The NREL Sensor Laboratory: Status and Future Directions for Hydrogen Detection

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ABSTRACT

The NREL Hydrogen Sensor Laboratory was commissioned in 2010 as a resource for the national and international hydrogen community to ensure the availability and proper use of hydrogen sensors. Since then, the Sensor Laboratory has provided unbiased verification of hydrogen sensor performance for sensor developers, end-users, and regulatory agencies and has also provided active support for numerous code and standards development organizations. Although sensor performance assessment remains a core capability, the mission of the NREL Sensor Laboratory has expanded toward a more holistic approach regarding the role of hydrogen detection and its implementation strategy for both assurance of facility safety and for process control applications. Active monitoring for detection of unintended releases has been identified as a viable approach for improving facility safety and lowering setbacks. The current research program for the Sensor Laboratory addresses both conventional and advanced developing detection strategies in response to the emerging large-scale hydrogen markets, such as those envisioned by H2@Scale. These emerging hydrogen applications may require alternative detection strategies that supplement and may ultimately supplant the use of traditional sensors for monitoring hydrogen releases. Research focus areas for the NREL Sensor Laboratory now encompass the characterization of released hydrogen behavior to optimize detection strategies for both indoor and outdoor applications, assess advanced methods of hydrogen leak detection such as hydrogen wide area monitoring for large scale applications, implement active monitoring as a risk reduction strategy to improve safety at hydrogen facilities, and to provide continuing support of hydrogen safety codes and standards. In addition to assurance of safety, detection will be critical for process control applications, such as hydrogen fuel quality verification for fuel cell vehicle applications and for monitoring and controlling of hydrogen-natural gas blend composition.

1.0 INTRODUCTION

Early detection of unintended hydrogen releases is critical for ensuring safety within hydrogen facilities. The most direct, and to date the most common approach to detect an unintended release has been with hydrogen sensors, which are devices that output a measurable indication in response to the presence of hydrogen. The sensor indication is usually electrical in nature and based upon a chemical to electrical transduction mechanism, although other transduction mechanisms exist that do not rely on an electrical response. For example, there are low-cost hydrogen-sensing devices with a transduction mechanism that is based upon a visually-interrogated color change that forms following exposure to hydrogen [1], [2]. However, most sensors will typically output a response that is a change in an electrical parameter (e.g., voltage, current, resistance) that can then be shown on a display or integrated into a facility control system. As part of a safety system, sensors can perform several important functions, including indication of an unintended hydrogen release, activation of mitigation strategies to preclude the development of dangerous situations (e.g., initiate corrective measures to prevent accumulation or the possibility of delayed ignition), activation of alarm and communication systems, and to initiate system shutdown. The

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role of hydrogen sensors for assurance of safety is recognized, and accordingly, their use in hydrogen facilities is often mandated by code [3], [4].

The term "sensor" can have different meanings among stakeholders. For example, a sensor has been defined *as a small device that, as the result of a chemical interaction or process between the analyte gas and sensor device, transforms chemical information of a quantitative or qualitative type into an analytically useful signal* (adapted from [5]). Other definitions have been proposed, including by the International Union of Pure and Applied Chemistry (ISUPC) [6] and from other groups [7], [8]. Specific definitions for a *hydrogen sensor*[2] and *hydrogen sensing element*[3] were given in ISO 26142 ("*Detector Apparatus for Stationary Applications*") [9]. There is, however, no universally accepted definition of "sensor" and the term sensor is often used interchangeably for detection apparatus[4] (e.g., instruments, detectors, analyzers) and even sensing elements. By the ISO 26142 definition, the sensing element would be the component within a hydrogen sensor or detection apparatus where the presence of hydrogen is transduced into a measurable quantity, usually electrical in nature. Accordingly, the type of sensing element (e.g., the sensor platform) is a controlling factor for the sensor metrological performance including especially cross-sensitivity to other gases. An illustration of the distinction between sensing element, sensor, and detection apparatus is shown in Figure 1. A sensor consists of sufficient support elements (e.g., electronic circuitry) to transform the electrical or physical response of the sensing element into useful information, such as vol% H_2 or an electrical signal easily converted into hydrogen concentration through a transformation function (or a calibration expression). Additional elements may be added to the sensor to improve performance of specific metrics (e.g., chemical filters for minimizing cross-sensitivity to other gases). A detection apparatus may include displays, user interfaces, and additional elements for control systems, such as alarm activation and other advanced operations.

