# NREL Hydrogen Sensor Testing Laboratory

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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) 2019 Objectives

- Enable safe infrastructure deployment by providing sensor testing capabilities 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 the safe deployment of FCEVs through participation in the SAE International (SAE) Fuel Cell Standard Committee, which includes the development and publication of the SAE Technical Information Report J3089 Characterization of On-board Vehicular Hydrogen Sensors” [3].
- Advance the science of hydrogen safety by empirical profiling of 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 R&D activities to support code and standard 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
- (C) Safety is Not Always Treated as a Continuous Process
- (D) Lack of Hydrogen Knowledge by Authorities Having Jurisdiction

[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

- (F) Enabling National and International Markets Requires Consistent Regulations, Codes and Standards
- (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 Milestones

This project contributes 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 4.8: Revision of NFPA 2 to incorporate advanced fueling and storage systems and specific requirements for infrastructure elements such as garages and vehicle maintenance facilities. (3Q, 2016)
- Milestone 4.9: Completion of GTR Phase 2. (1Q, 2017)
- Milestone 5.1: Update safety bibliography and incidents databases. (4Q, 2011–2020)

## FY 2019 Accomplishments

- Received NREL Provisional Patent, "Hydrogen Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)," December 18, 2018, W. Buttner [4]. This provisional patent formed the basis of a DOE Technology Commercialization Fund (TCF) project [5] and the corresponding cooperative research and development agreement with KWJ, Inc. (CRD 18-00784: Commercialization of the NREL Hydrogen Wide Area Monitor).
- Contributed to development of SAE Technical Information Report (TIR) J3089, "Characterization of On-board Vehicular Hydrogen Sensors," which was formally published on October 9, 2018 [3].
- Designed, built, and demonstrated an analyzer for verifying that hydrogen levels in FCEV exhaust are within the levels prescribed by GTR-13 [2]. The analyzer was demonstrated on a commercial FCEV in collaboration with Environment and Climate Change Canada (ECCC) [6].
- Characterized indoor hydrogen releases: performed and validated quantitative characterization of the behavior of indoor hydrogen releases through computational fluid dynamic (CFD) models, enabling improved understanding of the impact of forced ventilation vs. on-demand ventilation on indoor hydrogen dispersions and the development of preliminary guidance on indoor sensor placement strategy [7–9].
- Deployed NREL HyWAM for liquid hydrogen (LH2) release characterization at the Health and Safety Executive (HSE) test site in the United Kingdom to profile cold hydrogen dispersions during releases [10–13].

## INTRODUCTION

Hydrogen sensors are an enabling technology for the safe use of hydrogen as a renewable fuel. To assure the availability of reliable safety sensors and their proper use, the DOE Fuel Cell Technologies Office (FCTO) established the NREL Safety Sensor Laboratory [14]. To facilitate the expansion of the hydrogen infrastructure, the NREL Sensor Laboratory is now exploring active monitoring and other risk reduction strategies (e.g., hydrogen component reliability and impact studies) as part of an integrated approach to improve hydrogen facility safety. However, the NREL Sensor Laboratory continues to provide 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 [15] and international sensor standards [16], as well as by the sensor performance targets established by DOE in the Multi-Year Research, Development, and Demonstration Plan [17]. In addition to laboratory assessment, the Sensor Laboratory strives to assure the proper use of hydrogen sensors through outreach activity such as participation on code and standard development organizations, 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 systems. An emerging mission of the NREL Sensor Laboratory is to develop hydrogen gas detection and monitoring strategies to support H2@Scale [18] and to incorporate active monitoring as a risk mitigation strategy to improve facility safety [19].

