**) Effect of background gas on sensor response. For example MOX sensors require oxygen for reversibility
Operational Lifetime	(**Lif**) Expected useful life of the sensor under operating conditions
Orientation Effect	Change in sensor response to a test gas as the sensor is rotated through various orientations (side, upside down, etc.)
Sample size	(**Sam**) Volume of gas sample required by sensor to perform accurate measurements
Signal Management	(**SM**) Interfacing the sensor signal to the DAQ system.
Warm-up Time	The time required for a sensor to produce analytically useful outputs following powering up.

Appendix B The Hydrogen Sensor Workshop

Rosemont, Illinois (June 8, 2011)

Hydrogen Sensor Workshop

The Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL) invites you to participate in a one-day workshop on hydrogen sensors, with emphasis on safety as well as process control requirements. The workshop shall identify and review sensor applications and required performance specifications for each application. Attendees shall represent a cross section of the hydrogen industry. Participants must preregister for the workshop.

To encourage interaction and open discussion, we are limiting the attendance to this workshop to 50 active participants. A diverse group is expected to attend this workshop providing sensor end-users and sensor developers the opportunity to work together to identify existing and emerging markets and to identify areas for improvements in sensor technologies. Participants will consist of stakeholders in product development, infrastructure support, health and safety, as well as sensor developers.

We hope you will be able to join us for this free workshop to learn more about the emerging use of hydrogen sensors. The discussion and outcomes of this workshop are vital to the hydrogen community and our nation as we shift to a greater use of hydrogen technologies.

DATE & TIME:
Wednesday, June 8, 2011
8:00AM – 5:00PM

LOCATION:
Donald E. Stephens
Convention Center
Rosemont, IL

MORE INFORMATION:
Please contact Jessica Cole
at MorEvents **888-329-0664**
or **jessica@morevents.com**

Held in conjunction with
sensors expo
& conference
JUNE 6 - 8, 2011 • ROSEMONT, IL
DONALD E. STEPHENS CONVENTION CENTER

Organized by:
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. DEPARTMENT OF
ENERGY

DOE-NREL Hydrogen Sensor Workshop (June 8, 2011) List of Attendees

Last Name	First Name	Job Title	Company
Alexander	Michael	Project Engineer	Underwriters Laboratories Inc.
Ashton	Curtis	Principal Power Maintenance Engineer	CenturyLink
Barilo	Nick	Senior Fire Protection Engineer	Pacific Northwest National Laboratory
Behnke	Jim	Regional Sales Mgr.	Honeywell Analytics
Bernstein	Irwin	Business Development	H2scan
Burgess	ROBERT	Senior Engineer	NREL
Buttner	William	Senior Scientist	NREL
Cohen	Joe	Lead Engineer	Air Products
Cole	Jessica	Event Planner	MorEvents
Cummings	Steve	Product Development Engineer	NexTech Materials, Ltd.
Graff	Tim	VP Strategic Development	Emerson / Therm-O-Disc
Grasso	Glenn	Instrumentation Engineer	Affiliated Engineers
Groppetti	Claudio	VP Business Development Gas Detec.	Xtralis
Harris	Aaron	EHS and Product Compliance Manager	Nuvera Fuel Cells
Hayashi	Fujio	Director of Business Development	NexTech Materials
Hoagland	William	President	Element One, Inc.
Hogan	Patrick	Vice President Marketing	Honeywell Analytics
Hunter	Gary	Electronics Engineer	NASA Glenn Research Center
Kostelecky	Clayton	Operations Manager	Synkera Technologies
Lieberman	Robert	President	Intelligent Optical Systems
Mahnken	Glenn	Senior Engineering Specialist	FM Global
Maynard	Terry	Senior Account Manager	Argonne National Laboratory
McWhorter	Scott	Technical Advisor	US DOE Fuel Cell Technologies
Mollner	Larry	Advisor	H2Scan
Novkovic	Josip	Project Manager	CSA Standards
O'Malley	Kathleen	Energy Analyst	SRA International
Perera	Trevor	Manager certification services	CSA International
Poche	Snapper	Energy and Sustainability Consultant	LMI
Post	Matthew	Technician	NREL
Rivkin	Carl	Senior Engineer	NREL
Stetter	Ed	CFO	KWJ Engineering Inc.
Stetter	Josep	PRESIDENT	KWJ ENGINEERING
Voecks	Gerald	Consultant	Self
Ward	Benjamin	Senior Engineer	Makel Engineering
Weiner	Steven	Program Manager, Hydrogen Safety	Pacific Northwest National Laboratory
Wichert	Robert	Engineer / Technical Director	Fuel Cell & Hydrogen Energy Assoc.
Xiao	Zhili	Physicist & Professor	Argonne Nat Lablaboratory and NIU
Zeng	Xiaoqiao	Graduate Student	Northern Illinois University

Appendix C Hydrogen Sensor Codes and Standards

(Partial List)

ANSI/ISA–12.13.01 – Performance Requirements for Combustible Gas Detectors
www.isa.org/Template.cfm?Section=Standards8&Template=/Ecommerce/ProductDisplay.cfm&ProductID=6740

CSA C22.2, No 152 – Performance of Combustible Gas Detection Instruments
www.csa-international.org/product_areas/hazloc_equip/special_services/performance_of_combustable_gas_detection_instruments/

DOT Transport of flammable material

FM Global Class Number 6310 and 6320 – Approval Standard for Combustible Gas Detectors
www.fmglobal.com/assets/pdf/fmapprovals/6310.pdf

IEC 61508 – Functional Safety
www.iec.ch/functionalsafety/

IEEE/ASHRAE – Guide for the Ventilation and Thermal Management of Batteries for Stationary Applications
http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5399268&abstractAccess=no&userType=inst

ISO 26142:2010 – Hydrogen detection apparatus – Stationary applications

ISO 26262 – Road Vehicles – Functional Safety
www.iso.org/iso/catalogue_detail.htm?csnumber=43464

NFPA 2 – Hydrogen Technologies Code
www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=2

NFPA 52 – Vehicular Gaseous Fuel Systems Code
www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=52&cookie_test=1

OSHA 1910.146 – General Environmental Controls – Permit Required Confined Spaces
www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=9797

SAE J2579 – Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles
http://standards.sae.org/j2579_200901/

UL 2075 – Gas and Vapor Detectors and Sensors
http://ulstandardsinfonet.ul.com/scopes/2075.html

UL 2267 – Fuel Cell Power Systems for Installation in Industrial Electric Trucks
http://ulstandardsinfonet.ul.com/scopes/scopes.asp?fn=2267.html

UL 60079-15 – Electrical Apparatus for Explosive Gas Atmospheres
http://ulstandardsinfonet.ul.com/scopes/scopes.asp?fn=60079-15.html