VIII.7 NREL Hydrogen Sensor Testing Laboratory

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

Overall Objectives

- Quantify performance of commercial hydrogen sensors relative to DOE metrics.
- Support development and assess performance of advanced sensor technologies.
- Support development and updating of hydrogen sensor codes and standards.
- Support infrastructure and vehicle deployment by providing expert guidance on the use of hydrogen sensors and analyzers.
- Educate the hydrogen community on the proper use of hydrogen sensors.

Fiscal Year (FY) 2016 Objectives

- Support Department of Transportation (DOT)/ National Highway Traffic Safety Administration on the development of the Federal Motor Vehicle Safety Standard (FMVSS) for hydrogen fuel cell vehicles (FCEVs), especially with regards to hydrogen detection requirements identified in the Global Technical Regulation (GTR) 13 [1].
- Quantify performance metrics of developmental sensor technologies from both the private sector and government laboratories.
- Support infrastructure deployment by providing sensor testing capability and guidance to stakeholders in the hydrogen energy field.
- Qualify hydrogen safety sensors for specific infrastructure and vehicle applications.
- Facilitate safe deployment of FCEVs by participation on the SAE Fuel Cell Vehicle Crash Testing Safety Guidelines Task Force and the Fuel Cell Safety Task Force. As part of the Fuel Cell Task Force, the NREL Sensor Laboratory is leading the development of SAE Technical Information Report J3089, "Characterization of On-board Vehicular Hydrogen Sensors," which is to provide guidance for qualifying on-board hydrogen sensors.
- Support NREL component testing and facility upgrades with sensors and expertise for both safety and quantitation of hydrogen releases.
- Support hydrogen safety code and standard development by performing prenormative research on intended and unintended hydrogen releases.
- Support the deployment and implementation of hydrogen sensors for safety and fuel quality.

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.

(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 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 Safety, Codes & 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 2016 Accomplishments

- Implemented or maintained multiple formal agreements with industrial partners on the use of sensors in support of infrastructure deployment, for on-board vehicle applications, and in support of new advanced sensor technology development.
- Provided technical support to DOT/National Highway Traffic Safety Administration pertaining to FCEV hydrogen detection requirements as specified in the GTR, including requirements for both FCEV crash test and allowable tailpipe emissions. A prototype tailpipe analyzer has been demonstrated in the laboratory and will be configured for field deployment. This activity supports the development of the FMVSS (Milestone 4.9).
- In collaboration with the Joint Research Centre (JRC), Institute for Energy and Transport (IET), completed a study quantifying the impact of potential chemical poisons as identified in International Organization for Standardization (ISO) 26140 [2] on the major hydrogen sensor platform types (Milestone 3.1).
- Supported the development of the first draft of SAE Technical Information Report J3089, "Characterization of On-board Vehicular Hydrogen Sensors," under the auspices of SAE Fuel Cell Standards Committee.
- Formed an experts group among the NREL and the JRC sensor experts with computational fluid dynamics modelers and risk assessment experts to provide guidelines on hydrogen sensor placement.
- Developed a prototype analyzer for the in situ deployment in cold hydrogen releases to characterize plume dispersion in support of dispersion models and code development.
- Co-authored a book on hydrogen sensors (published January 2016): "Sensors for Safety and Process Control in Hydrogen Technology," Thomas Hűbert, Lois Boon-Brett, and William J. Buttner, CRC Press, Taylor and Francis Group, Boca Raton, ISBN 13-978-1-4665-9654-2 (2016).