## APPROACH

The NREL Sensor Laboratory research, development, and deployment (RD&D) effort is guided by the needs of the hydrogen community and is evolving as infrastructure strives to accommodate the growing FCEV fleet of commercial vehicles and other emerging hydrogen markets (e.g., fuel cell trains, maritime applications, heavy duty vehicles). Although the mission and activity focus of the NREL Sensor Laboratory is evolving, the unbiased and confidential performance evaluation of hydrogen sensors remains a core capability. In this function, the NREL Sensor Laboratory supports sensor developers, end users, permitting officials, and standard and code developers. This expertise also supports the qualification of sensors for specialized application, such as HyWAM. Sensor metrological 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 [20]), these can be adapted for specialized applications. Results and data are reported back to the client to support their future development work. Attributed data are treated as confidential and are not openly disseminated, although sanitized data without reference to specific technology is used by the NREL Sensor Laboratory in publications and talks to demonstrate sensor performance and behavior. NREL sensor testing also supports end users by qualifying sensor technology for their application (e.g., [21]) 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 are also maintained with other government organizations, which have included both national collaborations, such as DOT [22], and international partnerships, most notably with the European Commission’s Joint Research Centre (JRC) in Petten, Netherlands. Ongoing since 2008, this international collaboration was most recently formalized under a DOE-JRC agreement [23] and has resulted in numerous joint outcomes, including a book on hydrogen sensors [24] and one study highlighted in this report [9]. In the past year, the NREL Sensor Laboratory expanded its collaborations with international government agencies. NREL and HSE in the United Kingdom initiated a collaboration [12] to characterize the behavior of cold hydrogen releases performed under the auspices of Prenormative Research for the Safe Use of Liquid Hydrogen (PRESLHY) [11]. HSE has extensive experience in handling LH2 and performing release studies (e.g., [25]), whereas the NREL Sensor Laboratory provides critical gas measurement expertise, including experience with LH2 releases [26] so as to quantitatively profile the hydrogen releases. The NREL Sensor Laboratory is also collaborating with ECCC [27] and Transport Canada to validate test methods for verification of FCEV safety requirements as prescribed in GTR 13 [2]. Such collaborations provide a platform for the national and international distribution of the NREL sensor research and development.

Figure 1. The NREL hydrogen sensor test apparatus

The NREL Sensor Laboratory maintains a presence on a variety of national and international codes and standards development organizations and safety committees, including NFPA 2, ISO Technical Committee 197, SAE Fuel Cell Standards Committee, UL, Compressed Gas Association, ASTM International, HySafe, and the GTR. The support provided by the NREL Sensor Laboratory to standard development organizations, code development organizations, and safety committees include (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 [4] and a hydrogen analyzer to verify compliance of FCEV exhaust requirements as prescribed in GTR 13 [2]. Dissemination of results is through a variety of venues, including participation on hydrogen safety committees, presentations at international conferences and workshops, publications in the open literature, and direct outreach to the hydrogen community.

The NREL Sensor Laboratory continues to maintain an ongoing commitment to training young scientists and engineers in the field of renewable energy and has for several years provided internship opportunities to undergraduate engineering majors. While supervised by senior NREL Sensor Laboratory personnel, interns are assigned a specific project and allowed the opportunity for independent research and professional growth. 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 and accordingly are often coauthors on presentations and papers, as exemplified by some of the work highlighted in this report [6, 13].

Finally, verification of hydrogen purity is important for the success of the FCEV market. National [28] and international standards [29] mandate a very high purity level for hydrogen with prescriptive restrictions on the allowable maximum concentrations of several potential contaminants (e.g., 100 ppb for carbon monoxide, 4 ppb for total sulfur, and others). As a gas detection problem, the NREL Sensor Laboratory is supporting the development and implementation of strategies to assure that hydrogen for FCEVs at the dispenser meets required purity levels. This includes a review of gas analyzers that can meet at least some of the critical fuel purity requirements and adaptation of the analyzers for installation at the dispenser for the near real-time verification that the dispensed hydrogen is compliant to regulations. Several commercially mature analyzers have been acquired and are currently being configured for use at hydrogen stations. Preliminary results on analyzer performance and dispenser integration will be presented at the 2019 Fuel Cell Seminar and Energy Exposition [30].

## RESULTS

The RD&D focus of the NREL Sensor Laboratory is evolving beyond sensor performance evaluation and use to a holistic approach for improved facility safety using active monitoring and other risk reduction strategies. Significant progress was achieved in FY 2019, especially in conjunction with strategic partnerships with hydrogen energy stakeholders. Highlights are discussed below.

