NREL Hydrogen Sensor Testing Laboratory

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Subcontractors:
- Element One, Boulder, Colorado
- A.V. Tchouvelev & Associates, Inc. (AVT), Mississauga, Ontario, Canada

Project Start Date: October 1, 2010
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Support the safe implementation of hydrogen as an alternative fuel by assuring the availability of gas detection technology.
- Quantify performance of commercial and developing hydrogen sensors relative to DOE metrics.
- Support infrastructure and vehicle deployment by providing expert guidance on the use of hydrogen sensors and analyzers.
- Support development and assess performance of advanced hydrogen sensor technologies, including hydrogen wide area monitoring (HyWAM)[1] [1].
- Develop active monitoring as a mitigation strategy for more efficient facility designs with improved safety.
- Support development and updating of hydrogen safety codes and standards.
- Educate the hydrogen community on the proper use of hydrogen sensors.

Fiscal Year (FY) 2018 Objectives

- Enable safe infrastructure deployment by providing sensor testing capability and guidance to stakeholders in the hydrogen energy field.
- Quantify performance metrics of commercial as well as emerging and novel developmental sensor technologies.
- Support the U.S. Department of Transportation (DOT) on the development of the Federal Motor Vehicle Safety Standard (FMVSS) for hydrogen fuel cell electric vehicles (FCEVs), especially with regard to hydrogen detection requirements identified in the Global Technical Regulation (GTR) 13 [2].
- Facilitate safe deployment of FCEVs through participation in the SAE Fuel Cell Standard Committee and by developing the SAE Technical Information Report J3089, “Characterization of On-board Vehicular Hydrogen Sensors” [3].
- Advance the science of hydrogen safety by empirically profiling hydrogen releases (indoor and outdoor) for the validation of hydrogen plume dispersion models.
- Enable science-based revisions of hydrogen codes and standards by active participation within standard and code development organizations and committees and by research and development activity to support codes and standards development.

Technical Barriers

This project addresses the following technical barriers identified in the Hydrogen Safety, Codes and Standards section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.[2]

(A) Safety Data and Information: Limited Access and Availability

[1] HyWAM may be defined as the 3-dimensional temporal and spatial profiling of planned or unintentional hydrogen releases.
[2] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

(C) Safety is Not Always Treated as a Continuous Process

(D) Lack of Hydrogen Knowledge by AHJs

(F) Enabling National and International Markets Requires Consistent RCS

(G) Insufficient Technical Data to Revise Standards

(H) Insufficient Synchronization of National Codes and Standards

(K) No Consistent Codification Plan and Process for Synchronization of R&D and Code Development.

Contribution to Achievement of DOE Hydrogen Safety, Codes, and Standards Milestones

This project will contribute to the achievement of the following DOE milestones from the Hydrogen Safety, Codes and Standards section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 2.15: Develop holistic design strategies. (4Q, 2017)
- Milestone 2.19: Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)
- Milestone 3.1: Develop, validate, and harmonize test measurement protocols. (4Q, 2014)
- Milestone 4.9: Completion of GTR Phase 2. (1Q, 2017)
- Milestone 5.1: Update safety bibliography and incidents databases. (4Q, 2011–2020)