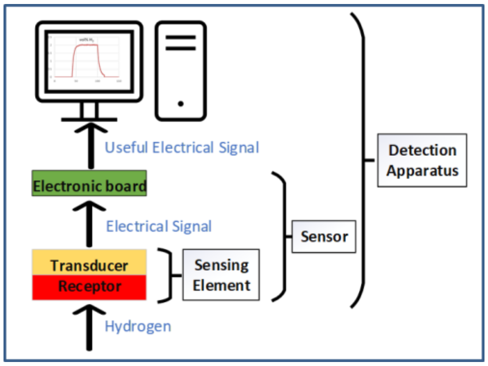

Figure 1: Distinction between Sensing Element, Sensor, and Detection Apparatus as per definitions in ISO 26142.

There are a variety of chemical to electrical transduction mechanisms by which the stimuli (e.g., hydrogen) interacts with a sensing element to produce an electrical response. Several types of hydrogen sensing elements with different transduction mechanisms have been incorporated into commercially successful sensors and detection apparatus, such as the following:

- Electrochemical sensors, that produce a voltage or current due to the electrochemical activity of hydrogen [10], [11], [12].

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[2] Hydrogen Sensor: *assembly, which contains one or more hydrogen sensing elements and may also contain circuit components associated with the hydrogen sensing elements, that provides a continuously changing physical quantity or signal in correlation to the physical quantity provided by the hydrogen sensing element(s)* [9].

[3] Hydrogen Sensing Element: *component that provides a continuously changing physical quantity in correlation to the surrounding hydrogen volume fraction* [9].

[4] Hydrogen Detection Apparatus: *assembly with an integrated or a remote hydrogen sensor that is intended to detect and measure hydrogen concentration over a declared measuring range* [9].

- Combustible gas sensors that measure an elevation in temperature within the device from the catalytic surface combustion of hydrogen,
- Thermal conductivity sensors that respond to heat transfer properties of the surrounding gas. [13]. Thermal conductivity sensors are sensitive to any change in the gas composition, but hydrogen is noted for having the highest thermal conductivity of any known gas, and thus produces the largest response per molecule on the thermal conductivity sensor.
- Metal oxide semiconductor sensors that exhibit a change in conductivity or other property due to electron donation into the crystal from the electron-donating (reducing) property of hydrogen. These include conductometric sensors based on high-temperature semiconductors [14] [12] and low-temperature field effect devices [15].
- Sensors based upon palladium thin films, which have been produced in various platform types (e.g., resistive [16], semiconductor [15], optical [17]). Sensing elements with palladium films are noted for a very high selectivity to hydrogen.

These platforms are typically configured as “point sensors”, which are devices that respond to a direct interaction with hydrogen at a specific location (e.g., the hydrogen must get to the sensor to be detected) and involve either a chemical or physical interaction with the sensing element. Point sensors are the most common approach used for quantitative hydrogen measurements. Further discussions on types of sensing elements and their advantages and limitations can be found in several recent reviews on hydrogen sensor technologies [18] [19] [20]. There is also an extensive activity in developing new hydrogen sensor technologies, including platforms based on advanced materials such as nanomaterials, advanced fabrication methods, and sensors based upon unique transduction mechanisms. Microfabrication methodology such as that used in the electronics industry has been successfully applied to the manufacturing of miniaturized sensing elements, most notably combustible gas and semiconductor sensing platforms [21]. Advanced manufacturing methods have been also applied to electrochemical sensors [22]. Miniaturization improved response times and significantly lower power requirements relative to conventional sensor configurations. Advanced manufacturing methods also reduce cost through economy of scale production, while essentially maintaining the powerful metrological performance of the conventional configuration. Hydrogen sensor platforms with advanced nanomaterials have been demonstrated in the laboratory and are moving toward commercialization. For example, an[23] and is being assessed for commercial development.