### Support of the GTR 13 and the FMVSS

GTR 13 [1] is the defining document regulating hydrogen vehicle safety requirements and is to serve as the basis for national regulations on FCEV safety. 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, while within Canada, Transport Canada is the national authority and the prevailing regulatory code is the Canadian Motor Vehicle Safety Standard. Included within GTR 13 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 GTR 13 [22]. In the past year, the analyzer was deployed on an FCEV operating under simulated driving conditions using a chassis dynamometer at the ECCC Emissions Research and Measurement Section facility in Ottawa, Canada. The NREL analyzer was configured to be compatible with a gas collection and transfer system developed by the ECCC vehicle test facility for hydrogen-powered vehicles; this gas collection and transfer system was analogous to designs routinely used in exhaust measurements on vehicles with conventional internal combustion engines. Figure 2 shows the hydrogen profile measured from the FCEV during simulated driving operation on a dynamometer. In this test, the net hydrogen response was within compliance to the GTR regulations. Figure 2 presents the results of one out of nearly 20 tests performed on the FCEV, which included standard protocols for simulated highway and urban driving conditions, as well as the specific test protocol prescribed in GTR 13 during vehicle shutdown. The results and methodology are to be reviewed by DOT and Transport Canada. The test methods being developed by the NREL Sensor Laboratory and ECCC will be proposed for incorporation into the upcoming revision of GTR 13.

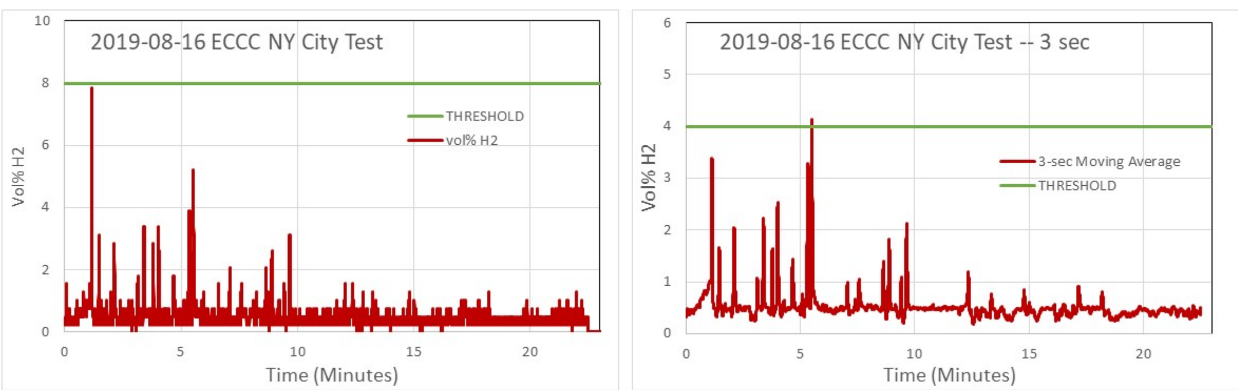


Figure 2. Hydrogen concentrations as measured with the NREL FCEV Exhaust Gas Analyzer. (Left) Real-time hydrogen measurements. GTR 13 requires that the instantaneous hydrogen level must remain below 8 vol %. (Right) 3-second moving average of the analyzer readings. GTR 13 requires that the hydrogen level must be maintained below 4 vol % over a 3-second moving average.

### Characterization of Outdoor LH2 Releases with HyWAM

The behavior of cold hydrogen plumes formed during LH2 releases is not well understood because real-world field data is essentially nonexistent. This lack of understanding contributed to the establishment of overly conservative safety distances at LH2 facilities, such as the 75-foot setback mandated by NFPA 2 for LH2 storage [7]. To address this knowledge gap, the NREL Sensor Laboratory developed a HyWAM system that can be deployed to empirically monitor LH2 venting [26]. The NREL HyWAM consists of multiple sampling points for gas measurements (e.g., hydrogen) and can be expanded to include physical (e.g., temperature and humidity) and environmental (e.g., wind speed and direction) sensors [31]. The NREL HyWAM has been configured for research deployments and a 32-measurement point system is presently deployed at the HSE LH2 test site. Under the auspices of PRESLHY [11], HSE is performing a series of large-scale LH2 releases. Initial testing on unignited releases has been performed at the HSE test site. The LH2 release included the NREL HyWAM along with supplemental sensors, including temperature, wind speed and direction, and sensors monitoring the release parameters within the LH2 release apparatus. Figure 3 shows hydrogen profiles at four of the NREL HyWAM hydrogen measurement points. A thorough analysis of the hydrogen sensor data and other parameters (wind, localized temperatures) by HSE modelers is ongoing. Ultimately, it is desired to incorporate cold hydrogen behavior, HyWAM active monitoring, and other mitigation strategies (e.g., facility design parameters) into quantitative risk analysis (QRA) to improve safety and ease setbacks associated with LH2 storage. Figure 4 shows the NREL and HSE team reviewing the LH2 release site just prior to installing the NREL HyWAM.

