



SURFACE VEHICLE TECHNICAL INFORMATION REPORT

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Characterization of On-Board Vehicular Hydrogen Sensors

RATIONALE

Standards (such as SAE J2578 [1], SAE J2579 [2], and ISO 23273 [3]) and regulations such as the Global Technical Regulation Number 13 (GTR) for hydrogen powered vehicles [4] provide requirements for hydrogen and fuel cell vehicles and associated hydrogen systems. While these standards and regulations do not explicitly prescribe that hydrogen sensors are to be used on-board the vehicle, vehicle manufacturers and hydrogen system integrators may chose to use hydrogen sensors as part of their process control and fault management strategies to protect occupants of the vehicle and by-standers from flammable gas hazards.

This SAE report defines tests and describes protocols that can be employed by hydrogen system integrators and vehicle manufacturers and their suppliers to evaluate the performance of hydrogen sensors under conditions likely to exist within their systems/vehicles. By so doing, the proper sensor can be selected for on-board their vehicles.

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1. SCOPE

This SAE Technical Information Report (TIR) provides test methods for evaluating hydrogen sensors when the hydrogen system integrator and/or vehicle manufacturer elect to use such devices on board their hydrogen vehicles, including hydrogen fuel cell electric vehicles (FCEV).

The tests described in 5.1 of this document are performance-based and were developed to assess hydrogen sensor metrological parameters. These tests were designed to accommodate a wide range of environmental and operating conditions based on different possible situations and sensor implementations within the vehicle. Section 5.2 covers supplemental electrical safety and physical stress tests. These are based upon standard tests developed for qualifying electrical and other components for use on vehicles and do not explicitly pertain to gas sensor metrological performance assessment. Since the use of on-board hydrogen sensors is not standardized or mandated, their implementation can vary greatly from vehicle to vehicle and among potential applications or functions. For example, an on-board sensor could be located in a relatively dry environment such as in the passenger compartment or in a “highly humidified” environment, such as within the process exhaust from the fuel cell system. As this is a guidance document and not a standard, no specific application will be identified. Also, as a guidance document, no performance specification or pass/fail criteria will be defined. For this reason, the hydrogen system integrator and/or vehicle manufacturer need to determine which tests and associated test conditions are relevant for their application(s). Thus, it is the prerogative of the hydrogen system integrator and/or vehicle manufacturer to define specific test acceptance criteria necessary to achieve the required performance of their process control and protective systems within the vehicle. The sensor manufacturer or testing laboratory is to present results of each test to the hydrogen system integrator and/or vehicle manufacturer, who will then use the results to ascertain the suitability of a sensor technology for their application.

1.1 Background

The test methods provided in this TIR were derived from methods originally developed by researchers at the NREL Hydrogen Safety Sensor Test Laboratory [5]. Many are analogous to the test procedures presented in ISO 26142 [6]. As part of the development of this TIR, the original NREL test methods were modified to be more compatible with the on-board vehicular environmental and operating conditions and accordingly are consistent with SAE component standards. The sensor test protocols in 5.1 were adapted to allow test procedures that can be performed within a more practical time period than that afforded by the methods specified in either ISO 26142 or the standard NREL sensor test protocols while maintaining rigorous data quality. Practical guidance on the implementation of the test procedures is presented in Appendices B and C.

1.1.1 Hydrogen Concentration Units

The amount of a minor constituent (MC) in a background matrix (e.g., hydrogen in air, carbon monoxide in hydrogen, salt dissolved in water) can be expressed in different ways. In liquids, the minor component is called the solute, while the background matrix is the solvent. Liquid solutions (solvent + solute) are often defined in concentration units (e.g., $\text{g}_{\text{solute}}/\text{L}_{\text{solution}}$ or $\text{moles}_{\text{solute}}/\text{L}_{\text{solution}}$, which is the definition of molarity), or as a mass fraction or mass ratio (e.g., $\text{g}_{\text{solute}}/[\text{g}_{\text{solvent}} + \text{g}_{\text{solute}}]$). Ratios are unitless. Also, depending on the amount of solute, ratios are often presented as parts per million (ppm), which is generated by multiplying the mass fraction by 10^6 (e.g., 1 μg solute in 1 g of solution would be 1 ppm) or percent which is generated by multiplying the mass fraction by 100 (e.g., a mass fraction of 0.04 would be 4%). The symbols ppm_{wt} and $\text{wt}\%$ are sometimes used to indicate that the expressed quantity is based upon a mass fraction.

Alternatively, in gas mixtures, the amount of a minor component (MC) is commonly presented as a volume ratio, $V_{MC}/(V_{MATRIX} + V_{MC})$, which from the ideal gas law is equivalent to the mole ratio ($\text{moles}_{MC}/[\text{moles}_{MATRIX} + \text{moles}_{MC}]$). Volume ratios are also often represented as percent or parts per million (ppm). To differentiate between ratios based on mass, volume ratios will sometimes be indicated as vol% or ppm_v¹. An equivalent definition of ppm_v is $\mu\text{mole}/\text{mole}$. The amount of a flammable gas is also indicated by the fraction of the lower flammable limit (LFL), which is the lowest concentration that a flammable mixture of gas or vapor in air that can be ignited. For example, the LFL of hydrogen is 4 vol%; thus, 2 vol% H₂ may be indicated as 50% LFL. This is useful because LFL varies among different gases, but regulations are often dictated by the concentration of a specific gas relative to its LFL. Table 1 indicates the preferred unit for expressing hydrogen concentrations as specified in a variety of sources. The term lower explosion unit (LEL) is often used as synonymous with the LFL, although this is not correct, since there are distinctions between flammability and an explosion and thus the corresponding LEL and LFL for a specific gas [7] [8].

In this document, unless noted otherwise, the amount of hydrogen or other minor components in a gas mixture will be indicated as either vol% or ppm_v. The background matrix will be air unless otherwise indicated. Also, the testing laboratory is to report sensor test results in a numerical format equivalent to vol% H₂. See Appendix A for details on data analysis and reporting of test results.

Table 1 - Preferred hydrogen concentration units

Source	Preferred Unit
ISO 26142	Volume Fraction
GTR 13	vol% (as percent)
SAE J2719	ppm _v (as $\mu\text{mole}/\text{mole}$)
International Journal of Hydrogen Energy	vol% (as percent)
Commercial Combustible Gas Analyzers (typical)	% LFL (or % LEL)

1.1.2 Description of a Hydrogen Sensor

There are numerous definitions for chemical or physical sensors. One definition is as follows: A sensor is a small device that, as the result of an interaction or process between a chemical or physical stimulus and the sensor device, transforms chemical or physical information of a quantitative or qualitative type into an analytically useful signal [9]. A hydrogen sensor is the special case where the target stimulus is hydrogen. There is, however, no universally accepted definition of a chemical sensor, and the concept of what constitutes a chemical sensor varies considerably in the literature. Accordingly, some clarification will be provided as to the meaning of “hydrogen sensor” as it pertains to this TIR and the needs of the hydrogen system integrator and/or vehicle manufacturer.

Figure 1 illustrates the functional design of a “sensor” as the term is used within this TIR. A sensor consists of several components. The sensing element is the component that performs the basic sensing operation and provides a measurable, continuously changing electrical signal in correlation to the presence or magnitude of the stimulus, such as the amount of hydrogen. The sensing element can include a receptor and one or more transducer elements. The receptor is the site of interaction with the stimulus. For chemical sensing elements, the receptor is the site of the chemical interaction, which is then converted by the transducer into an analytical quantity that is usually electrical in nature. Thus, two distinct functions are associated with the sensing element; it is the site for the interaction of the stimulus at the receptor and the generation of electrical signal by the (electrical) transducer. The transducer and receptor may be the same physical component within the sensing element. Sensing elements based on different transduction mechanisms are commercially available for the detection of hydrogen.

¹ Mass ratios are not directly converted into volume ratios. For example, if the solute in 1 L of a 1 ppm_w solution of dissolved hydrogen was volatilized into 1 L of air, the room temperature hydrogen composition would be about 12000 ppm_v.

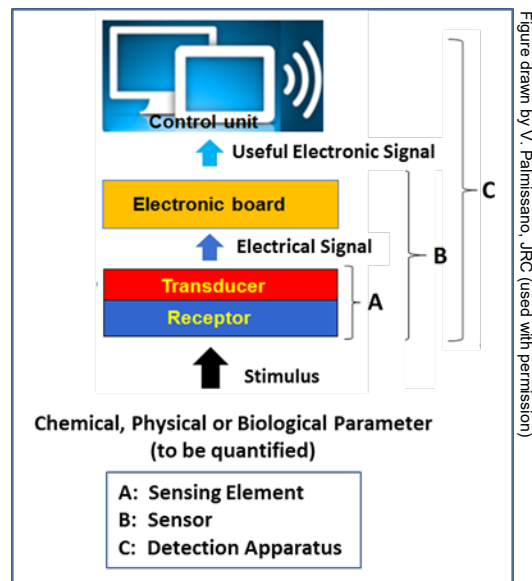


Figure 1 - Distinction between a sensing element, a sensor, and a detection apparatus. This TIR pertains to the evaluation of sensors for vehicle applications.