2.0 APPROACH

The NREL Sensor Laboratory has conducted performance evaluations on sensors, sensing elements, and instruments (detection apparatus) for developers, manufacturers, and for end-use applications, which included field deployment demonstrations. Much of this work has focused on performance verification in the laboratory using test protocols designed to quantify specific sensor performance parameters (e.g., measurement range, repeatability, impact of chemical and environmental interferences). The sensor performance parameters and test protocols were guided by test methods and performance metrics prescribed in standards or technical reports such as ISO 16142 [9], SAE Technical Information Report J3089 (*Characterization of On-Board Vehicular Hydrogen Sensors*) [24], or UL 2017 (*Standard for Gas and Vapor Detectors and Sensors*) [25], or by the needs of the application as required by facility operators or local authority having jurisdiction (AHJs). Although sensor performance assessment remains a core capability, the mission of the NREL Sensor Laboratory has expanded to a more holistic approach on the role of hydrogen detection and its implementation strategy for both assurance of facility safety and for process control applications. Active monitoring for the detection of unintended releases has been identified as one strategy for improving facility safety and lowering setbacks. There is a need to integrate detection into a smart active monitoring system into a facility control system to improve safety. Recent Sensor Laboratory research efforts have been addressing sensor deployment strategies. Guidance on sensor placement was identified as the top safety research priority at the 2018 HySafe Research Priority Workshop [26]. Optimal sensor placement for early and effective detection is dependent upon hydrogen plume behavior. Thus, one current critical role for sensors is the characterization of hydrogen dispersion behavior, which can then be used for model validation and integrated into quantitative risk analysis (QRA) to guide the design of a facility to optimize the effectiveness of active monitoring and other mitigation strategies for risk reduction. Active monitoring is germane for safety assurance of indoor and outdoor GH2 and LH2 operations.

The NREL Sensor Laboratory has been using a distributed array of sensors for hydrogen wide area monitoring (HyWAM) to characterize released hydrogen behavior to develop the optimal use of active monitoring as a risk mitigation strategy for both indoor applications [27] and outdoor deployments [28]. The NREL HyWAM was able to validate a CFD model of indoor hydrogen dispersion in a ventilated indoor facility which led to sensor placement guidelines currently proposed for inclusion in NFPA 2. The outdoor deployment of the NREL HyWAM was to elucidate the behavior of cold hydrogen plumes formed from the venting of LH2. Both studies are covered in other presentations at the 2021 ICHS (e.g., ICHS ID 103: "*Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors – Phases 2 and 3*" [27] and ICHS 153: "*Hydrogen Wide Area Monitoring of LH2 Releases at HSE for the PRESHLY Project*" [28]). The evolving mission and research direction of the Sensor Laboratory from supporting the prescriptive use of hydrogen sensors with validated performance metrics to an integrated active monitoring system as a risk reduction strategy is illustrated in Figure 2.

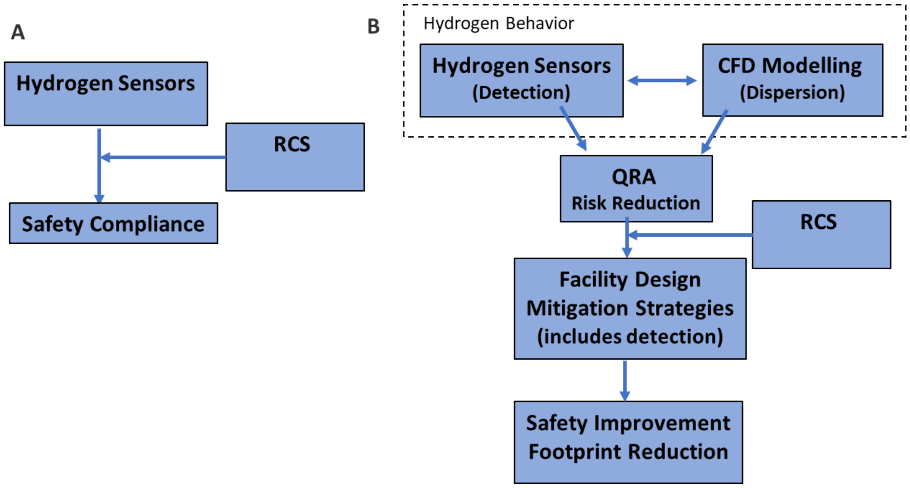

Figure 2: The evolving role of hydrogen detection and the NREL Sensor Laboratory research efforts. A: Traditional sensor evaluations to verify performance specifications as per RCS requirements. B: Sensor performance validation to verify RCS compliance as well as quantitative risk reduction through implementation of an integrated active monitoring system.