FY 2018 Accomplishments

- **Provisional Patent (NREL Prov 17-94A):** Filed "Interface for a High-Pressure Hydrogen Dispenser" (2018), which specifically addresses a means to provide gas samples at low-pressure gas compatible for analysis by all potential on-site hydrogen contaminant detectors (W. Buttner and K. Harrison).
- **NREL Record of Invention (ROI):** Filed NREL ROI "Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)" (2018, W. Buttner), which describes the use of a distributed network of point sensors (chemical, physical, and environmental) as a basis for HyWAM. This ROI formed the basis of a DOE Technology Commercialization Fund project [4].
- **Hydrogen Safety Sensor Gap Analysis:** Published a gap analysis for hydrogen safety sensors [5]. The gap analysis, which identified critical gaps in hydrogen safety sensor performance, was an outcome of a workshop which was jointly organized by NREL, the European Joint Research Centre (JRC), and the Fuel Cell and Hydrogen Joint Undertaking (FCH JU).
- **FCEV Exhaust Gas Measurement Technology:** The NREL Sensor Laboratory collaborated with DOT to design, build, and demonstrate an analyzer capable of verifying that hydrogen levels in FCEV exhaust are within the levels as prescribed by GTR 13 [2].
- **Characterization of Indoor Hydrogen Releases:** Profiled indoor hydrogen releases through the development of empirically validated computational fluid dynamics (CFD) models in collaboration with A. V. Tchouvelev & Associates, Inc. (AVT) to enable an improved understanding of indoor hydrogen dispersion. This work is anticipated to be incorporated into NFPA 2 [6] as a guidance document on sensor placement.
- **SAE Technical Information Report (TIR) J3089, "Characterization of On-board Vehicular Hydrogen Sensors":** SAE J3809 development was led by the NREL Sensor Laboratory under the auspices of the SAE Fuel Cell Standard Committee. The TIR passed ballot and has been published as a formal SAE document [3].

INTRODUCTION

Hydrogen sensors are an enabling technology to assure the safe use of hydrogen as an alternative renewable fuel. To assure the availability of reliable safety sensors and their proper use, the DOE Fuel Cell Technologies Office established the NREL Hydrogen Sensor Testing Laboratory [7]. The NREL Sensor Laboratory provides stakeholders (e.g., sensor developers and manufacturers, end users, and code officials) a resource for an independent, unbiased evaluation of hydrogen sensor performance. Sensor evaluations are performed using test protocols that were guided by the requirements in national [8] and international sensor standards [9], as well as by the sensor performance targets established by DOE [10]. In addition to laboratory assessment, the NREL Sensor Laboratory strives to assure the proper use of hydrogen sensors through outreach activity such as participation on code and standards development organizations (CDOs/SDOs), safety committees, workshops, conferences, and webinars. The NREL Sensor Laboratory further facilitates deployment by partnering directly with end users to assist in the design and implementation of their sensor system. An emerging mission of the NREL Sensor Laboratory is to develop HyWAM strategies to support H2@Scale [11] and to characterize hydrogen dispersion as a means to improve facility safety [12].

APPROACH

The NREL Sensor Laboratory research, development, and demonstration (RD&D) effort is guided by the needs of the hydrogen community, which is evolving as infrastructure strives to accommodate the growing FCEV fleet of commercial vehicles. Although the mission of the NREL Sensor Laboratory is evolving, the unbiased and confidential performance evaluation of hydrogen sensors has been a core activity within the NREL Sensor Laboratory. In this function, the NREL Sensor Laboratory supports sensor developers, end users, as well as permitting officials and standard and code developers. This expertise also supports the qualification of sensors for specialized application, such as HyWAM. Sensor evaluations are performed using a custom-built sensor test apparatus (Figure 1), which was designed with advanced capabilities, including simultaneous testing of multiple hydrogen sensors, sub-ambient to elevated temperature, sub-ambient to elevated pressure, active humidity control, and accurate control of gas parameters with multiple precision digital mass flow meters operating in parallel. In addition, other test fixtures have been developed for life tests and chemical poison studies, as well as for specialized applications. The test apparatuses are fully automated for control and monitoring of test parameters and for data acquisition with around-the-clock operation capability. Test sensors are subjected to an array of tests to quantify the impact of variation of environmental parameters and chemical matrix on performance. Although standard protocols have been developed (e.g., [3] and more recently [13]), these can be adapted for specialized requirements. Results are reported back to the client to support their future development work. NREL sensor testing also supports end users by qualifying sensor technology for their application (e.g., [14]) and by educating the hydrogen community on the proper use of hydrogen sensors.

The NREL Sensor Laboratory maximizes its impact by direct collaborations with stakeholders in the hydrogen community; this is achieved in part through formal agreements with industrial partners, including nondisclosure agreements, technical service agreements, and cooperative research and development agreements. Strategic partnerships have also been maintained with other government organizations, most notably with the JRC in Petten, Netherlands, under which the respective sensor test facilities collaborated on hydrogen sensor research projects of common interests. Currently, this collaboration is formalized under a DOE-JRC agreement [15] and has led to multiple publications including several cited in this report (e.g., [5], [12]). Such collaborations provide a platform for the international distribution of the NREL sensor research and development.