Although related to the magnitude of the stimulus, the sensing element's electrical signal is often of an arbitrary magnitude with a low-output impedance to render it easily corrupted. Thus, additional circuitry is typically required to produce a usable electrical signal. As illustrated in Figure 1, a sensor is the integration of the sensing element and appropriate control circuitry to transduce a raw electrical response into a useful signal via electronic buffering, amplification, or transduction into more conveniently measurable electrical responses (e.g., a current-to-voltage transduction). This supplemental circuitry can also control sensor operation such as to maintain the operating temperature for heated sensors or the operating potential for electrochemical sensors. Multiple sensing elements that respond to different target stimuli can be incorporated into a sensor. For example, there may be sensing elements that can be used to independently measure environmental parameters such as the temperature (T), pressure (P), and relative humidity (RH) within a chemical sensor.

Although some international standards (e.g., ISO 26142 [6]) explicitly distinguish between the sensing element and sensor, the term "sensing element" is not commonly used in the scientific, engineering, and commercial literature. Instead, the term sensor is often used to refer to either a sensing element or a sensor, or even a detection apparatus (as defined above). Sensing elements and sensors as illustrated in Figure 1 are commercially available for the detection and quantitation of hydrogen. However, the use of sensing elements will require development of electrical circuitry by the end-user to get a useful signal, while a sensor will only need electrical power. Table 2 lists the major sensing element types that are commonly available for the detection of hydrogen along with a brief description of the transduction mechanism and the nature of the electrical signal. Sometimes the term "sensor platform" is used to indicate the sensing element type. More details on the different sensor platforms developed for the detection of hydrogen can be found in Hübert et al [10].

The electrical output of a sensor can be integrated into a detector apparatus. Other terms used for the detection apparatus are "instrument" or "instrument system," "control unit," and "analyzer." The detector apparatus can also be the integration of the sensor with an on-board microprocessor. A detection apparatus utilizes the sensor response to perform functions such as warning and alarm activation, implement corrective measures such as increased ventilation, shutoff or isolation of the fuel supply or even system shutdown, and display of prevailing conditions such as concentration of hydrogen in the surrounding environment. However, there is no formal definition as to what distinguishes a sensing element, sensor, or control system from each other. The working definition for a "hydrogen sensor" within the context of this document will be a device that outputs a signal that is either directly related to the amount of hydrogen in a test gas or is easily transformed to the amount of hydrogen through the use of a calibration expression.

Table 2 - Common sensor platforms used for the detection of hydrogen

Sensor Type	Abbreviation	Transduction Mechanism	Electrical Signal
Thermal Conductivity Sensor	TC	Heat transfer from a sensing element	Change of resistance (ΔR)
Combustible Gas Sensor (Catalytic Bead Sensor)	CGS	Heat generated from flammable gas	Change of resistance (ΔR)
Electrochemical	EC	Faradaic oxidation of hydrogen	Generation of current (ΔI)
Metal Oxide (High T)	MOX	Electron transfer to conduction band	Change of resistance (ΔR)
Palladium Thin Film	PTF	Selective absorption of hydrogen into the Pd	Platform dependent: ΔR for resistive films ΔHZ for mass-based ΔI for semiconductor

1.1.3 Sensor Output in Response to Hydrogen

The response of a hydrogen sensor is typically a change in electrical signal (current, voltage, or frequency change) in response to a change in the concentration of hydrogen in the environment surrounding the sensor. The electrical signal of a hydrogen sensor can be expressed in a variety of formats. Many sensors have an analog output that is pre-calibrated to hydrogen. Common types of calibrated analog outputs are 4 to 20 mA, or 0 to 5 V that are assumed to be linear over a specified range (e.g., 0 to 2 vol% H_2 , or 0 to 4 vol% H_2). Figure 2(A) illustrates the response to 1 vol% H_2 for a sensor with a 4 to 20 mA output with a measuring range of 0 to 4 vol% H_2 , while Figure 2(B) shows the conversion of the sensor output to vol% H_2 using the linear transformation derived from this relationship. There are also hydrogen sensors whose output signal is in units of vol% or other common concentration units (e.g., ppm_v or % LFL). Typically, these will be sensors with a digital output, such as CAN (Controller Area Network). Such sensors typically cannot be recalibrated by the end-user, but end-users should confirm sensor accuracy, such as through performing the measuring range test described in 5.1.2.

A sensor signal depends on the magnitude and time profile of the stimulus. A standard method to evaluate a hydrogen sensor performance is to measure the sensor signal in response to what is often represented as a step-change in the hydrogen concentration. Typically, this is performed with other parameters (e.g., T, P, and RH) defined. In this idealized exposure profile, the normalized input stimulus (e.g., hydrogen) is given by:

$$[H_2] = 0 \text{ for } t < t_{H_2-ON}$$

$$[H_2] = 1 \text{ for } t > t_{H_2-ON} \text{ and } t < t_{H_2-OFF}$$

$$[H_2] = 0 \text{ for } t > t_{H_2-OFF}$$

In the above expressions, t refers to the test time, starting at time zero, while t_{H_2-ON} is the time at which the test gas is applied or injected into the test fixture and t_{H_2-OFF} is the time at which the test is removed from the test fixture. This test protocol is illustrated in Figure 2. The sensor response profile consists of several empirically observed regions [10] associated with the hydrogen exposure. There is a dead time (t_{dead}), which is associated with the time required for the hydrogen to reach the sensing element following the establishment of the hydrogen concentration setpoint in the test apparatus and is controlled by the pneumatic design of the test fixture. The dead time does not contribute to the fundamental sensor response time. However, in a properly designed test apparatus, t_{dead} can be negligible. There is also the delay time (t_{delay}) which is the time following actual test gas exposure to the sensor and the observation of a sensor response. Following the delay time, the signal rises in response to the hydrogen (the adjustment time, t_a) and then levels off to a time-invariant response. As illustrated in Figure 2, the response for a well-behaved sensor will reach or approach a time-invariant (steady-state) output for a fixed hydrogen concentration, the magnitude of which has been termed the “final indication” (F.I.) of the sensor. The F.I. is the analytical response of the sensor that is most often correlated hydrogen concentration.

Signal noise and drift are associated with every real sensor response. Thus, criteria for verifying that a sensor signal has reached an appropriate time invariant state have to be defined. It is typically based upon defining an acceptable change in the sensor response over a prescribed period. For those applications where the hydrogen level is normally zero, the time-invariant response can be defined as when the sensor response to a constant hydrogen concentration does not change more than 5% of reading over one minute, which is consistent with the definition provided in international standards (e.g., ISO 26142 [6]); a more stringent requirement may be imposed by the hydrogen system integrator and/or vehicle manufacturer for certain applications where real-time accuracy is necessary.

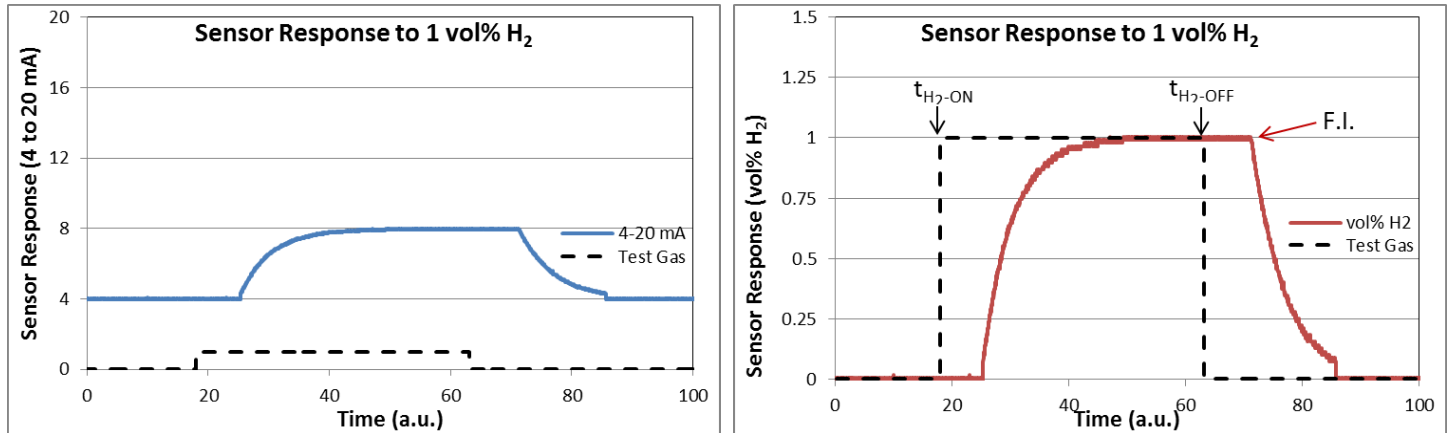


Figure 2 - (Left): Response to a 1 vol% H₂ exposure for a hydrogen sensor with a 4 to 20 mA output and a measuring range of 0 to 4 vol% H₂. (Right): Transformation of the mA output into vol% H₂. Also indicated are t_{H_2-ON} and t_{H_2-OFF} for the hydrogen exposure and the F.I. of the sensor response. Time is in arbitrary units.