The use of hydrogen is growing, and new markets are emerging, and this will impact the optimal strategy for hydrogen monitoring and detection. Within the United States, hydrogen market development is being driven by H2@Scale [29]. The scope of potential markets addressed by H2@Scale is illustrated in Figure 3. The unique features and scope among these new markets will affect detection strategies. The focus of the NREL Sensor Laboratory has adapted to respond to the needs of the expanding hydrogen market, which includes large scale production, storage, and use. The use of point sensors for detection of unintended releases has been demonstrated for many applications. However, these sensors may not be an optimal detection strategy for some large-scale operations and may be cost prohibitive because of the number of sensors that would be required for adequate monitoring (e.g., consider pipeline leak detection). Sensor costs include both capital cost and maintenance costs, including mandatory periodic calibrations.

In addition, new hydrogen markets are often coupled with complex chemical environments that may challenge the effectiveness of current detection methods (e.g., mixed use facilities, the addition of hydrogen into natural gas [30], hydrogen to support ammonia production and the use of ammonia as a hydrogen carrier [31]).

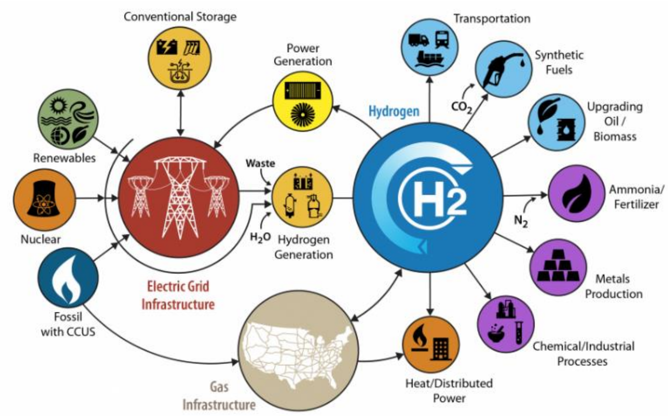

Figure 3: Growing use of hydrogen as envisioned by H2@Scale.

Performance assessment of hydrogen sensors to standard test protocols remains a unique core capability of the NREL Sensor Laboratory, albeit at a significantly lower level than in the past. This activity supports sensor developers and manufacturers as well as end users. The Sensor Laboratory now addresses additional focus areas to support H2@Scale, including development and validation of advanced hydrogen detection strategies (e.g., hydrogen wide area monitoring [32], [28] and standoff methods [33], [34]), hydrogen behavior modeling and integration into risk reduction strategies [29], [27], and monitoring technology for process control application (e.g., fuel quality verification [35], hydrogen in natural gas).

2.1 Hydrogen Sensor Performance Assessment (Sensor Test Apparatus)

Assessment of gas sensor performance is normally performed in the laboratory under controlled conditions using an apparatus specifically designed for that purpose. Since its commissioning, the NREL Sensor Laboratory has extensively used a sensor test apparatus of in-house design and construction for hydrogen sensor evaluations (Figure 4), which has been previously described [19] [36]. The NREL Safety Sensor Test Apparatus (SSTA) was designed to evaluate the metrological performance of hydrogen safety sensors and can measure the sensor response from 0 to 4 vol% H_2 in air (or 0 to 10 vol% H_2 in nitrogen). Test gas generation is with gas cylinders of a hydrogen mixture with a certified concentration (typically 2 vol% H_2 in air or 10 vol% H_2 in nitrogen) that is dynamically mixed with air or nitrogen or other gas background matrix. The relative gas flow rate of the hydrogen mixture and background gas determines the final test gas concentration exposed to the sensors; the respective flow rates are controlled by precision mass flow controllers. The SSTA is a fully automated system with capabilities that include simultaneous testing of multiple hydrogen sensors (and other sensor types), real-time control of test gas composition and concentration through the use of up to 6 precision mass flow controllers, control and monitoring of environmental parameters (e.g., T, P, and RH) with calibrated sensors and an integrated temperature control system and humidification system, and the ability to study the impact of chemical stressors on sensor performance (e.g., chemical interferences, poisons, and variations in the background gas). The SSTA was designed to test hydrogen sensors at or below the lower flammable limit (LFL) of 4 vol% in air or up to 10 vol% H_2 in nitrogen.