In addition to sensor performance assessment, the scope of the NREL Sensor Laboratory has expanded its active participation on a variety of national and international codes and standards development organizations and safety committees, including National Fire Protection Association (NFPA) 2, International Standards Organization (ISO) Technical Committee (TC) 197, SAE Fuel Cell Standards Committee, UL, Compressed Gas Association (CGA), ASTM International, HySafe, and the GTR. The type of support provided by the

NREL Sensor Laboratory to SDOs, CDOs, and safety committees includes (1) pre-normative research to support code and standard requirements; (2) document development; (3) development and deployment of verification technology; and (4) expert guidance and recommendations. Increasingly, the NREL Sensor Laboratory uses its expertise to develop sensor-based tools for the hydrogen community; currently this includes developing HyWAM for hydrogen plume profiling to support NFPA 2 and a hydrogen analyzer to verify compliance of FCEV exhaust requirements as prescribed in the GTR. Dissemination of results is through a variety of venues, including participation on international hydrogen safety committees, presentations at international conferences and workshops, publications in the open literature, and direct outreach to the hydrogen community.

Finally, the NREL Sensor Laboratory has an ongoing commitment to training young scientists and engineers in the field of renewable energy. Accordingly, the NREL Sensor Laboratory has for several years provided internship opportunities to undergraduate engineering majors. While supervised by the director of the NREL Sensor Laboratory, interns are assigned a specific project. Responsibilities include experimental design and data analysis, as well as direct interaction with clients. Interns have made significant contributions to numerous projects within the NREL Sensor Laboratory, including several described in this report. They are included as coauthors on numerous presentations and papers.

Figure 1. The NREL hydrogen sensor test apparatus

RESULTS

Although activity of the NREL Sensor Laboratory was hindered somewhat by FY 2018 budget uncertainties, significant progress was achieved. Highlights are discussed below.

Support of the GTR 13 and FMVSS

GTR 13 [1] is the defining document regulating hydrogen vehicle safety requirements. GTR 13 has been formally implemented by the international regulatory community, and as such, national authorities overseeing development and enforcement of vehicle regulations are to endeavor to harmonize their national regulations with the GTR. Within the United States, the national authority for vehicle safety is the DOT and the prevailing regulatory code is the FMVSS. Included within the GTR are safety requirements on allowable hydrogen levels in FCEVs. The NREL Sensor Laboratory, in cooperation with DOT, has been developing an off-vehicle exhaust gas analyzer and analytical methods for compliance verification to the hydrogen emission requirements specified in the GTR. In the past year, the analyzer was deployed on an FCEV operating under simulated road conditions using a dynamometer (testing was performed at an original equipment manufacturer facility under a non-disclosure agreement). Figure 2 shows a series of hydrogen pulses that were discharged from the FCEV during operation, all of which were within compliance to the GTR regulations. The NREL analyzer was configured to be compatible with a gas collection system used by a vehicle test facility identified by DOT (Air Quality Division, Environment and Climate Change Canada). Plans are being formulated to deploy the NREL analyzer on a commercial FCEV at the Environment and Climate Change vehicle test facility.