The imposition of a change in the test gas composition is often depicted as a step change, as described above and illustrated in Figure 2 (the dashed lines). Such an ideal step change in the test gas composition is not possible, although it can be approximated with some test apparatus designs (e.g., a flow-through apparatus, such as that described in Appendix C). However, an instantaneous change in test gas composition is not required to evaluate the sensor performance as per the protocols presented in 5.1. There will always be a lag time between the establishment of the apparatus control parameters to a new test gas set point and actually supplying the desired composition at the sensor. This effect is illustrated in Figure 3. The lag time will vary with apparatus design. In 5.1, the test protocols are presented as a series of discrete steps in which test conditions (e.g., test gas composition, temperature, humidity, pressure, orientation, or other parameters) are defined. The step changes in the protocol figures in 5.1 are not meant to imply an instantaneous adjustment of the test gas composition at the sensor, but rather to define the adjustment to a new gas composition set point, and, although not explicitly indicated in the protocol figures, there will be a stabilization time for the test gas composition at the sensor to reach the new set point. The stabilization time to achieve the gas composition set point at the sensor is not explicitly defined in the protocol because it will vary with apparatus design and operational parameters. It is not necessary to explicitly define this stabilization time. Rather, the protocols require that each step be sufficiently long to allow the test sensor to reach a stable final indication, which can only occur when the test gas exposed to the sensor is invariant in composition.

A step-change in gas composition can be approximated, however, if the pneumatic system of the test apparatus can be quickly purged. This can be achieved with a flow-through apparatus (see C.2.2), providing the apparatus is designed with fast valves or mass flow controllers to quickly adjust the incoming test gas composition to the desired set point and small internal gas volume, coupled with a high gas flow rate to minimize the purge time of the pneumatic system. Only the response time determination requires that the test gas composition be changed quickly (see 5.1.1 and 5.1.10). The actual apparent (observed) sensor response time will be a convolution of the fundamental sensor response kinetics and the purge time of the gas that is exposed to the sensor. A good approximation for the fundamental sensor response time may be achieved in a flow-through system with a fast purge time. Alternatively, in a chamber test apparatus, the kinetics of the sensor response will often be dominated by gas purge time of the chamber. As a result, chamber methods should not be used for the determination of the sensor response time but are very useful for measuring the sensor concentration dependence and stability, as well as to quantify the impact of environmental parameters (e.g., T, P, RH, and orientation) on sensor performance.

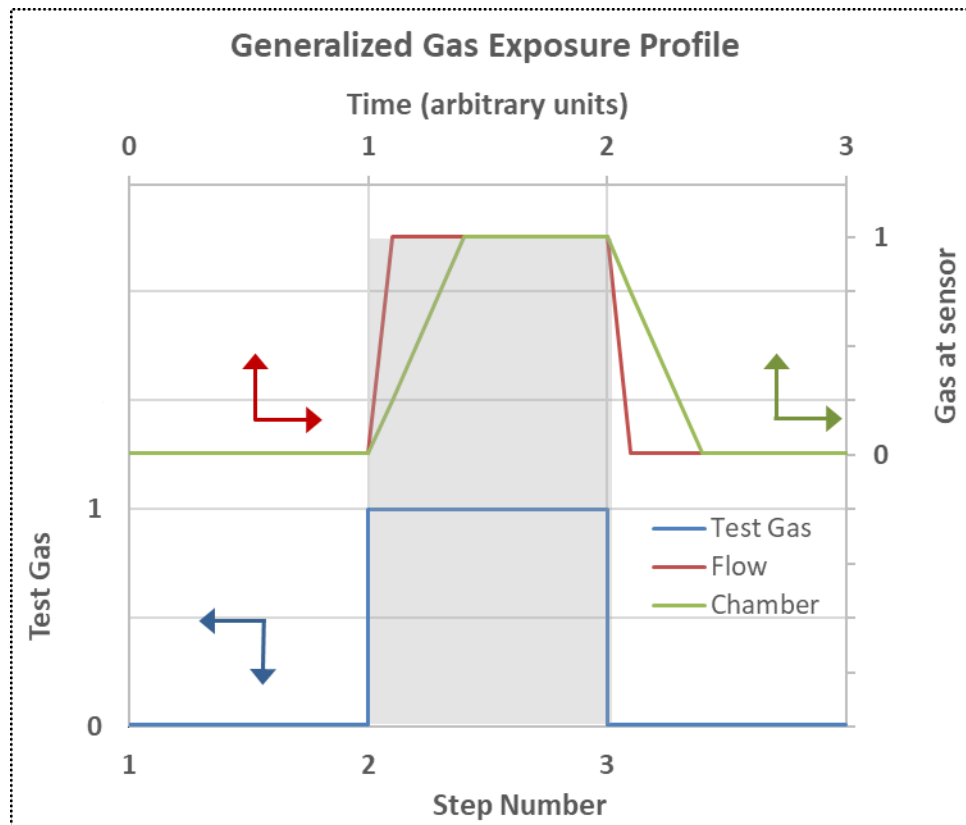


Figure 3 - Sensor test protocols are often illustrated as a series of steps presented as a step change in the test gas composition (blue trace). The blue trace represents the change in the test gas composition set point. The actual test gas composition exposed to the sensor will have a characteristic stabilization time following adjustment of the set point, which will depend upon apparatus design (e.g., chamber versus flow through). Accordingly, it is specified in the TIR test protocols (see 5.1) that the step duration be sufficiently long for the sensor to achieve a stable final indication.

The output of most hydrogen sensors is an electrical signal that continuously changes over the sensor measurement range in response to changes in the magnitude of the hydrogen. In other words, the F.I. of the sensor is a function of the hydrogen concentration. With appropriate electronics and with calibration, the electrical signal can be used to determine the hydrogen concentration; the calibration is typically performed by the manufacturer. Test protocols for performance assessment of sensors with an electric signal that varies with hydrogen concentration are presented in 5.1. Alternatively, the response of some sensors may only provide information pertaining to whether the hydrogen is present above some threshold value. The threshold value is typically set by the manufacturer. This sensor type shall be referred to as an "indicator" or "indicator sensor." The response of an indicator sensor can be either visual (e.g., a colorimetric indicator) or electrical. Indicator sensors typically have only two output states: corresponding to low when the hydrogen level is below a threshold value, and high for when the hydrogen level is above a threshold value. While colorimetric indicators are commercially available for hydrogen, reliable electronic indicator sensors are currently not very common. Indicator sensors require different test protocols for evaluation than sensors with a continuously varying output; the TIR will be updated should commercial indicator sensors become commonly available.

1.2 Purpose

The purpose of this document is to align the terminology, to define a common set of tests that can be used to evaluate hydrogen sensors, and to encourage the development of sensors suitable for on-board vehicular applications.

1.2.1 Field of Application

This document is applicable to sensors for the detection of hydrogen in hydrogen-powered fuel cell electric vehicles or vehicles powered by hydrogen internal combustion engines (ICEs).

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of these documents shall apply.

2.1.1 SAE Publications

SAE standards and documents are available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org. Applicable Federal Motor Vehicle Safety Standards (FMVSS) and regulations should supersede any SAE recommended practices as described in this document.

SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety [1]

SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles [2]

2.1.2 Other Publications

ISO 23273 Fuel Cell Road Vehicles - Safety Specifications: Protection Against Hydrogen Hazards for Vehicles Fuelled with Compressed Hydrogen [3]

Global Technical Regulation No. 13. Global technical regulation on hydrogen and fuel cell vehicles, established in the global registry on 27 June 2013. [4].

2.2 Related Publications

The following publications are provided for information purposes only and are not an required part of this SAE Technical Report.

ISO 15916 Basic Considerations for the Safety of Hydrogen Systems [7]

ISO 16750-3-4.1 Road Vehicles - Environmental Conditions and Testing for Electrical and Electronic Equipment - Part 3: Mechanical Loads [15]

ISO 16750-4-5.1.1

ISO 16750-4-5.1.2

ISO 16750-4-5.3.2 Road Vehicles - Environmental Conditions and Testing for Electrical and Electronic Equipment - Part 4: Climatic Loads [12]

ISO 26142 Hydrogen Detectors for Stationary Applications [6]

"Standard Hydrogen Test Protocols for the NREL Sensor Testing Laboratory," *National Renewable Energy Laboratory (NREL)*, December 2011, <https://www.nrel.gov/docs/fy12osti/53079.pdf>. [5]

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3. DEFINITIONS

Standard fuel cell vehicle (FCV) terminology is provided in SAE J2574. Terminology specific to this document is contained in this section. Further details on these definitions can be found in the literature [10].

ACCURACY: The closeness of agreement between a test result and the accepted reference value. For chemical sensors, accuracy compares the sensor final indication with the nominal (accepted) concentration of the analyte.

BASELINE: Sensor response at the reference stimulus, which for hydrogen sensors is typically 0 vol% H₂. This can also be termed “offset.”

CROSS SENSITIVITY: The sensitivity of a sensor generated from stimuli other than the intended use for sensing (e.g., interfering gases).

DRIFT: Gradual change of the sensor output signal, under conditions where the input stimulus is constant. Drift in hydrogen sensors manifests itself as an apparent change in concentration per unit time and is associated with a change in baseline (baseline drift) or degree of response to hydrogen change (change in sensitivity).

ENVIRONMENTAL EFFECT: A change in the sensor signal induced by a change in an environmental parameter, such as pressure (barometric pressure), temperature, or relative humidity. If uncompensated, such changes may be misinterpreted as a change in hydrogen concentration.

FALSE NEGATIVE ALARM: A situation where a sensor does not activate an alarm even though the stimulus (e.g., hydrogen) is present at levels above the alarm threshold concentration. Exposure of the sensor to poisons or interferents can contribute to false negative alarms.

FALSE POSITIVE ALARM: A situation where a sensor activates an alarm even though the stimulus (e.g., hydrogen) is present below the alarm threshold concentration. The presence of interferents can contribute to false positive alarms.