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INTRODUCTION

Safety is a major concern for the emerging hydrogen infrastructure. A reliable safety system is comprised of various elements that can include intrinsic design features (e.g., pressure control systems), engineering controls (e.g., sample size minimization), and the use of hydrogen sensors to monitor for releases. Both the International Fire Code 2009 and National Fire Protection Association (NFPA) 2 require hydrogen sensors for numerous applications, and accordingly sensors will be mandatory in all jurisdictions that adopt either the International Fire Code or NFPA 2. To assure the availability of reliable safety sensors, DOE established the NREL Safety Sensor Testing Laboratory. The NREL sensor test facility provides stakeholders (e.g., sensor developers and manufacturers, end users, and code officials) a resource for an independent, unbiased evaluation of hydrogen sensor technologies. Test protocols are guided by the requirements in national and international sensor standards, as well as sensor performance targets established by DOE [3] or by the requirements of the application. In addition to laboratory assessment of sensor performance, a critical mission of the NREL Safety Sensor Testing Laboratory is to educate end users on the proper use of hydrogen sensors. This is achieved, in part, through topical studies designed to illustrate fundamental properties and limitations of various hydrogen sensor technologies, and through outreach activity such as participation on standards development organizations committees, workshops, conferences, and webinars. The NREL sensor laboratory also facilitates deployment by partnering with end-users to assist in the design and implementation of their sensor system.

APPROACH

Evaluation of hydrogen safety sensors is an on-going activity at NREL. This activity supports sensor developers and end-users, as well as code developers and permitting official. The goal of the sensor laboratory is to assure that stakeholders in the hydrogen community have the sensor technology they need. Sensor performance evaluation is performed using custom-built NREL sensor test apparatus, which were designed with advanced capabilities, including parallel 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. The test apparatus are fully automated for control and monitoring of test parameters and for data acquisition with around-the-clock operation capability. Selected sensors are subjected to an array of tests to quantify the impact of variation of environmental parameters and chemical matrix on performance. Although standard test protocols have been developed [4], these can be adapted for specialized requirements. Results are reported back to the developer or manufacturer to support their future development work.[1] NREL sensor testing also supports end users by qualifying sensor technology for their application and by educating the hydrogen community on the proper use of hydrogen sensors. The NREL sensor laboratory maximizes its impact by working directly with stakeholders in the hydrogen community; this is achieved in part through numerous formal agreements with industrial partners. Strategic partnerships have also been maintained with other government organizations, most notably with the Sensor Testing Facility at the JRC–IET, under which we collaborate on hydrogen sensor research projects of common interests. The NREL–JRC collaboration provides a platform for the international distribution of the sensor research and development.

In addition to sensor performance characterization, the scope of the NREL Safety Sensor Testing Laboratory has expanded its active participation on a variety of national and international codes and standards development organizations, including NFPA 2, ISO Technical Committee (TC) 197, ISO TC 158, SAE, UL, ASTM International, and the GTR. Various levels of support is provided by the NREL Safety Sensor Testing Laboratory for codes and standards development:

- Prenormative research to support code and standard development
- Document development
- Development and deployment of verification technology
- Expert support/guidance/recommendations
- Dissemination of results is through a variety of venues, including participation on international hydrogen safety panels, including the International Association for Hydrogen Safety [5] and International Energy Agency, Hydrogen Implementing Agreement, Task 37 (Safety) [6], presentations at international conferences and workshops, publications in the open literature, and direct outreach to the hydrogen community.

RESULTS

To support hydrogen deployment, the NREL sensor test facility strives to assure the availability of hydrogen sensors to meet stakeholder needs. This is achieved in part by providing an unbiased assessment of sensor performance to developers and manufacturers as well as end-users. NREL has also performed numerous topical studies aimed at educating the hydrogen community on the proper use of hydrogen sensors. The sensor laboratory also supports the implementation of codes and standards by providing tools for normative research (see below: *Hydrogen Cold Plume Release Analysis*) and verification technology (see below: *Support of the GTR 13 and the United States FMVSS*. Results reported here summarize major studies or critical steps in ongoing activity completed in FY 2016 on the characterization and use of hydrogen sensors.