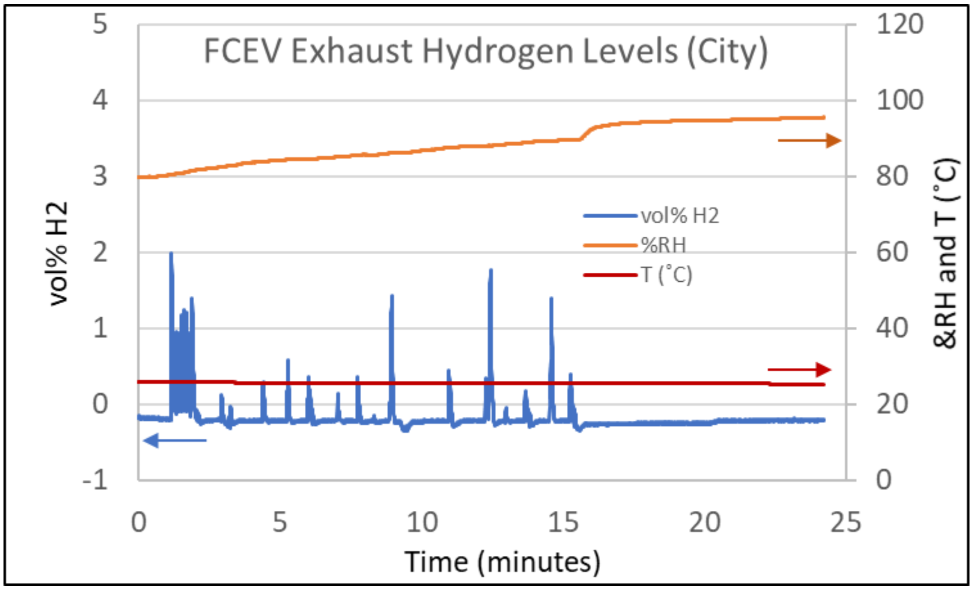

Figure 2. Hydrogen concentrations as measured from an actual FCEV operating under simulated load conditions (using a dynamometer) as measured with the NREL Exhaust Gas Analyzer. Although hydrogen transients were observed, they were within the regulated levels prescribed by GTR 13 [2].

The NREL Sensor Laboratory has also supported DOT on the upcoming revision of GTR 13. Currently within the GTR, one proposed means to quantify hydrogen in closed spaces (e.g., passenger compartments, trunks) is through oxygen displacement. Earlier work by NREL and the JRC has shown this method to be insufficiently accurate and plagued with potential false readings for regulatory purposes [6]. It was thus jointly proposed by NREL and the JRC that reference within GTR 13 to the proposed use of oxygen displacement as a means to quantify hydrogen or helium buildup in the FCEV be removed in future revisions. This recommendation was made to the to the representative on the GTR development committee (Nha Nguyen/DOT).

Characterization of Outdoor Liquid Hydrogen Releases with HyWAM

Cold hydrogen plumes formed during liquid hydrogen (LH2) releases are currently not well understood because field data is essentially nonexistent. This lack of understanding leads to overly conservative safety distances at LH2 facilities. To address this need, the NREL Sensor Laboratory, in collaboration with the NFPA 2 Hydrogen Storage Task Group, developed the prototype Hydrogen Plume Analyzer to empirically monitor LH2 storage tank venting. The prototype analyzer, which consisted of multiple sampling points for gas (e.g., hydrogen and oxygen) and physical (e.g., temperature and humidity) sensors, could form the basis for a Hydrogen Wide Area Monitor (HyWAM) [16]. A HyWAM is now being developed for research purposes and general deployment. Active monitoring has been identified by the NFPA 2 Hydrogen Storage Task Group as a mitigation strategy to alleviate the large setbacks associated with LH2 storage.

Characterization of Indoor Hydrogen Releases:

Sensors are mandated by both the International Fire Code [17] and NFPA 2 [6] for numerous indoor hydrogen infrastructure applications. However, no guidance is provided on the selection or use of sensor technology. Rational sensor placement guidance requires an understanding of hydrogen dispersion behavior within the deployment environment, which in turn requires the development of validated models. Working in collaboration with the NREL Sensor Laboratory, AVT performed CFD modeling of a leak scenario associated with an electrolyzer system housed within a 20 foot ISO container. Independent CFD modeling was performed by the JRC under a collaboration agreement [15]. In this study, CFD modeling of the hydrogen dispersion was validated by the NREL Sensor Laboratory using a HyWAM system based upon an array of point sensors. As expected, it was shown that the dispersion of indoor hydrogen releases is predicated upon the facility ventilation flow patterns. Somewhat unexpectedly, however, the modeling demonstrated that optimal sensor placement may be achieved in locations of low ventilation flow within the facility (as modeled by CFD), and that in doing so, leaks can be more predictably and quickly detected than by placing the sensor in front of a ventilation exhaust system as is currently more frequently performed. Furthermore, low-level leaks can be detected that would have been undetectable by other means (e.g., pressure sensors mounted on pneumatic lines). Detection is achieved before dangerous levels of hydrogen can accumulate. A more thorough analysis will be presented at the 2019 International Conference on Hydrogen Safety (www.hysafe.info/ichs2019/). The effectiveness of optimized sensor placement to reduce hazards has not yet been quantified by a quantitative risk analysis (QRA). Expansion of indoor releases to other larger facilities and incorporation into QRA tools, such as HyRAM [18], is planned.