Figure 4: The NREL Safety Sensor Test Apparatus (SSTA) is capable of quantitatively assessing critical sensor metrological performance metrics.

Several upgrades have been made to the NREL Sensor Laboratory to increase sensor assessment capability. One limitation of the SSTA is that it was designed to measure a sensor response to hydrogen (or other flammable gas such as methane or natural gas) below the respective lower flammable limit (LFL) of the test gas. Recently, the Process Gas Sensor Test Apparatus was developed to allow testing of gas sensors in 100% flammable gas and lower concentrations in an inert gas. The Process Gas Sensor Test Apparatus is shown in Figure 5 (Left) and was originally built to support the assessment of hydrogen contaminant detectors to verify compliance of hydrogen fuel quality requirements as specified by SAE J2719 (*Hydrogen Fuel Quality for Fuel Cell Vehicles*) [37] or ISO 14687 (*Hydrogen fuel quality — Product specification*) [38]. The Process Gas Sensor Test Apparatus was designed to safely exposed sensors to hydrogen (or other flammable gas) with trace impurities. Many candidate process sensors, including potential hydrogen contaminant detectors are not listed for hazardous locations within the United States per the NFPA 70 *National Electric Code* requirements [33]. However, NFPA 70 provides guidance on the deployment of electrical components that are not listed for use in environments that may be classified as hazardous due to the presence or potential presence of flammable gas. To achieve NFPA 70 compliance for use with non-listed sensors, the Process Gas Sensor Test Apparatus includes a ventilated enclosure with a flammable gas monitoring system that is listed for hazardous locations. These adaptations allow use of otherwise unlisted devices for testing in a flammable gas environment. Operationally, the Process Gas Sensor Test Apparatus allows for the real-time mixing up to two gases for adjusting test gas concentration, but this can be expanded to accommodate multiple component mixtures. Unlike the SSTA, the Process Gas Sensor Test Apparatus does not have active control of environmental parameters (e.g., T and RH), but internal process pressure can be increased above ambient.

The SSTA and Process Gas Sensor Test Apparatus operate in a controlled indoor laboratory environment with regulated T and RH. Each apparatus allows for delivery of the test gas to the sensor under test, with regulated composition and flow rates. The NREL sensor laboratory also performs sensor deployment studies in an outdoor setting. Figure 5 (Right) shows a test fixture that was developed to provide a gaseous leak under controlled release rates and head pressures up to 90 MPa (13000 PSI). The leak-on-demand apparatus was originally developed to quantify hydrogen leak rates from failed high-pressure hydrogen pneumatic components as part of the NREL Hydrogen Component Reliability Research and Development Program [39], and for this application has been identified as the Leak Rate Quantification Apparatus (LRQA). The LRQA has been adapted to support development of outdoor hydrogen detection strategies. The LRQA has been installed into the NREL Hydrogen Infrastructure and Test Facility (HITRF) [40], which is shown in Figure 6. HITRF is a hydrogen infrastructure test bed that includes on-site production, medium- and high-pressure storage and handling capabilities, and operational hydrogen dispensers for fuel cell vehicle refueling. HITRF provides a real-world environment to support hydrogen infrastructure development, including heavy duty applications. HITRF also provides a test bed for sensor research and development as well as sensor deployment and released hydrogen behavior studies.

Figure 5: (Left): The Process Gas Sensor Test Apparatus allows sensor testing to pure hydrogen or other flammable gas. It was designed to be compliant to NFPA 70 even when using non-listed instruments and sensors. (Right): The “leak-on-demand” test apparatus allows for the outdoor production of a hydrogen release under controlled conditions and is deployed within HITRF.