FINAL INDICATION (F.I.): Indication given by the sensor after stabilization under defined test conditions, typically a steady-state value obtained under a time-invariant stimulus.

HYDROGEN SENSING ELEMENT: Component that provides a continuously changing electrical quantity in correlation to the surrounding hydrogen volume fraction [6].

HYDROGEN SENSOR: Assembly, which contains one or more hydrogen sensing elements and may also contain electronic circuit components associated with the hydrogen sensing elements, that provides a continuously changing electrical signal in correlation to the physical quantity provided by the hydrogen sensing element(s) [6].

HYSTERESIS: The dependence of sensor indication on whether the condition is approached from above or below the value of interest.

INTERFERENT: Any stimulus, chemical or physical, other than the target stimuli, that reversibly affects the sensor indication (in contrast, see Poison).

LIMIT OF QUANTITATION: Smallest value of the target stimulus which can be quantitatively determined. In many cases, the limit of quantitation is set as 9 times the standard deviation of the background signal added to the background signal.

LINEAR RANGE: The range over which the sensor F.I. is proportional to the change in value of the target stimulus (e.g., hydrogen concentration). The output can be represented by the following equation:

Concentration = (Signal × Sensitivity).

LOWER DETECTION LIMIT (LDL): The smallest value which can be reliably detected by a sensor; frequently calculated as twice the standard deviation of the background signal added to the background signal. Also called “limit of detection” (LOD). (Some users incorrectly use LDL synonymously with limit of quantitation.)

MEASURING RANGE: Range of sensor output values defined by the two extreme values between which a parameter can be measured within a specified accuracy. May also be termed measuring interval.

MECHANICAL STABILITY: Durability against mechanical vibrations and shock.

NOISE: A random fluctuation in sensor signal.

OPERATING RANGE: Upper and lower temperature, pressure, and humidity environments in which the sensor can be used.

OPERATIONAL LIFETIME: The expected useful life of the sensor under normal operating conditions.

POISON: A stimulus which produces a permanent or slowly recovering negative impact on the ability of the sensor to perform its designated function.

POWER REQUIREMENT: The voltage and current requirements to operate the sensor and its control circuitry.

RECOVERY TIME: The time for a sensor to adjust to the baseline after exposure to the stimulus. For sensors that reach well-defined steady-state signals, it is often calculated as the time to reach a certain fraction of the former response (e.g., 10% of the previous final indication; t_{10}).

RESPONSE TIME: The time for a sensor signal to adjust during exposure to the stimulus. For sensors that reach well-defined steady-state signals, it is calculated as the time to reach a certain fraction of the response (e.g., 90% of the final indication; t_{90}).

REVERSIBILITY: The ability of the sensor to recover to baseline following an exposure to the stimulus (also called “recovery”).

SATURATION: A condition such that a further increase in magnitude of the target stimulus does not produce a measurable change of sensor output.

SATURATION STABILITY: The ability of the sensor to provide quantitative information regarding the stimulus within the specified measuring range of the device following a brief exposure to the stimulus of magnitude in excess of the specified range. For a hydrogen sensor, this could be exposure to pure hydrogen. 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 other user-defined concentration following a brief exposure to pure hydrogen.

SELECTIVITY: Robustness of a sensor to not respond to stimuli other than the target stimulus.

SENSITIVITY: Ratio of the change of the sensor signal to the change in the stimulus (or, more formally, the first derivative of the calibration function). It is the ratio of the electronic response of a sensor or instrument to the amount of an analyte and has units of concentration/electronic-signal. In a linear system the sensitivity is a constant equal to the slope of the calibration curve. For non-linear systems, sensitivity will vary with concentration, typically decreasing with higher concentrations. (The term sensitivity is frequently, but improperly, used as a synonym for LDL.)

TIR: Technical Information Report.

UNCERTAINTY: The closeness of agreement between independent test results obtained under stipulated conditions.

vol% H₂: The ratio of the volume of hydrogen in a gas mixture to the total gas volume multiplied by 100. Based on the Ideal Gas Law, the vol% is equivalent to mole%. vol% H₂ is the preferred concentration unit to report the amount of hydrogen detected by sensors evaluated by this TIR.

(vol% H₂)_{EQ}: The change in the readout of a hydrogen sensor induced by stimuli other than hydrogen (e.g., temperature, chemical interferents, drift due to age). It is also used to quantify a non-zero baseline sensor response in the absence of the target stimulus.

WARM-UP TIME: The time required for a sensor to produce output signals of acceptable accuracy upon powering up.

ZERO LEVEL: An electronic adjustment point such that the sensor provides a null indication corresponding to a zero value of a quantity to be measured.

4. SYMBOLS AND ABBREVIATIONS

Ar	Chemical formula for argon
a.u.	Arbitrary units
atm	Atmosphere (unit of pressure)
CAN	Controller Area Network
CGS	Combustible gas sensor
CH ₄	Chemical formula for methane
C ₃ H ₈	Chemical formula for propane
C ₄ H ₁₀	Chemical formula for butane
CH ₄ O	Chemical formula for methanol
C ₂ H ₆ O	Chemical formula for ethanol
CO	Chemical formula for carbon monoxide
CO ₂	Chemical formula for carbon dioxide
DAQ	Data Acquisition System
DP	Dew point
EC	Electrochemical (a sensor platform)
FCEV	Fuel cell electric vehicle
FCV	Fuel cell vehicle
F.I.	Final indication, the steady state response of a sensor in response to a fixed-value stimulus
FP	Frost point
FR	Flow rate
FMVSS	Federal Motor Vehicle Safety Standard
g	Gram
GTR	Global Technical Regulation
GTR 13	Global Technical Regulation #13

h	Hour
H ₂	Chemical formula for hydrogen
H ₂ S	Chemical formula for hydrogen sulfide
HMDS	Hexamethyldisiloxane
Hz	Hertz
ICE	Internal combustion engine
IEC	International electrotechnical commission
ISO	International Standards Organization
JRC	Joint Research Centre
kPa	Kilopascal (1 atm = 101.325 kPa)
LEL	Lower explosion limit
LFL	Lower flammable limit
mA	Milliampere
MC	Minor constituent in a mixture or solution
MFC	Mass flow controller
MFM	Mass flow meter
min	Minute
MOX	Metal oxide (a sensor platform)
NFPA	National Fire Protection Association
NH ₃	Chemical formula for ammonia
N ₂	Chemical formula for nitrogen
NO ₂	Chemical formula for nitrogen dioxide
NREL	National Renewable Energy Laboratory
O ₂	Chemical formula for oxygen
P	Pressure
PEL	Permissible exposure limit
ppm _v	Parts per million by volume
ppm _{wt}	Parts per million by weight
Pr#	Pressure release device (in test apparatus)
PSD	Power spectral density function

PTF	Palladium thin film (a sensor platform)
R	Resistance, usually in units of ohms (Ω)
RH	Relative humidity by fraction
% RH	Relative humidity as a percent
rms	Root mean square
s	Seconds
SO ₂	Chemical formula for sulfur dioxide
S.R.	Sensor Response
sccm	Standard cubic centimeters per minute
SLPM	Standard liters per minute
T	Temperature
T _{max}	The maximum temperature setpoint in the Thermal Stress Test
T _{min}	The minimum temperature setpoint in the Thermal Shock Test
t	Time
t ₁₀	Recovery time to 10% of the initial baseline
t ₉₀	Response time to 90% of the final indication
TC	Thermo-conductivity (a sensor platform)
TIR	Technical Information Report
TWA	Time-weighted average
U.S.	United States
V	Volume
vol%	Volume percent
wt%	Weight percent

5. GUIDANCE FOR THE EVALUATION OF ON-BOARD HYDROGEN SENSORS

Suggested test methods for the general metrological characterization of on-board hydrogen sensors are provided in 5.1 (5.1.1 through 5.1.11). Section 5.2 provides suggested physical stress and electrical safety tests, which are based upon qualification tests frequently performed on other vehicle components. Each test protocol includes introductory text providing the rationale for the test and the specific sensor performance metrics that can be extracted from the test results.

Since the use of on-board hydrogen sensors is not standardized and therefore can vary greatly from vehicle to vehicle, the hydrogen system integrator and/or vehicle manufacturer needs to determine which tests are relevant to the application of interest in their systems and/or vehicles. Accordingly, specific test conditions prescribed in 5.1 and 5.2 may be modified to accommodate the hydrogen system integrator and/or vehicle manufacturer requirements. Furthermore, a specific test may be omitted or additional tests may be added at the discretion of the hydrogen system integrator and/or vehicle manufacturer.

Guidance for the analysis of data and reporting of results is presented in Appendix A. Suggestions for generating test gas standards is given in Appendix B, while Appendix C provides guidance on the general design and operation of test fixtures for hydrogen sensor evaluations.