SAE Technical Information Report J3089 [3]

SAE TIR J3089, "Characterization of On-board Vehicular Hydrogen Sensors," was prepared under the auspices of the SAE Fuel Cell Standards Committee. The TIR passed ballot and was approved for publication. The TIR provides original equipment manufacturers and sensor suppliers with a common set of test protocols to be performed by the manufacturer for the assessment of sensor performance.

CONCLUSIONS AND UPCOMING ACTIVITIES

The NREL Sensor Laboratory has been a resource to the national and international hydrogen community since 2010. The unbiased and confidential performance evaluation of hydrogen sensors remains a core capability for the NREL Sensor Laboratory. In this function, the NREL Sensor Laboratory continues to support sensor developers, end users, and permitting officials as well as SDO and CDOs. The NREL Sensor Laboratory remains active on CDOs and SDOs, including UL, CGA, NFPA, SAE, and ISO, as well as safety committees such as HySafe. However, the mission of the NREL Sensor Laboratory is evolving. Increasingly, the NREL Sensor Laboratory is using its expertise to develop sensor-based tools for improved safety and risk reduction in hydrogen infrastructure. Currently this includes developing HyWAM for indoor and outdoor hydrogen plume profiling, and the hydrogen analyzer to verify compliance of FCEV exhaust requirements as prescribed in the GTR.

The NREL Sensor Laboratory is actively participating with the NFPA 2 Hydrogen Storage Task Group, which was formed to facilitate the use of LH2 at commercial fueling facilities. Active monitoring, such as with HyWAM, has been identified by the task group as a potential mitigation strategy to alleviate the prohibitive setbacks associated with LH2 storage, which can be as high as 75 feet [6]. This setback precludes the use of LH2 storage in many urban fueling stations. The current LH2 setbacks appear to have been established on consensus rather than a scientific basis. This is because of an inadequate understanding of hydrogen plume behavior, especially cold hydrogen plumes, which in turn is due, in part, to a lack of real-world data on hydrogen cold plume dispersions. There are two main themes to be addressed for the use of HyWAM and sensors in active monitoring for LH2 storage. First, it has been recognized that to implement mitigation strategies to lower the prescribed setbacks it will be necessary to more fully elucidate the behavior of real-world hydrogen releases, especially cold hydrogen releases; in part this is to identify the deployment number and location of measurement points. Thus, one critical role for sensors is the empirical characterization of real-world hydrogen dispersion behavior, which in turn can then be used to validate theoretical models and integrated into QRA to guide the design of a facility to optimize and quantify the effectiveness of active monitoring as a mitigation strategy. To do this, the NREL Sensor Laboratory is forming strategic partnerships to deploy HyWAM technology during planned LH2 releases; several of these were identified through participation in the HySafe Workshop [19] and include the Health and Service Laboratory (Buxton, United Kingdom) and Karlsruhe Institute of Technology (Karlsruhe, Germany). There are in addition studies within the United States investigating LH2 release behavior and being planned by the Compressed Gas Association and by Lawrence Livermore National Laboratory. NREL also has a pending partnership with a developer of commercial hydrogen fueling stations (First Element) through the DOE Technology Commercialization Fund project [4]. In addition to validating the fundamental behavior of released hydrogen dispersion, sensors will also be needed for deployment within and around a facility as elements in the active monitor. Thus, in addition to validating the fundamental behavior of released hydrogen dispersion (e.g., a “research HyWAM”), sensors will also be used in a deployed monitoring system (e.g., a “deployed HyWAM”). Cost and ease of operation are critical metrics for the deployed HyWAM. Hydrogen safety sensors have been part of a hydrogen safety system for many years to assure safety integrity level compliance and because they were prescribed in codes such as NFPA 2 and the International Fire Code. As with the conventional use of hydrogen sensors in a facility safety system, the elements of an active monitoring system must cost-effectively meet stakeholder expectations with respect to critical performance metrics that must be validated through performance testing. The distinction and interrelation between the two sensor applications and the role of the NREL Sensor Laboratory are illustrated in Figure 3. At present, however, there is no viable HyWAM technology available, although various approaches have been proposed [1] and even demonstrated, although usually under highly controlled conditions. HyWAM may be based upon stand-off strategies, such as Raman [20], Schlieren [21], and acoustic, or through a distributed network of point sensors [12]. The NREL Sensor Laboratory has developed a hydrogen analyzer that can simultaneously measure hydrogen concentration (and other parameters) from multiple locations; this system can form the basis of a HyWAM. The development of HyWAM for assurance of hydrogen safety is a critical component in the FY 2019 NREL Sensor Laboratory RD&D program.