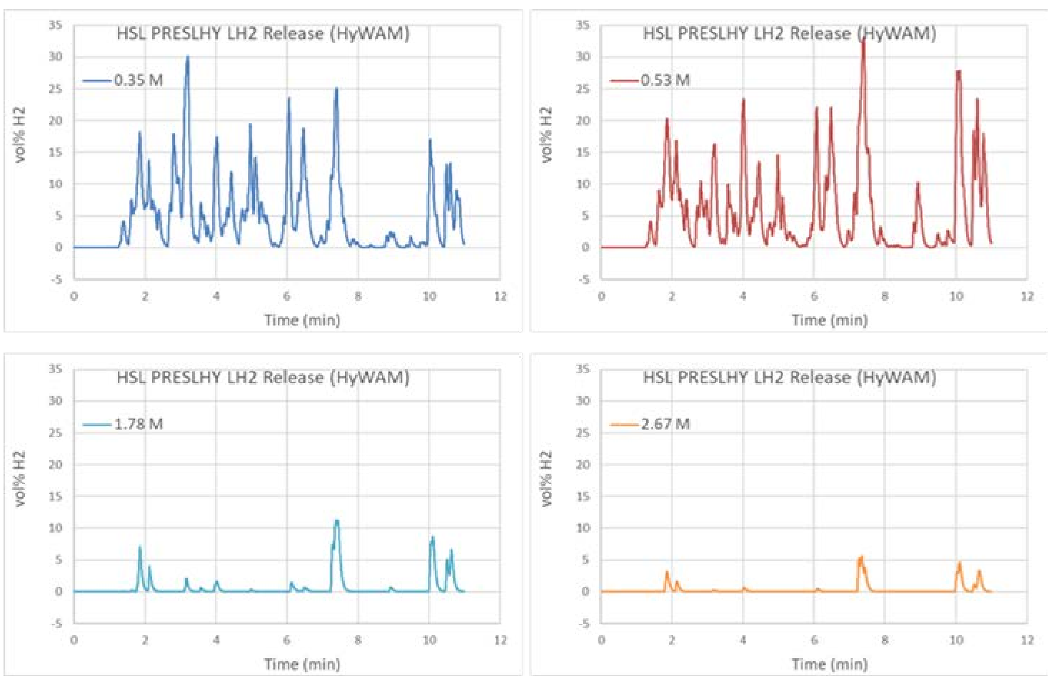


Figure 3. Hydrogen profiles of a horizontal LH2 release as measured with the NREL HyWAM. Four of 32 measurement points are shown. The measurement points were positioned 0.35 m to 2.67 m (as indicated) directly downstream from the LH2 release point.

Figure 4. The HSE-NREL team installing the NREL HyWAM at the HSE LH2 release apparatus. (L-R: Simon Coldrick/HSE, Jonathan Hall/HSE, Tashi Wischmeyer/NREL, and William Buttner/NREL)

**Characterization of Indoor Hydrogen Releases**

Sensors are mandated by both the International Fire Code [32] and NFPA 2 [7] 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, Inc. developed a CFD model for a leak scenario associated with an electrolyzer system housed within a 20-foot ISO container. The CFD model was validated by the NREL HyWAM. Independent CFD modeling was performed by the JRC under a collaboration agreement [23]. As expected, it was shown that the dispersion of indoor hydrogen releases is predicated upon the facility ventilation flow patterns. The CFD allowed for assessment of the impact of ventilation parameters (forced ventilation at various flow rates vs. on-demand ventilation). The modeling demonstrated that optimal sensor placement may be achieved in locations of low ventilation flow within the facility, 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 or even sensors designed to detect hydrogen at or near the lower flammable limit deployed by the exhaust of a facility ventilation system). Thus, detection is achieved before dangerous levels of hydrogen can accumulate. A thorough analysis was presented at the 8$^{th}$ International Conference on Hydrogen Safety [9]. The effectiveness of optimized sensor placement to reduce hazards has not yet been completely analyzed by a QRA but is ongoing. Expansion of indoor releases to other larger facilities and incorporation into QRA tools, such as HyRAM [8], to quantify risk reduction is ongoing.