Sensor Testing and Evaluation—Support of Deployment: Sensor testing and evaluation remains a core activity within the NREL sensor laboratory. The NREL sensor laboratory continues to provide the resources necessary to quantify sensor performance for specific applications; clients include sensor developers and manufacturers, as well as end-users, including both infrastructure and vehicular applications. NREL has numerous agreements with industrial partners to facilitate these collaborations. The NREL sensor laboratory activity includes topical studies, such as evaluating the impact of environmental stress on chemical sensor performance [7].

Support of the GTR 13 and the United States FMVSS: GTR 13, which is the defining document regulating hydrogen vehicle safety requirements, has been formally implemented. Accordingly, national authorities overseeing development and enforcement of vehicle regulations shall 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 emission levels in vehicle enclosures during in-use and post-crash test conditions, and on the allowable hydrogen content in vehicle exhaust during certain modes of normal operation. However, methods to verify compliance must exist in order for specific requirements to be incorporated into regulations. The NREL Safety Sensor Testing Laboratory, in cooperation with DOT, has been developing an analytical apparatus and methods for compliance verification of the various hydrogen emission requirements specified in the GTR. The NREL sensor laboratory had successfully qualified a commercial hydrogen sensor for use in an FCEV crash test [8]. These results have been shared with the SAE Hydrogen Fuel Cell Vehicle Crash Testing Safety Guidelines Task Force. In cooperation with the DOT, Transport Canada is preparing for an FCEV crash test as part of their mission to verify compliance to vehicle safety regulation. This FCEV crash test is tentatively scheduled for the fourth quarter of 2016. NREL will assist by instrumenting the crash test vehicle with hydrogen sensors, including sensors that have been previously qualified for this application along with models from other manufacturers; the qualified sensor product line has been discontinued by the manufacturer. In a second application, GTR 13 also specifies allowable hydrogen levels in tailpipe emission—specifically the exhaust gas shall not exceed 4 vol% H_2 during any moving three-second time interval but with a maximum short-term hydrogen level remaining below 8 vol%. The NREL Safety Sensor Testing Laboratory is developing an off-

[1] It is the policy of the NREL sensor laboratory to treat test results as proprietary, and thus results pertaining to specific clients will not be disclosed without permission.

vehicle analyzer for use by regulatory agencies such as DOT to verify compliance to this GTR specification. A laboratory bench top prototype analyzer has been demonstrated [9] (Figure 1 shows an early probe design), which is currently being configured by NREL for in-field use by DOT and Transport Canada. Several vehicle manufacturers have also expressed interest in this technology, and agreements are in place to facilitate this testing.

Hydrogen Cold Plume Release Analysis: Liquid hydrogen is routinely delivered to a facility using road transport vehicles and transferred on-site to a stationary storage tank. Following transfer, up to 60 kg of cold hydrogen, which may include liquid hydrogen droplets, is vented from the transport vessel. A liquid hydrogen dispersion model is under development, but there is little data for verification. The NFPA 2 Hydrogen Storage Task Group has been tasked with developing a scientific basis for liquid hydrogen set back distances, which will support permitting of hydrogen stations with on-site liquid hydrogen storage. Liquid hydrogen storage at commercial fueling stations will increase as the number of hydrogen FCEVs grows. The task group specifically identified a need to characterize the plume generated during a liquid hydrogen release from the vent stack. Empirical profiling of the plume is needed to

- Better understand the behavior of cold plume releases.
- Determine if the plume can drop below the release point based on interactions with the atmosphere such as the liquefaction of the atmosphere that plume is being released in to.
- Further validate computer model.