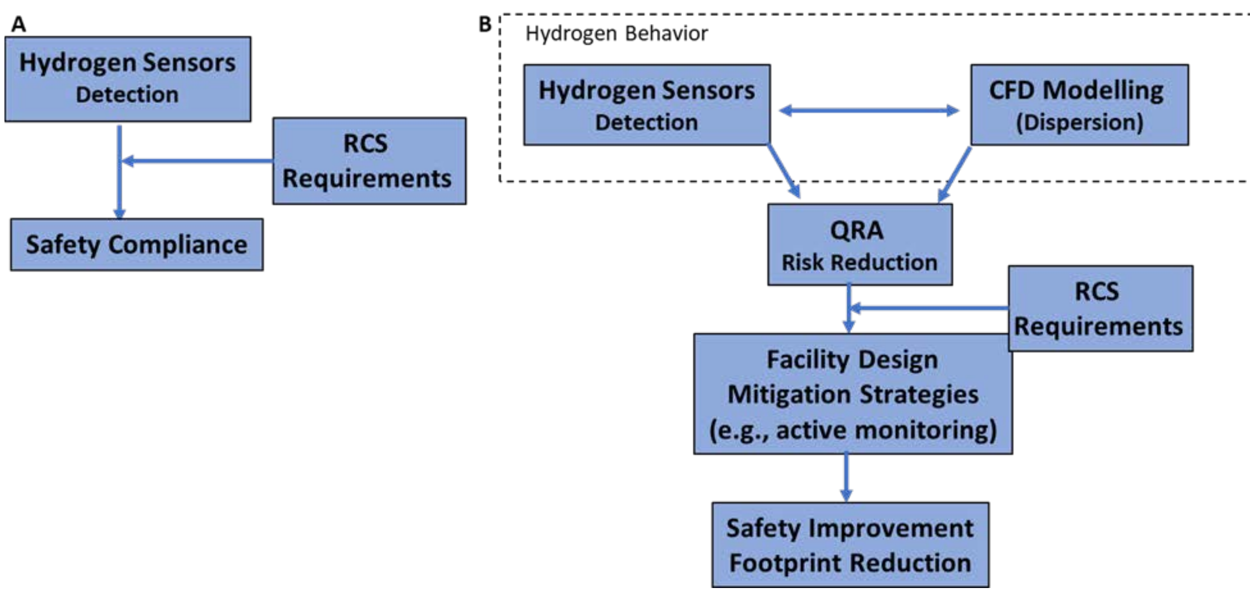

Figure 3. Evolving mission of the NREL Sensor Laboratory. (A) Hydrogen sensors have been routinely used as part of a facility safety system to achieve an appropriate safety integrity level and at the same time to assure compliance to prescriptive code requirements. (B) Detection is also needed to verify released hydrogen behavior (e.g., using HyWAM) to validate dispersion models and for a facility active monitoring system. Coupled with other mitigation strategies, active monitoring can assure improved safety in smaller footprints.