## CONCLUSIONS AND UPCOMING ACTIVITIES

The NREL Sensor Laboratory has been a resource to the national and international hydrogen community since 2010. From its inception, the NREL Sensor Laboratory was part of the NREL Hydrogen Safety, Codes, and Standards Group, with Annual Operating Plan funding provided by DOE through the FCTO Safety, Codes and Standards subprogram. A major effort of the NREL Sensor Laboratory has been sensor performance assessment and assurance of the proper use of sensors by the hydrogen community. This activity supported sensor manufacturers and developers, end users, including vehicle and infrastructure applications, and the development of regulations, codes and standards. The RD&D focus of the NREL Sensor Laboratory is evolving to a more fundamental approach for assuring facility safety to beyond just the use of hydrogen sensors to comply with regulations, codes and standards. In response to this evolving mission of the NREL Sensor Laboratory, a separate Annual Operating Plan with FCTO was established for the NREL Sensor

Laboratory in FY 2019. The NREL Sensor Laboratory's expertise in hydrogen measurement technology is now being applied to elucidating the fundamental behavior of released hydrogen and integration of this knowledge into QRA for improved facility safety. This is already being implemented for indoor hydrogen facilities [9] and is being explored for outdoor LH2 operations through ongoing deployment of the NREL HyWAM at HSE [13] and other facilities. The evolving RD&D structure of the NREL Sensor Laboratory is illustrated in Figure 5, where hydrogen detection, such as HyWAM, plays a critical role in fundamental research on released hydrogen behavior, which in turn supports the design of an active monitoring system to help assure facility safety. In FY 2020, the structure of the DOE Annual Operating Plan integrates the NREL Sensor Laboratory into a holistic approach to the science of hydrogen safety (Figure 6). In addition to the NREL Sensor Laboratory, RD&D activity will include investigation into other factors that may impact facility safety, including specifically an assessment of hydrogen component reliability and to quantify the hazards associated with unintended hydrogen releases resulting from failed components. The ultimate integration of the findings into QRA (e.g., HyRAM) will support facility designs with improved safety and smaller size. This can directly ease the setbacks required by NFPA 2 for LH2 operations and facilitate the development of hydrogen infrastructure.

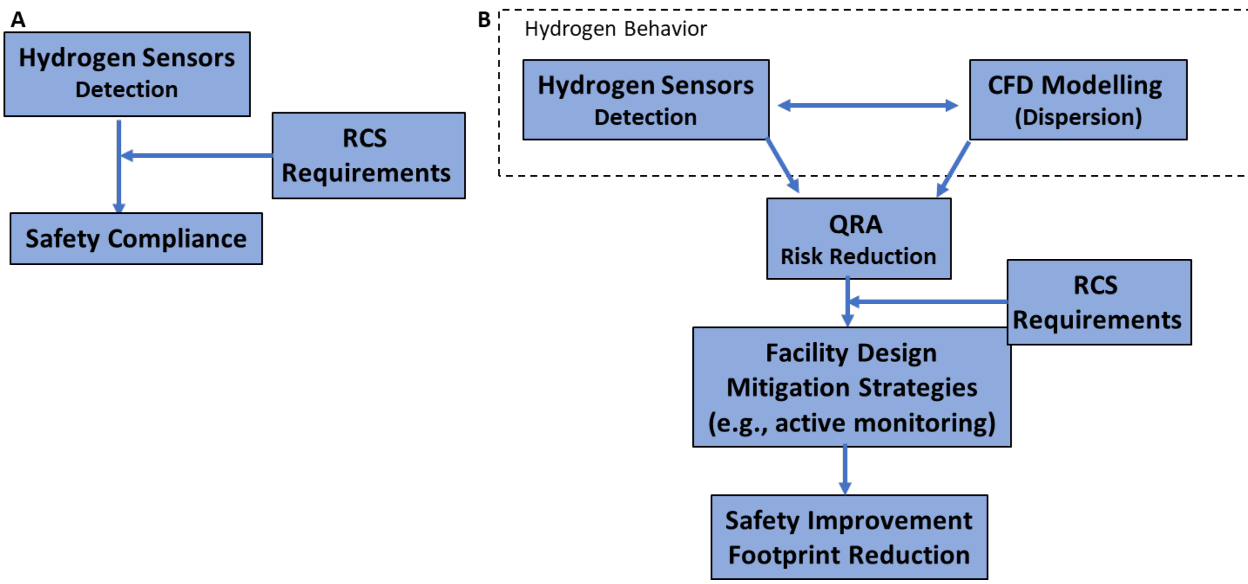


Figure 5. Evolving mission of the NREL Sensor Laboratory. (A) Hydrogen sensors have been routinely used as part of a facility safety system to achieve an appropriate safety integrity level while at the same time to assure compliance to prescriptive code requirements. (B) Detection is also needed to verify 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.