Figure 6: The NREL Hydrogen Infrastructure Testing Research Facility (HITRF)

2.1 Strategic Partnerships and Collaborations

The NREL Sensor Laboratory strives to support the safe and efficient development of hydrogen as an energy carrier. To achieve this, the Sensor Laboratory has historically maintained an extensive number of national and international partnerships and collaborations within the hydrogen community. These partnerships include various agreements with government, academic, and private stakeholders, and are exemplified by the number of joint presentations at the 2021 ICHS:

- (ICHS 157) in collaboration with the University of Maryland, (College Park, Maryland) Hydrogen Component Leak Rate Quantification for System Risk and Reliability Assessment through QRA and PHM Frameworks [39].
- (ICHS 103) in collaboration with AVT and Associates, (Mississauga, Ontario, Canada) Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors – Phases 2 and 3 [27].
- (ICHS 155) in collaboration with Transport Canada and Environment and Climate Change Canada, (Ottawa, Ontario, Canada) Safety Compliance Verification of Fuel Cell Electric Vehicle Exhaust, [41]
- (ICHS 153) in collaboration with the Health and Safety Executive, (Buxton, U.K.) Hydrogen Wide Area Monitoring of LH2 Releases at HSE for the PRESHLY Project [28].

The Sensor Laboratory remains active on numerous codes and standards development committees (e.g., ISO/TC1 97 WG 27 and WG 28, NFPA 2, SAE Fuel Cells Standard Committee, and ASTM D03 committee on gaseous fuels) as well as active participation in hydrogen safety organization such as HySAFE [42] and the Center for Hydrogen Safety [43].

3.0 ON-GOING RESEARCH ACTIVITY

The NREL Sensor Laboratory has numerous projects to advance the effectiveness of hydrogen detection technology for facility safety and process optimization. The following is a summary of existing projects and research directions for the NREL Sensor Laboratory, several of which were initiated within the past year. As previously indicated, several projects are also featured in other 2021 ICHS presentations.

3.1 Released Hydrogen Behavior and Hydrogen Wide Area Monitoring

Hydrogen wide area monitoring is defined as the quantitative spatial and temporal 3-dimensional profiling of planned and unintentional hydrogen releases. The NREL Sensor Laboratory developed a prototype hydrogen wide area monitor (HyWAM) in response to a need for empirical data on released hydrogen behavior, which can then be used to develop and validate dispersion and behavior models. The NREL HyWAM is based upon an array of point sensors distributed around a hydrogen facility to continuously profile hydrogen dispersion following a release (intended or unintentional) and was originally developed to characterize outdoor cold hydrogen plume behavior following venting of liquid hydrogen (LH2) from a stationary storage tank [44]. The characterization of cold hydrogen releases by the NREL HyWAM is on-going. In 2019, NREL deployed a 32-point HyWAM system at the United Kingdom’s Health and Safety Executive (HSE) to profile LH2 release behavior. The HSE LH2 release study was under the auspices of the FCH JU Prenormative Research for the Safe Use of Liquid Hydrogen (PRESLHY) program [45], during which HSE performed a series of controlled LH2 venting tests at their facility. Details on the HSE LH2 release apparatus and their support of the PRESLHY project has been published [46] and is a topic of a 2021 ICHS paper (*HSE SD experimental summary for the characterisation, dispersion and electrostatic hazards of LH2 for the PRESLHY project*) [47]. An initial summary on the performance of NREL HyWAM at the HSE LH2 release study was presented at the 2019 ICHS [48], but only preliminary results were available because the release study was only initiated just prior to the conference (releases had been scheduled to start in May or June 2019, but were delayed). Further assessments on the NREL HyWAM performance and an analysis of hydrogen behavior have since been performed. An updated analysis of the LH2 release behavior is a topic of a paper at the 2021 ICHS [28]. Details and data on both the HSE experimental setup and the HyWAM measurements were delivered to the PRESHLY program office to allow for dissemination to the hydrogen community. The HSE testing, including the NREL HyWAM data is to be available to the hydrogen community to support cold hydrogen plume modelling. Several other HyWAM deployments at LH2 facilities had been planned for 2020 and 2021 but were hampered due to COVID-19 related travel restrictions, and thus remain pending.