5.1 Test Methods for Evaluating On-Board Hydrogen Sensors - General Test Methods

The following tests have been designed to quantify metrological performance of on-board hydrogen sensors:

- 5.1.1 Sensor Kinetics and Validation Test (Initial Validation)
- 5.1.2 Measuring Range/Accuracy of Response
- 5.1.3 Short-Term Stability/Repeatability Test
- 5.1.4 Pressure Dependence Test
- 5.1.5 Temperature Dependence Test
- 5.1.6 Humidity Dependence Test
- 5.1.7 Operation Above the Measuring Range Test
- 5.1.8 Orientation Effect Test
- 5.1.9 Sensor Power Tests
 - 5.1.9.1 Cold Power-Up
 - 5.1.9.2 Over- and Under-Power Test
- 5.1.10 Sensor Kinetics and Validation Test (Final Validation)
- 5.1.11 Chemical Stress Test - Impact of Chemical Interferents and Chemical Poisons
 - 5.1.11.1 Impact of Chemical Interferents (Cross Sensitivity)
 - 5.1.11.2 Impact of Chemical Poisons

For each test, the sensor response, test gas concentration, and other parameters including test temperature, pressure, and humidity level are to be logged in an electronic data file for analysis and record keeping. The time between measurement points (logging frequency) is up to the test laboratory, but should allow for statistical analysis of data; a rate of between 1 point/s and 10 points/s is adequate for most purposes, except possibly for kinetic analysis (e.g., response time; see 5.1.1), which may require faster logging rates so as to accurately measure fast transients.

Each test protocol consists of a number of steps in which conditions such as hydrogen concentration or ambient parameters (T, P, and RH) are varied from step to step. The duration of each step in an individual test is up to the test laboratory, but should be sufficiently long (e.g., 10 minutes if using a well-designed flow-through apparatus, see Appendix C) so as to achieve a stable sensor final indication for a defined set of test conditions.

It is specified that the test protocol start with the test described in 5.1.1 and to then perform the other tests which have been selected by the hydrogen system integrator and/or vehicle manufacturer. The 5.1.10 test is to be performed following test 5.1.9 to verify that the sensor was not adversely affected by the test protocols prescribed in 5.1.1 through 5.1.9. The tests in 5.1.11.1 and 5.1.11.2, and the tests in 5.2.1 through 5.2.5 may be performed using sensors other than those used in tests 5.1.1 through 5.1.10.

Test conditions described in 5.1.1 through 5.1.11 are based on environmental and operating conditions defined in SAE J2578 [1] and were selected to provide guidance on how the tests should be conducted. The hydrogen system integrator and/or vehicle manufacturer should review these recommended standard test conditions and may make adjustments as necessary to these values so that the planned tests are consistent with the use in their system and vehicle conditions.

Specialized sensor test fixtures and equipment are required to conduct the tests so that environmental parameters such as T, P, RH, and gas composition can be accurately controlled and monitored. Appendix C provides guidance on the design and operation of hydrogen sensor test fixtures. Nominal test conditions are to adhere to the following specifications:

1. "Air" shall be defined as a mixture of oxygen ($20.9 \text{ vol\% O}_2 \pm 1 \text{ vol\% O}_2$), argon ($0.9 \text{ vol\% Ar} \pm 0.1 \text{ vol\% Ar}$) with a balance of nitrogen (nominal $78.2 \text{ vol\% N}_2$). Alternatively, cylinders of "synthetic air" comprised of $20.9 \text{ vol\% O}_2 \pm 2 \text{ vol\% O}_2$ with a balance of nitrogen can be used, providing it can be shown that the lack of normal air constituents (argon, carbon dioxide) and minor variations in oxygen content do not impact the sensor performance. For example, thermo-conductivity sensors can be sensitive to the composition of the background gas such that an error may result if the sensor is calibrated in "synthetic" air (e.g., without argon) and operated in a real atmosphere.
2. Hydrogen test gas concentrations are to be generated using certified gas mixtures, such as pressurized cylinders from commercial suppliers that are within $\pm 5\%$ of the nominal concentration specified in the protocol (e.g., a gas cylinder for $2.5 \text{ vol\% H}_2$ may have a nominal listed concentration between $2.625 \text{ vol\% H}_2$ and $2.375 \text{ vol\% H}_2$), but the actual hydrogen concentration is to be certified by the gas provider to within $\pm 1\%$ of the stated nominal concentration (e.g., a gas cylinder containing a stated nominal concentration of $2.5 \text{ vol\% H}_2$ shall have a certified concentration between $2.525 \text{ vol\% H}_2$ and $2.475 \text{ vol\% H}_2$). The concentration accuracy of test gas mixtures generated by blending 100% hydrogen gas with air are to be verified on a regular basis. The verification can be through a comparison of the sensor responses to a certified cylinder gas of known composition (e.g., $0.5 \text{ vol\%}$, $1 \text{ vol\%}$), or by an alternative means involving direct gas composition analysis using methods based upon mass spectrometry or gas chromatography. If alternative analytical methods are used to verify the accuracy of gas generation system, the test laboratory must provide test procedures, including instrument calibration protocols, and data for this verification.
3. If the test gas concentrations prescribed in the test protocol are generated from pure hydrogen, the hydrogen should be certified to 99.99% purity.
4. The minimum recommended hydrogen concentration range is $0 \text{ vol\% H}_2$ to $4.0 \text{ vol\% H}_2$ in air, but can be adjusted based upon the measuring range of the sensor as specified by the manufacturer and with the agreement of the hydrogen system integrator and/or vehicle manufacturer.
5. The temperature tolerance is to be within $\pm 5^\circ\text{C}$ of the nominal temperature set point.
6. The test humidity is to be within $50 \text{ \%RH} \pm 25 \text{ \%RH}$, unless the test protocol specifies that the RH be above or below a specified set point (e.g., dry $\{< 5 \text{ \%RH}\}$ or $> 90 \text{ \%RH}$), in which case the humidity must meet the conditional requirements. However, during a test, the relative humidity shall be maintained to within $\pm 10 \text{ \%RH}$. Humidity can be reported as RH, $\text{\%RH}$, or dew point/frost point. If the humidity is reported as RH or $\text{\%RH}$, the temperature must be specified and reported.
7. The pressure tolerance is to be within typically $\pm 0.05 \text{ atm}$ of the nominal pressure set point.
8. All sensors under evaluation shall have a signal that is in $\text{vol\% H}_2$ or as $(\text{vol\% H}_2)_{\text{eq}}$ or other concentration units readily converted to $\text{vol\% H}_2$, or an analog signal in electrical units (e.g., V, mA) that is readily transformed to hydrogen concentration using a manufacturer-supplied calibration expression.

Actual values for flow, T, P, and humidity are to be independently verified with sensors calibrated using methods traceable to national or international metrology institutes.

In each of the described tests, the sensors under evaluation are to be warmed up and operated according to the manufacturer specifications. The tests are to be adapted to be within the measuring range of the sensor.

An example of a gas exposure sequence is presented for each of the described tests (see Figures 4 through 18). The test laboratory may use an alternative gas exposure sequence if agreed upon by the system integrator and/or vehicle manufacturer. Examples of different gas exposure sequences for some test protocols are given in Appendix D. The evaluation protocols presented in 5.1 are presented as a series of discrete steps, in which the change in test gas composition set point is presented as a step-change. As discussed in 1.1.3, this step change represents only the test gas composition set point and does not refer to the temporal behavior of the test gas composition at the sensor. As illustrated in Figure 3, there will be a lag time between the establishment of the test gas composition set point and introducing gas with the new composition at the sensor. This lag time will vary with sensor test apparatus design. Thus, in 5.1, the duration of each step of a test procedure is prescribed to be sufficiently long to allow the test sensor to reach a stable final indication.

The number of sensors that are to be subjected to the test protocols prescribed in 5.1 shall be established by the hydrogen system integrator and/or vehicle manufacturer. The sensor manufacturer or test laboratory may also determine the number of test sensors, predicted upon approval from the vehicle manufacturer or hydrogen system integrator.

5.1.1 Sensor Kinetics and Validation Test (Initial Validation)

The Sensor Kinetics and Validation Test was designed for both the determination of the sensor response and recovery times (i.e., sensor kinetics) and as an independent verification of the test gas generation system. Many of the tests described in 5.1.2 through 5.1.9 require hydrogen test gas at levels greater than 2.5 vol% in air. It is often necessary to generate specific test gas concentrations on-site at the test facility because gas cylinders of hydrogen-air mixtures above 2.5 vol% cannot be commercially obtained in the United States. On-site generation of hydrogen test gases typically involves the mixing of pure hydrogen or other elevated concentrations with air to generate the desired concentration. Appendix B describes methods to do this. To validate the test gas generation system, it is recommended that the Sensor Kinetics and Validation Test be performed using a test gas demonstrated to contain 1 vol% H₂ in air or other hydrogen concentration specified by the hydrogen system integrator and/or vehicle manufacturer. The 1 vol% H₂ in air validation gas is best obtained from a gas cylinder with a certified concentration of 1 vol%. However, the 1 vol% H₂ validation gas may also be obtained from the test gas generation system, but with this gas concentration verified by an independent gas analysis, such as with a calibrated mass spectrometer or gas chromatograph. The sensor response to the validation gas of 1 vol% H₂ is compared to the sensor response to 1 vol% H₂ test gas as obtained for the test in 5.1.2. See A.2 for guidance.

The Sensor Kinetics and Validation Test (Initial Validation) subjects the hydrogen sensors to the three-step exposure sequence illustrated in Figure 4. The sensors are first exposed to air, followed by an exposure to 1 vol% H₂. The sensors are then allowed to recover in air following the hydrogen exposure step. The duration of each step is to be sufficiently long to allow the sensor to reach a stable, steady-state response (e.g., the F.I.). A constant fixed time for each step (e.g., 1 minute or 10 minutes) is allowed providing it is of sufficient duration to allow the sensor to reach a proper final indication.