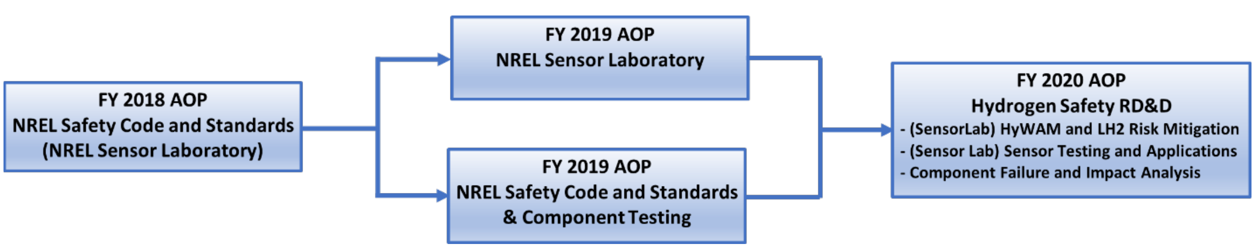


Figure 6. Evolution of the NREL Sensor Laboratory program structure

The DOT, Transport Canada, and ECCC have supported development and the recent deployment of the NREL FCEV Exhaust Gas Analyzer. The analytical performance of the NREL FCEV Exhaust Gas Analyzer was demonstrated on an FCEV operating under simulated driving conditions. Although functional, some improvements of the FCEV exhaust analyzer were identified during its deployment at the ECCC vehicle emissions testing facility, which will be addressed in the current year's activity. Optimization of the probe for improved reliability and user interface are planned and will be implemented and assessed by NREL and ECCC. Furthermore, the test methodology based upon the NREL FCEV Exhaust Gas Analyzer will be jointly developed by NREL and ECCC/Transport Canada for incorporation into the next version of the GTR.

## FY 2019 PUBLICATIONS/PRESENTATIONS

### Talks and Presentations

1. William Buttner, Jonathan Hall, Phil Hooker, Simon Coldrick, and Tashi Wischmeyer, "Hydrogen Wide Area Monitoring of LH2 Releases," presented at the 8th International Conference on Hydrogen Safety, Adelaide, Australia, September 24–26, 2019.
2. William Buttner, Aaron Loiselle-Lapointe, and Tashi Wischmeyer, "Compliance Measurements of Fuel Cell Electric Vehicle Exhaust," presented at the 8th International Conference on Hydrogen Safety, Adelaide, Australia, September 24–26, 2019.
3. Carl Rivkin, Crystal Xie, and William Buttner, "Safety Code Equivalencies in Hydrogen Infrastructure Deployment," presented at the 8th International Conference on Hydrogen Safety, Adelaide, Australia, September 24–26, 2019.
4. A.V. Tchouvelev, W. Buttner, D. Melideo, D. Baraldi, and B. Angers, "Development of Risk Mitigation Guidance for Sensor Placement Inside Mechanically Ventilated Enclosures Phase 1," presented at the 8th International Conference on Hydrogen Safety, Adelaide, Australia, September 24–26, 2019.
5. William Buttner and Tashi Wischmeyer, "NREL Hydrogen Sensor Testing Laboratory," DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting, Washington, DC, April 29–May 1, 2019.
6. William Buttner, Tashi Wischmeyer, Matthew Post, Jacob Thorson, and Kevin Hartmann, "NREL Hydrogen Sensor Testing Laboratory," Codes and Standards Tech Team Webinar, September 19, 2019.
7. W. Buttner and T. Wischmeyer, "Update on Hydrogen Wide Area Monitoring (Active Monitoring as a Mitigation Strategy for LH2 Setbacks)," Presented at the NFPA 2 Hydrogen Storage Task Group, Albuquerque, NM, October 23–24, 2018.

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3. William Buttner, Aaron Loiselle-Lapointe, and Tashi Wischmeyer, "Compliance Measurements of Fuel Cell Electric Vehicle Exhaust," *Proceedings of the 8th International Conference on Hydrogen Safety*, Adelaide, Australia, September 24–26, 2019.
4. Carl Rivkin, Crystal Xie, and William Buttner, "Safety Code Equivalencies in Hydrogen Infrastructure Deployment," *Proceedings of the 8th International Conference on Hydrogen Safety*, Adelaide, Australia, September 24–26, 2019.
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