The NFPA 2 Hydrogen Storage Task Group formed a sub-group to address the need to characterize the plume profile. The sub-group includes representatives from a hydrogen producer (the Linde Group), risk assessment and computational fluid dynamics experts (Sandia National Laboratories), and hydrogen safety, codes, and standards (NREL). The sub-group approached the NREL sensor laboratory to assist in the design, construction, demonstration, and deployment of an analyzer for the temporal, in situ profiling of the cold hydrogen plume formed during the liquid hydrogen venting. A prototype Cold Hydrogen Plume Analyzer design has been developed by the NREL Safety Sensor Testing Laboratory. The analyzer consists of a support structure for in situ deployment in the plume, a sample collection system with multiple sampling points, and a remote analyzer box consisting of multiple chemical (hydrogen and oxygen) and physical sensors (temperature and humidity) to provide quantitative information of the plume gas. The analyzer box also includes a pump and a multi-port valve to allow multiplexing of sample collection points for analysis by a single array of chemical and physical sensors. Figure 2 shows the analyzer box. Presently, all sub-systems have been demonstrated, including the support structure, the sample collection system, chemical and physical sensors, and implementation of a computer data acquisition system for control of experimental parameters and data acquisition. System integration is nearly complete and the first field deployment is expected sometime in the third quarter of 2016.

Assessment of a Colorimetric Hydrogen Leak Detection (DetecTape®): A highly selective colorimetric indicator for the detection of leaks from hydrogen pneumatic systems was recently developed by Element One, Inc. The colorimetric indicator was integrated into a pliable, self-adhesive tape that can readily wrap around pneumatic fittings, and is marketed under the tradename DetecTape. In its native state, the indicator pigment is a pale gray color, but becomes black upon exposure to hydrogen. The colorimetric change can be readily observed by the naked eye without the need for supplemental electronics or other hardware. Figure 3 shows the commercial version of DetecTape along with an indicator sample in its native state and one that had been exposed to hydrogen. Under the auspices of a Memorandum of Understanding with Element One, Inc. [10] and with support from the NREL Commercialization Assistance Program [11], the effectiveness of DetecTape as a hydrogen leak detector was evaluated. The deployment study lasted nearly eight months, and included both indoor and outdoor hydrogen operations, as well as supplemental laboratory assessments. During the course of the deployment study, several small but unexpected leaks were identified, thereby guiding appropriate

FIGURE 1. Prototype hydrogen probe for FCEV tailpipe exhaust. A ruggedized probe for field use is under development.

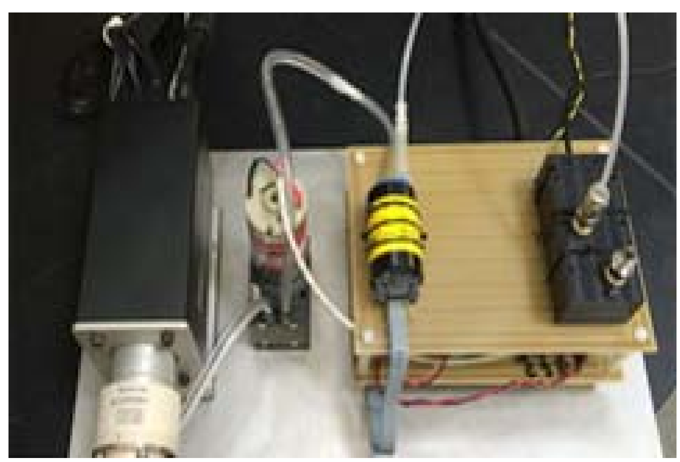

FIGURE 2. Analyzer box (bench top configuration) for the Cold Hydrogen Plume Analyzer

FIGURE 3. Colorimetric hydrogen leak detection (DetecTape). Exposure to hydrogen transforms the indicator from a pale gray color to black.

corrective measures. Furthermore, it was found that the indicator remained active (e.g., sensitive to hydrogen) for the eight-month deployment, demonstrating a robustness against normal outdoor environmental conditions. Details on the deployment study have been reported [12].