The Sensor Kinetics and Validation Test is to be performed under the following conditions unless modified by the hydrogen system integrator and/or vehicle manufacturer:

- Required Test Gases: 1 vol% H₂ in air, air.
 - It is recommended that the hydrogen test gas is to be obtained from a gas cylinder at the designated concentration and is to be used without dilution or blending with other gas sources.
 - If the test gas is not obtained from a gas cylinder with a certified gas concentration, an alternative means to verify the test gas concentration from the gas generation system shall be used. Such alternative means include, but are not limited to, methods based upon mass spectrometry and gas chromatography with validated calibration curves for hydrogen analysis.
- Temperature (T): 25 °C ± 5 °C.
- Pressure (P): 1.0 atm ± 0.05 atm.
- Relative Humidity (%RH): The humidity shall be within the range of 25 to 75 %RH, but maintained to within ±10 %RH during the test.
- Data logging frequency of 1 point/s or faster. The logging frequency shall be at least a factor of five times greater than the sensor response time.

The hydrogen system integrator and/or vehicle manufacturer may adjust the above values so that the test conditions are consistent with the intended use in their system and vehicle conditions. The sensor supplier or test laboratory may recommend adjustment to the test conditions, but the implementation of any change must be approved by the hydrogen system integrator and/or vehicle manufacturer. Actual values for flow, T, P, and humidity are to be independently verified with sensors calibrated using methods traceable to national or international metrology institutes.

No adjustment to the sensor electronics (e.g., calibration) is allowed following the Sensor Kinetics and Validation Test for performing all subsequent metrological testing (see 5.1.2 through 5.1.10). This includes adjustment of the sensor baseline and span.

The vehicle manufacturer may allow adjustment of the temperature, humidity, pressure, and test gas set points for the Sensor Kinetics and Validation Test as deemed appropriate based upon the end-use of the sensor and the sensor manufacturer recommendations.

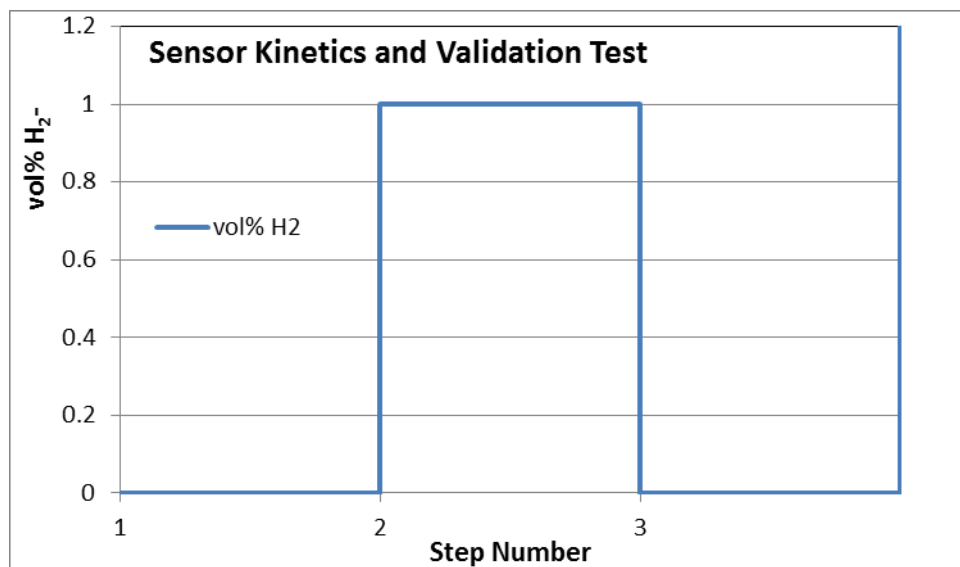


Figure 4 - An example of a gas exposure profile for the Sensor Kinetics and Validation Test. The vehicle manufacturer and/or system integrator may require that the test is repeated with additional test gas concentrations. The duration of each step shall be sufficiently long to allow the sensor to reach a stable F.I. or baseline response.

The response time and recovery times shall be reported as a t_{90} and t_{10} , respectively. These parameters may be determined using the data analysis methods described in Appendix A. Appendix C provides guidelines on the design of a test apparatus for the performance of the Sensor Kinetics and Validation Test, especially for the response time measurements.

The Sensor Kinetics and Validation Test (Initial Validation) is repeated as described in 5.1.10. A comparison of the sensor response as measured in the Initial Validation with that of the Final Validation allows for the determination of any possible negative impacts the various test protocols had on the sensor performance. If a negative impact is observed, it could be an indication of a poor operational lifetime and that the sensor model might experience premature failure in the field.

There shall be no exchange of test sensors during performance of tests 5.1.1 through 5.1.10. If a sensor fails during testing and a replacement sensor is used, the replacement sensor must be subjected to all test procedures requested by the vehicle manufacturer. All sensor failures are to be reported to the vehicle manufacturer.

5.1.2 Measuring Range/Sensor Accuracy Test

All sensors selected for evaluation by the hydrogen system integrator and/or vehicle manufacturer are to have an output signal that is in vol% H₂, or other concentration units such as ppm_v, or an analog signal that is readily transformed to vol% H₂ using a manufacturer-supplied calibration expression. The primary purpose for the Measuring Range/Sensor Accuracy Test is to verify that the sensor final indication corresponds to the imposed test gas concentration to within the desired accuracy from 0 to 4 vol%, or to the sensor measuring range specified by the manufacturer. Other sensor metrics that can be obtained from the Measuring Range/Sensor Accuracy Test include the lower detection limit (or verification that the lower detection limit is above a specified value), hysteresis, and linearity of the sensor.

In the Measuring Range/Sensor Accuracy Test, sensors are exposed to hydrogen gas mixtures whose concentration is changed stepwise from 0 vol% up to a maximum concentration defined by the measuring range specified by the manufacturer. For gas sensors with a manufacturer-specified measuring range of 0 to 4 vol% H₂ or higher, specific recommended test gas concentrations are 0.0, 0.5, 1.0, 2.0, 3.0, and 4.0 vol% H₂ in air. The test gases are exposed to the sensor in ascending and descending order of concentration as illustrated in Figure 5. Appendix C provides guidelines on the design of a test apparatus for performing the Measuring Range/Sensor Accuracy Test.

NOTE: Special operational and design considerations for the test apparatus must be implemented for any hydrogen concentration in excess of 4 vol%, including the source gas that is used to generate the test gas.

Typical test conditions for the Measuring Range/Sensor Accuracy Tests are:

- Required Test Gases: 0 to 4 vol% H₂ in air; an alternative test gas range and specific compositions may be used at the discretion of the vehicle manufacturer and/or hydrogen system integrator. This can be guided by the measuring range of the sensor as defined by the manufacturer's specification.
- Temperature (T): 25 °C ± 5 °C.
- Pressure (P): 1.0 atm ± 0.05 atm.
- Relative Humidity (%RH): Within the range of 25 to 75 %RH, but maintained to within ±10 %RH during the test.

The hydrogen system integrator and/or vehicle manufacturer may adjust the above values so that the test conditions are consistent with the intended use in their system and vehicle conditions. The sensor supplier or test laboratory may recommend adjustment to the test conditions, but the implementation of any change must be approved by the hydrogen system integrator and/or vehicle manufacturer.

The vehicle manufacturer may allow adjustment of the temperature, humidity, pressure, and test gas set points for the Measuring Range Test as deemed appropriate based upon the end-use of the sensor and the sensor manufacturer recommendations.

The exposure time of the test gas for each step in the Measuring Range/Sensor Accuracy Test is to be sufficiently long to assure that the sensor response has reached a stable final indication. A constant fixed time for each step is allowed providing it is of sufficient duration to allow the sensor to reach a proper final indication. Actual values for flow, T, P, and humidity are to be independently verified with sensors calibrated using methods traceable to national or international metrology institutes.

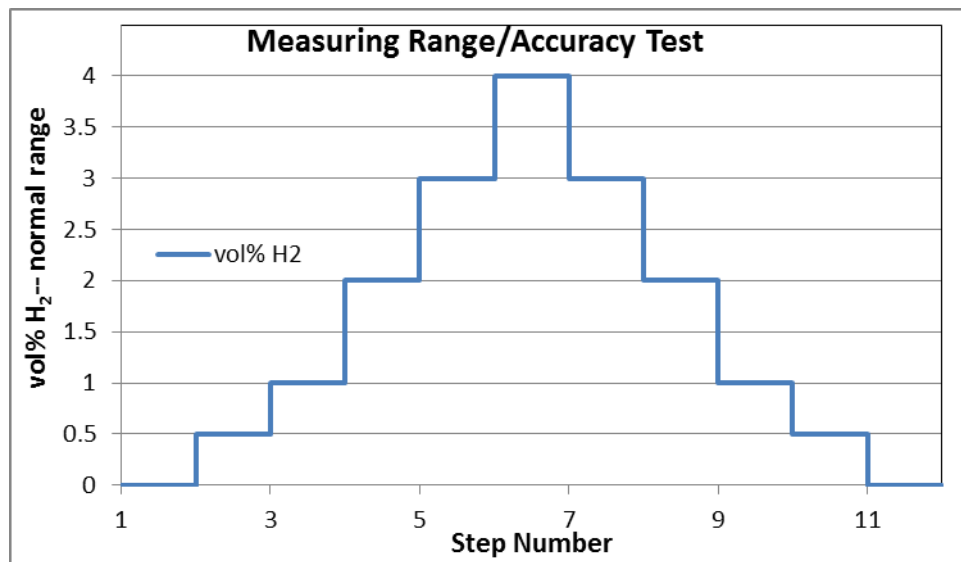


Figure 5 - An example of a gas exposure profile for the Measuring Range/Sensor Accuracy Test. The duration of each step shall be sufficiently long to allow the sensor to reach a stable F.I.