The NREL HyWAM has also been applied to validate CFD modeling of hydrogen dispersions within ventilated indoor hydrogen enclosures [49]. The validated modelling of hydrogen behavior led to the development of science-based guidelines for indoor sensor placement, which have been formally proposed to the NFPA 2 technical committee for inclusion as a technical annex in the next revision cycle [27]. These guidelines potentially provide for earlier, more reliable hydrogen leak detection within indoor facilities and enclosures relative to deployment protocols currently used. An update on this on-going effort to provide guidance for sensor placement is covered in a separate paper at the 2021 ICHS conference (‘Development of Risk Mitigation Guidance for Sensor Placement Indoors and Outdoors – Phases 2 and 3) [27]. We are now exploring strategies to incorporate the hydrogen behavior modelling and detection scheme into HyRAM, a quantitative risk reduction tool developed by Sandia National Laboratory [50].

The NREL HyWAM has been demonstrated for both indoor and outdoor application. It is currently being reconfigured for unattended operation and represents the basis for a potential commercial active monitoring system [51] [52].

3.2 Stand-off Approaches for Hydrogen Leak Detection

In addition to point sensors, other approaches to hydrogen leak detection have been proposed to detect the presence of released hydrogen over a wide area [34]. Strategies for advanced hydrogen detection were recently reviewed by the NREL Sensor Laboratory and presented as a Technical Seminar (*Next Generation Detection Strategies for Hydrogen Applications*) [33]. Different HyWAM strategies exist that can be categorized into two main groups: those based upon point sensors that directly measure in-situ the hydrogen concentration at discrete points within the hydrogen plume and stand-off methods that include Raman (e.g., [53]), Schlieren imaging (e.g.,[54]), and ultrasonic methods. Examples of HyWAM based on point sensors include the NREL HyWAM system and fiber optic sensors with sensing elements distributed along the length of the fiber. Some standoff methods are based upon a physical signature associated with hydrogen (e.g., Schlieren Imaging and Ultrasonic Leak Detection) and do not involve a chemical interaction. Sandia National Laboratory is using RAMAN to characterize LH2 jets, which is a non-destructive optical method of detection. However, this approach may not be amenable for general deployment applications (e.g., unattended operation). Schlieren has also been applied for LH2 release profiles [54] because of the need for a laser light source.

The NREL Sensor Laboratory is currently investigating ultrasonic detection strategies for remote interrogation of hydrogen leaks for possible deployment at hydrogen fueling stations. Ultrasonic leak detectors are commercially available but have not been extensively applied to hydrogen systems. The HITRF facility (Figure 6) and the leak-on-demand apparatus (Figure 5, right) are being used to characterize the performance of commercial systems. Detection is based upon a characteristic acoustic signature associated with pressurized gas passing through an orifice. In addition to remote detection, an advantage of acoustic leak detection technologies is that it does not rely on elevated concentrations of gas to detect a leak; the leak process itself is detected. This allows for the detection of leaks before gases have accumulated. The primary challenge of this detection strategy is the presence of background acoustic signatures created by normal operating conditions. These background sounds are often sporadic and not always predictable and are related to routine gas flow processes within pneumatic lines or associated with equipment like regulators, valve activation, and pressure release valves. Ultrasonic leak detectors must be tuned to differentiate between operational sounds and those associated with leaks, which is achieved by profiling background acoustic signal intensity and duration. Ultrasonic leak detectors do not quantify the hydrogen concentration or pinpoint the leak location but have the potential for unattended operation to remotely verify the presence of a hydrogen leak within a facility. At present, the NREL HITRF facility is being used as an evaluation test site. The project goal is to quantify the ability of ultrasonic methods for reliable leak detection within hydrogen facilities including fueling stations as a supplement to current leak detection strategies.

3.3 Support of Codes and Standards

The NREL sensor laboratory continues to support hydrogen codes and standards development by direct participation in committees, prenormative research on outdoor [48] and indoor hydrogen behavior [27], document development [24], and supporting the development of verification technology for allowable hydrogen levels in fuel cell vehicles [55]. In an on-going project, the Sensor Laboratory has been developing methodology to verify compliance to allowable hydrogen levels as prescribed by the Global Technical Regulation for hydrogen vehicles [56]. In the past year, an optimize Fuel Cell Exhaust Analyzer with an improved gas sampling system was developed by the Sensor Laboratory for monitoring hydrogen levels in fuel cell exhaust. Water entrainment in the FCEV exhaust gas adversely impacted the robustness of an early prototype of the Analyzer [55]; the improved sampling system alleviated water entrainment issues. The updated analyzer and sampling system has been demonstrated in the laboratory on a simulated FCEV Exhaust Fixture and is scheduled for a demonstration on an FCEV operating under simulated driving conditions using a chassis dynamometer operated by Environment and Climate Change Canada. The design and performance validation of the updated FCEV Exhaust analyzer is a topic of another ICHS presentation (ICHS 157 "*Safety Compliance Verification of Fuel Cell Electric Vehicle Exhaust*") [41].