The previous discussion focused on outdoor LH2 applications. Elucidation of hydrogen dispersion is germane for indoor and outdoor gaseous hydrogen and LH2 operations. Understanding hydrogen dispersion behavior can also improve safety of indoor hydrogen operations, and the NREL Sensor Laboratory is also actively working on improving safety of indoor operations. Indoor sensor placement guidance requires an understanding of hydrogen behavior within the deployment environment, which in turn requires the development of validated models. In our recent study on an indoor gaseous hydrogen facility, CFD modeling of the hydrogen dispersion was independently cross-verified by two groups (AVT and the JRC). The specific system was a hydrogen production system housed within a ventilated ISO container housing. The models were validated by the NREL HyWAM system, which is based upon an array of point sensors (preliminary results were briefly presented in [22]). As expected, it was shown that the dispersion of indoor hydrogen releases is predicated upon the facility ventilation flow patterns. Somewhat unexpectedly, however, the modeling demonstrated that optimal sensor placement may be achieved in locations of low ventilation flow within the facility (as modelled by CFD), and that in doing so, leaks can be more predictably and quickly detected than by placing the sensor in front of a ventilation exhaust system as is currently more frequently performed. Furthermore, low-level leaks can be detected that would have been undetectable by other means (e.g., pressure sensors mounted on pneumatic lines). A more thorough analysis will be formally presented at the 2019 ICHS in a paper to be coauthored by AVT, JRC and the NREL Sensor Laboratory. The effectiveness of optimized sensor placement to reduce hazards is to be quantified by a QRA. It is also planned to expand this study to larger-scale indoor hydrogen facilities.

The analytical performance of the NREL FCEV Exhaust Gas Analyzer has been demonstrated. The DOT has supported development of the analyzer and to perform real-world measurements on an FCEV. A probe that integrates the exhaust gas collection system to the analyzer was developed by NREL and tested on an FCEV operating under simulated load conditions using a dynamometer. It is planned to deploy the integrated system on an FCEV at a certified vehicle test facility identified by DOT (currently this is planned to be within the Air Quality Division, Environment and Climate Change Canada in Ontario, Canada).

SPECIAL RECOGNITIONS AND AWARDS/PATENTS ISSUED

1. 2018 DOE Hydrogen and Fuel Cells Program R&D Award in recognition "For outstanding dedication and contributions to hydrogen safety, sensor technologies, and the global hydrogen refueling community".
2. "EERE Success Story—NREL-KPA-Toyota Collaboration Facilitates Permitting of FCEV Repair Facilities," https://www.energy.gov/eere/success-stories/articles/eere-success-story-nrel-kpa-toyota-collaboration-facilitates, February 15, 2018.
3. Invited speaker and session organizer (Mitigation, Sensors, Hazard Prevention, and Risk Reduction) for the 2018 HySafe Research Safety Priorities Workshop, Buxton, United Kingdom, September 18–20, 2018.
4. W. Buttner, NREL Record of Invention ROI-18-28, "Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)," 2018.
5. W. Buttner and K. Harrison, NREL Provisional Patent PROV-17-94A, "Interface for High Pressure Dispensers," 2018.

FY 2018 PUBLICATIONS/PRESENTATIONS

Talks and Presentations

1. W. Buttner, E. Weidner, R. Ortiz-Cebolla, and C. Bonato, "Safety Sensors for the Hydrogen Infrastructure," Fuel Cell Seminar and Energy Exposition, Long Beach, CA (November 7–9, 2017).
2. W. Buttner, H. Wright, A. Tchouvelev, D. Meleido, D. Baraldi, and E. Weidner, "The NREL Hydrogen Sensor Laboratory—Indoor Sensor Placement Study and Hydrogen Wide Area Monitoring," DOE FCTO Codes and Standards Tech Team (2017).