5.1.3 Short-Term Stability/Repeatability Test

The Short-Term Stability/Repeatability Test was designed to determine sensor parameters such as short-term drift in the sensor response to hydrogen, drift of zero point, and F.I. repeatability of the sensor. The short-term stability test allows for differentiating between drift due to extended hydrogen exposure, temporal factors, or chemical and physical stresses imposed onto the sensor in subsequent tests.

For sensors that have a measuring range between 0 and 4 vol% H₂ or higher, the hydrogen exposure steps shall be 1.0 vol% and 3.0 vol% H₂ as illustrated in Figure 6. The test sequence is to include exposure to air prior to and following the hydrogen exposure, but not between the hydrogen exposure steps. This sequence is to be performed a minimum of five times, and there is to be no time delay between each of the nine four-step sequential runs.

The Short-Term Stability Test is to be performed under the following conditions:

- Required Test Gases: Air, 1 vol% H₂ in air, and 3 vol% H₂ in air; alternative hydrogen test gas concentrations may be used at the discretion of the vehicle manufacturer or hydrogen system integrator.
- Temperature (T): 25 °C ± 5 °C.
- Pressure (P): 1.0 atm ± 0.05 atm.
- Relative Humidity (%RH): Within the range of 25 to 75 %RH, but maintained to within ±10 %RH during the test.

The hydrogen system integrator and/or vehicle manufacturer may adjust the above values so that the test conditions are consistent with the intended use in their system and vehicle conditions. The sensor supplier or test laboratory may recommend adjustment to the test conditions, but the implementation of any change must be approved by the hydrogen system integrator and/or vehicle manufacturer.

The vehicle manufacturer may allow adjustment of the temperature, humidity, pressure, and test gas set points for the Short-Term Stability Test as deemed appropriate based upon the end-use of the sensor and the sensor manufacturer recommendations.

The exposure time of the test gas for each step in the Short-Term Stability Test is to be sufficiently long to assure that the sensor response has reached a stable final indication. A constant fixed time for each step is allowed, providing it is of sufficient duration to allow the sensor to reach a proper final indication. Actual values for flow, T, P, and humidity are to be independently verified with appropriate sensors calibrated using methods traceable to national standards to national or international metrology institutes.

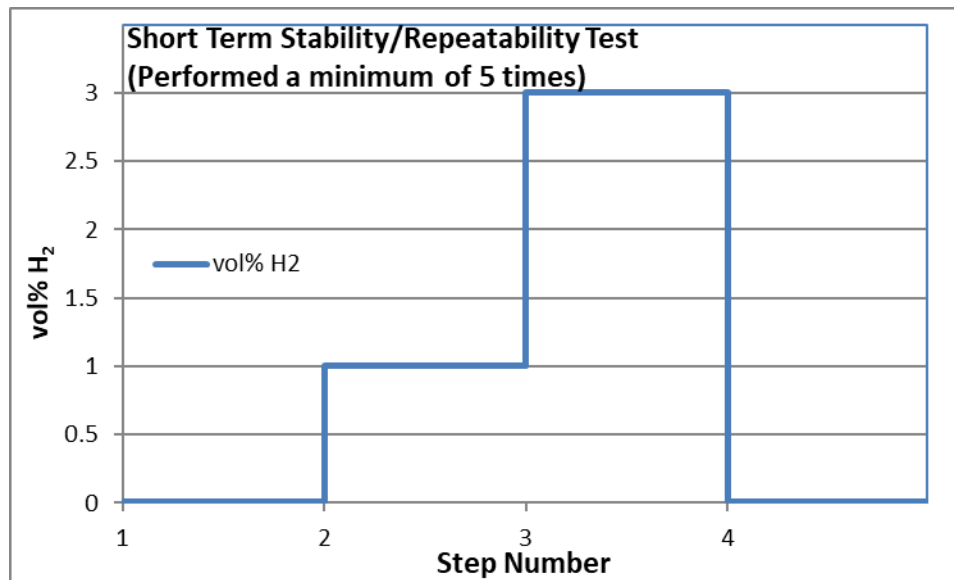


Figure 6 - An example of a gas exposure profile for the Short-Term Stability Test/Repeatability Test using 1 vol% H₂ and 3 vol% H₂. The duration of each step shall be sufficiently long to allow the sensor to reach a stable F.I. or baseline response.

5.1.4 Pressure Dependence Test

The response of many hydrogen sensors is controlled by the partial pressure of hydrogen, and, accordingly, will have a response that varies with fluctuations in ambient pressure, even if the vol% H₂ remains constant. Pressure-induced variations in the sensor response can occur from fluctuations in barometric conditions or by changes in elevation, which can occur when driving in the mountains. The aim of the Pressure Dependence Test is to quantify the influence of pressure changes on the sensor output in the absence and presence of hydrogen.

The sensor shall be subjected to at least three different pressure set points in the range of 0.6 to 1.0 atm, unless outside of the manufacturer's pressure specifications. The pressure set points correspond to altitudes ranging from sea level up to approximately 4250 m (14000 feet) [20]. The range of the pressure tests may be expanded to include lower or higher pressure set points as specified by hydrogen system integrator and/or vehicle manufacturer. The default pressure set points are 0.6, 0.8, and 1.0 atm. The set points are to remain within ± 0.05 atm during sensor testing. The test pressure is to be independently measured with a sensor calibrated using methods traceable to national or international metrology institutes.

The Pressure Dependence Test is performed under the following conditions:

- Required Test Gases: Air, 1 vol% H₂ in air, and 3 vol% H₂ in air; alternative hydrogen test gas concentrations may be used at the discretion of the vehicle manufacturer or hydrogen system integrator.
- Temperature (T): 25 °C $\pm$ 5 °C.
- Pressure (P): Set points of 0.6, 0.8 and 1 atm to within ± 0.05 atm.
- Relative Humidity (%RH): Within the range of 25 to 75 %RH, but maintained to within ± 10 %RH during the test.

- **Adjustment Time:** The adjustment time is established by the time required for the test conditions to reach a new stable pressure set point following the completion of the exposure cycle for the previous set point.
- **Stabilization Time:** >5 minutes (note: the stabilization time refers to a time to allow the sensor to equilibrate at the test pressure once the test apparatus has reached the desired pressure set point). Gas exposures should proceed only after the stabilization time.

The hydrogen system integrator and/or vehicle manufacturer may adjust the above values so that the test conditions are consistent with the intended use in their system and vehicle conditions. The sensor supplier or test laboratory may recommend adjustment to the test conditions, but the implementation of any change must be approved by the hydrogen system integrator and/or vehicle manufacturer.

The vehicle manufacturer and/or system integrator may allow adjustment of the temperature, humidity, pressure, and test gas set points for the Pressure Dependence Test as deemed appropriate based upon the end-use of the sensor and the sensor manufacturer recommendations.

The exposure profiles for the Pressure Dependence Test are illustrated in Figure 7. Once the pressure set point has been established, the sensor shall be allowed to stabilize and equilibrate within the pressure set point environment for a minimum of 5 minutes. Once stabilized, sensors are to be subjected to an exposure profile comprised of 1.0 vol% and 3.0 vol% hydrogen in air, which is preceded and followed by hydrogen-free exposure steps. Upon completion of the exposure cycle, the pressure of the test apparatus is to be adjusted to the next pressure set point (the adjustment step).

The exposure time of the test gas for each step in the Pressure Dependence Test is to be sufficiently long to assure that the sensor response has reached a stable final indication. A constant fixed time for each gas exposure step is allowed, providing it is of sufficient duration to allow the sensor to reach a proper final indication. Actual values for flow, T, P, and humidity are to be independently verified with appropriate sensors calibrated using methods traceable to national or international metrology institutes.

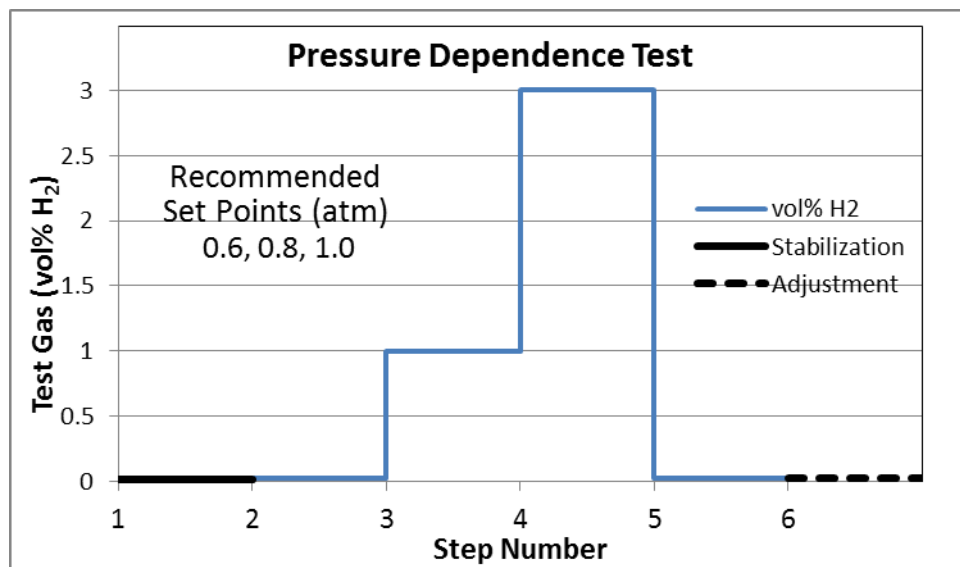


Figure 7 - An example of a gas exposure profile for the Pressure Dependence Test. The duration of each gas exposure step shall be sufficiently long to allow the sensor to reach a stable F.I. or baseline response.