3.4 Process Sensors—Hydrogen Fuel Quality Verification

Hydrogen detection is critical not only for assurance of safety, but also for optimal process control. This can include verification of hydrogen fuel quality as prescribed by ISO 14687 [38] or SAE J2719 [37]. Presently, fuel quality compliance verification is performed just prior to commissioning a fueling station for commercial dispensing by the collection of hydrogen samples from a hydrogen dispenser and transporting them to a remote laboratory for analysis. FQ verification is then performed periodically thereafter, ideally on a semi-annual schedule. Unfortunately, hydrogen fuel that is out of compliance has on occasion been dispensed into FCEVs. To alleviate this, the NREL Sensing Laboratory is partnering with the State of California to deploy hydrogen contaminant detector (HCD) technology on-site at commercial hydrogen fueling stations for near real-time FQ verification [35]. Two candidate HCDs have been acquired and evaluated in the laboratory using the NREL Process Gas Sensor Test Apparatus to confirm their ability to meet SAE J2719 requirements. One candidate HCD is an FT-IR instrument that can quantify multiple impurities, while the other is an electrochemical sensor for carbon monoxide developed by the Las Alamos National Laboratory [57]. Calibration curves for several regulated compounds have been obtained, including carbon monoxide, carbon dioxide, methane, and ammonia. It is noted that no single HCD has yet been identified that can verify compliance to all the impurities regulated by the SAE or ISO standards and that the HCDs thus far selected are designed for a critical subset of the regulated impurities. The HCDs are currently being integrated in the HITRF Hydrogen Dispenser to validate their performance in a real-world field setting. This integration involves an interface that will automatically collect high pressure hydrogen for delivery to an HCD for analysis (most potential HCDs operate at near ambient temperatures and pressures). Following the HITRF deployment, the HCDs will be installed into a commercial fueling station identified by the State of California for an extended demonstration

3.5 Emerging Market--Hydrogen Blending into Natural Gas

One emerging market identified by H2@Scale that is gaining significant international traction is the addition of hydrogen into natural gas. In the short term, up to 20% hydrogen is under consideration. There are numerous issues with regards to the compatibility of the natural gas infrastructure to accommodate hydrogen, and this includes the impact on methods and instrumentation currently used for natural gas sensing. The Center for Hydrogen Safety [43] has a working group to address topical areas related to the safe introduction of hydrogen into the natural gas system. As part of this working group, there is a Detection subgroup, which is chaired by the NREL Sensor Laboratory and has members from the natural gas industry. A market survey of current detection methods is being assembled and each method will be evaluated for compatibility with hydrogen. Simultaneously, the impact of the addition of hydrogen to the analytical methods is being assessed. It has already been recognized that there could be significant adverse impact on the reliability of some detection technology with the addition of hydrogen. A summary report reviewing the various methods and impact of hydrogen is being developed.

4.0 SUMMARY

The NREL Sensor Laboratory research program has been guided by the needs of the hydrogen community. The original mission to assure the availability and proper use of hydrogen sensors is evolving. The NREL Sensor Laboratory is now striving to maximize the effectiveness of detection strategies by the development of science-based deployment strategies and integration of active monitoring into QRA tools such as HyRAM. The sensor laboratory is supporting the development of advanced hydrogen detection methods to accommodate the deployment requirements associated with new emerging large-scale markets, including the need for distributed wide area detection. At the same time, hydrogen incorporation into existing markets, such as the natural gas infrastructure, may impact existing leak detection and gas monitoring system; the Sensor Laboratory is working with industrial stakeholders to review the potential impact on the current methods and to develop and verify appropriate alternative detection strategies. The NREL Sensor Laboratory will remain a resource to the hydrogen community as hydrogen markets emerge and continue to grow.

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