3. R. Ortiz-Cebolla, E. Weidner, C. Bonato, W. Buttner, and H. Wright, "Hydrogen Safety Sensor Stability Testing—Impact of the Chemical Environment," European Hydrogen Energy Conference, Costa del Sol, Spain (March 14–16, 2018).
4. J. Stetter, V. Patel, W. Buttner, and H. Wright, "Characterization of a Selective, Zero Power Sensor for Distributed Sensing of H2 in Energy Applications," International Meeting on Chemical Sensors, Vienna, Austria (July 15–19, 2018). This work was a summary of collaborative work performed under the DOE Small Business Voucher Program [23].
5. W. Buttner, A. Tchouvelev, D. Meleido, and L. Gardner, "Mitigation, Sensors, Hazard Prevention, and Risk Reduction," HySafe Hydrogen Safety Research Priorities Workshop, Buxton, United Kingdom, (September 19–22, 2018).
6. F. Markert, D. Cironne, N. Barilo, I. Azkarate, Iñaki, and W. Buttner, "General Aspects of Hydrogen Safety," HySafe Hydrogen Safety Research Priorities Workshop, Buxton, United Kingdom (September 19–22, 2018).
7. W. Buttner, "The NREL Hydrogen Sensor Testing Laboratory," DOE Hydrogen and Fuel Cells Program 2018 Annual Merit Review and Peer Evaluation Meeting, Washington, DC (June 13–15, 2018).

Publications

1. W. Buttner, M. Ciotti, K. Hartmann, K. Schmidt, H, Wright, and E. Weidner, "Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH2 Storage Vessels," *International Journal of Hydrogen Energy* (in press) (2018).
2. R. Ortez-Cebolla, E. Weidner, C. Bonato, W. Buttner, K. Hartmann, and K. Schmidt, "Test Methodologies for Hydrogen Sensor Performance Assessment: Chamber vs. Flow-Through Test Apparatus," *International Journal of Hydrogen Energy* (in press) (2018).
3. R. Ortiz-Cebolla, E. Weidner, C. Bonato, and W. Buttner, *Summary Report for a Hydrogen Sensor Workshop—Hydrogen Safety Sensors and Their Use in Applications with Hydrogen as an Alternative Fuel*, EUR 28852 EN, Brussels, Belgium (2017), https://ec.europa.eu/jrc/en/publication/summary-report-hydrogen-sensor-workshop-hydrogen-safety-sensors-and-their-use-applications-hydrogen.
4. SAE Technical Information Report, "J3089: Characterization of On-Board Vehicular Hydrogen Sensors," SAE (2018); completed under the auspices of the SAE Fuel Cell Standard Committee, https://saemobilus.sae.org/content/J3089_201810.
5. W. Buttner, "Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)," NREL Record of Invention ROI-18-28 (2018).
6. W. Buttner and K. Harrison, "Interface for High Pressure Dispensers," NREL Provisional Patent PROV-17-94A (2018).
7. EERE Success Story, "NREL-KPA-Toyota Collaboration Facilitates Permitting of FCEV Repair Facilities" (February 15, 2018), https://www.energy.gov/eere/success-stories/articles/eere-success-story-nrel-kpa-toyota-collaboration-facilitates.
8. W. Buttner, "NREL Hydrogen Sensor Testing Laboratory," DOE Hydrogen and Fuel Cells Program FY 2017 Annual Progress Report (2018), https://www.hydrogen.energy.gov/pdfs/progress17/viii_7_buttner_2017.pdf.

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4. Department of Energy Announces Technology Commercialization Fund Projects (2018).
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9. ISO 26142—Hydrogen Detector Apparatus for Stationary Applications, ISO 26142, International Standards Organization: 36 (2010).
10. Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan, Planned program activities for 2005–2015, U.S. DOE Office of Renewable Energy and Efficiency (2005).
11. DOE, "H2@Scale" (2017), https://www.energy.gov/eere/fuelcells/h2-scale.
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13. Standard Hydrogen Test Protocols for the NREL Sensor Testing Laboratory (2011), https://www.nrel.gov/docs/fy08osti/42666.pdf.
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16. Buttner, W., "Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)," NREL Record of Invention ROI-18-28 (2017).
17. 2015 International Fire Code (IFC) (2015).
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22. Buttner, W., "NREL Sensor Testing Laboratory," U.S. Department of Energy Hydrogen and Fuel Cells Program 2018 Annual Merit Review and Peer Evaluation, Washington, DC (2018).
23. Small Business Voucher—U.S. Department of Energy (2017), https://www.sbv.org/.