5.1.4.1 (Method 2): Alternative Sensor Pressure Dependence Test - Static Method

Other methods and apparatus designs exist to evaluate the pressure dependency of a sensor. As an alternative to the protocols prescribed in Pressure Dependence Test (see 5.1.4), which were developed to be performed automatically in a test apparatus with a dynamically flowing test gas in a flow-through system or to purge a test chamber (see Appendix C), a static chamber method for evaluating the sensor pressure dependence is allowed using the approach illustrated in Figure 8. The hydrogen sensors under test are placed in a hermetic chamber. The chamber is also instrumented with sensors for temperature, humidity, and pressure. The inlet to the chamber is connected to a test gas source (i.e., a test gas cylinder or gas generation system such as that described in Appendix C), while the outlet is vented to the test facility exhaust system. The chamber is purged with the desired test gas (e.g., 0, 1, or 3 vol% H₂ in air) by opening both the inlet and outlet shut-off valves to allow gas flow through the chamber. A mass flow controller or other method may be used to regulate the gas flow rate through the chamber. A vacuum pump is also connected to the outlet of the test chamber and vented to the facility exhaust system. The vacuum pump is used to achieve sub-ambient pressure set points; the vacuum pump is by-passed for pressure set points at or above ambient, if such set points are desired. Alternatively, an electronic pressure controller may be used to regulate the internal pressure of the chamber. Once the chamber has been purged with the test gas, Valves 1 and 2 are closed to seal the test chamber. Valve 1 may be momentarily opened to achieve the initial test pressure of 1 atm.

Figure 9 illustrates the sensor evaluation process using the hermetic chamber. For each pressure set point, the sensor should stabilize for a minimum of 5 minutes in the presence of the test gas at the designated test pressure. The first pressure set point is 1 atm. After the stabilization process, the sensor response is recorded. The outlet of Valve 2 is then connected to a vacuum pump, and Valve 2 is opened to allow the internal pressure of the test chamber to adjust to the second pressure set point (0.8 atm). Following the stabilization step at the pressure set point, the sensor response is recorded. The chamber should remain at the desired pressure set point as verified with a pressure sensor. Valve 2 is then opened to allow the internal pressure of the test chamber to adjust to the third set point (0.6 atm), which is achieved with the aid of the vacuum pump. Following the stabilization step, the sensor response is recorded. This pressure dependence test sequence is performed for 3 vol% H₂ in air, 1 vol% H₂ in air, and for air (0 vol % H₂). The test temperature shall be maintained at 25 °C ± 5 °C. The relative humidity set point shall be between 25 %RH and 75 %RH, but maintained to within ±10 %RH for the duration of the test.

The Pressure Dependence Test is performed under the following conditions:

- Required Test Gases: Air, 1 vol% H₂ in air and 3 vol% H₂ in air; alternative hydrogen test gas concentrations may be used at the discretion of the vehicle manufacturer or hydrogen system integrator.
- Temperature (T): 25 °C ± 5 °C.
- Pressure (P): Set points of 0.6, 0.8 and 1 atm to within ±0.05 atm.
- Relative Humidity (%RH): Within the range of 25 to 75 %RH, but maintained to within ±10 %RH during the test.
- Adjustment/Stabilization Time: The adjustment time is established by the time required for the test conditions to reach a new stable pressure set point following the completion of the exposure cycle for the previous set point.
- Stabilization Time: The stabilization time shall be no less than 5 minutes (note: the stabilization time refers to a time to allow the sensor to equilibrate at the test pressure once the test apparatus has reached the desired pressure set point).

The hydrogen system integrator and/or vehicle manufacturer may adjust the above values so that the test conditions are consistent with the intended use in their system and vehicle conditions. The sensor supplier or test laboratory may recommend adjustment to the test conditions, but the implementation of any change shall be approved by the hydrogen system integrator and/or vehicle manufacturer.

The vehicle manufacturer and/or system integrator may allow adjustment of the temperature, humidity, pressure, and test gas set points for the Pressure Dependence Test (Static Method) as deemed appropriate based upon the end-use of the sensor and the sensor manufacturer recommendations.

As a cautionary note, the test gas is not continuously replenished in this procedure since the measurements are performed in a closed pneumatic system. The transduction mechanism of many sensing elements will change the chemical and physical composition of the test gas (e.g., a combustible gas sensor will react with hydrogen to generate heat and water). A ramification of this is that the sensor signal may decrease during the measurement, not because of a drift in sensor response, but because the hydrogen in the test chamber is actually being depleted. The humidity may also measurably increase since water vapor is a product of the interaction of hydrogen with the sensing element. The temperature of the chamber may also increase over the test cycle. These effects can be minimized by using a large-volume test chamber, short test times, periodic purging the chamber with fresh test gas, and limiting the number of hydrogen sensors under test that have hydrogen-depleting sensing elements. Also, using material with a large heat capacity can minimize the temperature change.

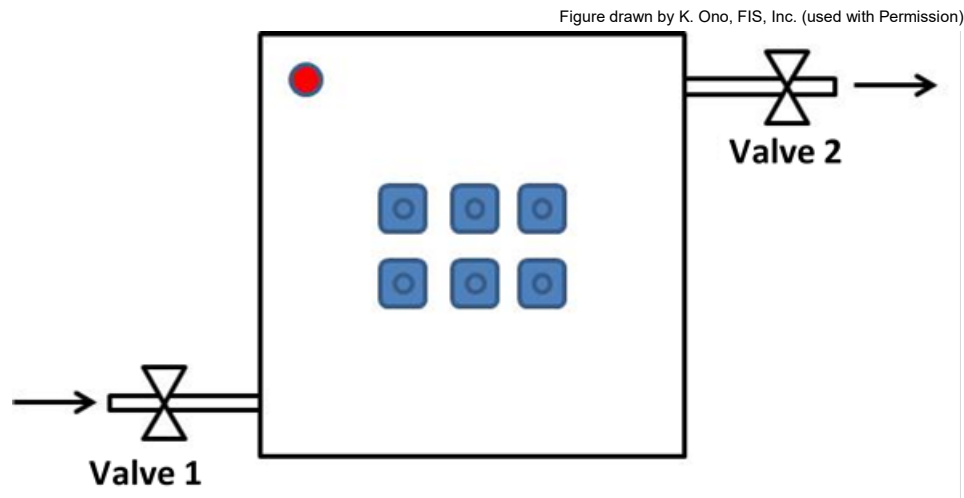


Figure 8 - Illustration of a hermetic test chamber for the Static Pressure Dependence Test. The internal pressure can be adjusted to sub-ambient set points by connecting a vacuum pump (not shown) to the outlet of Valve 2.

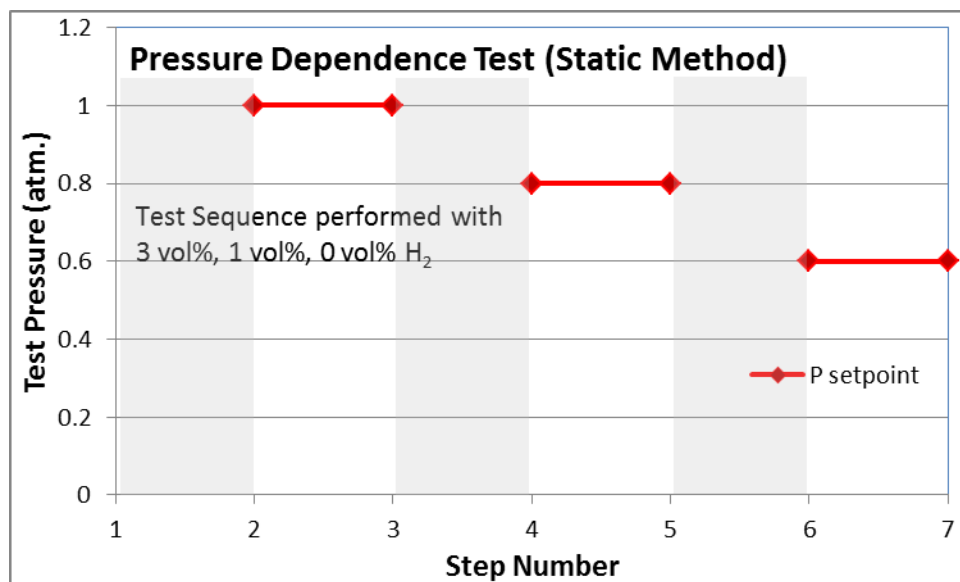


Figure 9 - Illustration of the Pressure Dependence Test procedure using a hermetic test chamber. The shaded area represents the pressure adjustment/stabilization steps required to adjust conditions to the next pressure set point and to allow for a stabilization time to assure a stable sensor response to the test gas at the new pressure set point. Pressure set points are 1.0, 0.8, and 0.6 atm.