International Collaborations (NREL and JRC Sensor Laboratories Collaboration): Recognizing the importance of hydrogen sensors, the European JRC independently established hydrogen sensor testing facilities at the Institute for Energy and Transport. The NREL and JRC sensor laboratories have been collaborating since 2008 in support of the international utilization of hydrogen as an energy carrier. This collaboration has been formalized under the auspices of different agreements, including a Memorandum of Agreement [13] and through a common call between DOE and the European Fuel Cell and Hydrogen Joint Undertaking, however each laboratory maintains independent research programs and directives. The NREL–JRC sensor laboratory arrangement synergizes the effort of each facility and leverages the respective impact of their output by minimizing duplicated research efforts to save resources and maximize throughput, increasing international exposure and visibility of results, and facilitating implementation of the hydrogen infrastructure via an expanding international collaboration among stakeholders. The scope and productivity of this collaboration is demonstrated in the FY 2016 Publications/ Presentations section, which list the NREL and JRC sensor laboratories joint publications, including four papers at the World Hydrogen Energy Conference (Zaragoza, Spain, June 13–16), one paper at the International Conference on Hydrogen Safety (Yokohama, Japan, October 19–21, 2015), plus collaborative talks at the International Energy Agency Hydrogen Implementing Agreement Task 37 Experts meetings. In addition, the NREL and JRC sensor laboratories co-authored one journal article and collaborated on a book on hydrogen sensors [14]. Current collaborative activity between NREL and the JRC include

- Hydrogen sensors for power to gas.
- Response time measurements on commercial and developing sensor.
- Development and comparison of sensor performance evaluation test methods for consistency of results.
- Experts team to develop Sensor Placement Guidance Document.

DOE Small Business Voucher Award Recipient: The DOE's Office of Energy Efficiency and Renewable Energy Small Business Voucher (SBV) program was implemented to foster collaborations between United States small businesses and the national laboratories [15]. While not a funding source for the small business, the SBV provides a venue to utilize the resources of the national laboratories. The SBV program is characterized by a simple application process and minimal administrative paperwork. The NREL sensor laboratory was a recipient of one SBV award and is supporting Los Alamos National Laboratory on a second award.

Publication of a Book on Hydrogen Sensors: In 2016, a book on hydrogen sensors was published by the CRC Press [14] — *Sensors for Safety and Process Control in Hydrogen Technology*. The authors included sensor experts from the Bundesanstalt für Materialforschung und –prüfung (Thomas Hűbert), the JRC (Lois Boon-Brett), and NREL (William J. Buttner).

CONCLUSIONS AND FUTURE DIRECTIONS

In the next year and beyond, the NREL sensor laboratory will build off its current accomplishment and capabilities through via two main themes—continued evaluation of hydrogen sensors in support of deployment, and support of hydrogen codes and standards development. Hydrogen sensor evaluations will continue to be guided through direct collaboration with stakeholders in the hydrogen community, including sensor developers and manufacturers as well as end-users, which includes infrastructure and vehicular applications.

Sensor Performance Assessment and Guidance

- End user support to support deployment
  - Guidance on the use of hydrogen sensors in infrastructure deployments, including repair facilities and fueling facilities.
  - Sensor performance testing protocol standards for vehicles.
  - Qualification support for use of sensors in infrastructure and vehicles.
  - Barriers to sensor certification and the impact.
- Manufacturer/developer support
  - Commercial and developmental sensor technology performance validation.

  - Assessment of wide area monitoring and distributed sensor technology.
  - Sensors and analytical methods for the detection of contaminants in hydrogen fuel.

Support of Codes and Standards

- Prenormative data
  - Hydrogen Cold Plume Release Analysis: Continued testing over a range of conditions. Results will be use to validate cold plume models and to assist in verifying appropriate set back distances.
    - Sensor Placement Guidance: An expert group consisting of sensor experts from NREL and JRC and computational fluid dynamics experts. The initial system will be ISO containers.
- Verification technology
  - Verification of FCEV crash test requirements (GTR and FMVSS).
  - Verification of FCEV tailpipe emissions requirements (GTR and FMVSS).
- Document development
  - SAE Technical Information Report J3089 "Characterization of On-board Vehicular Hydrogen Sensors:" The first draft is completed, but revisions are on-going and additional annexes are being considered.
  - ISO TC197/WG 28 (fuel quality verification): The document does not yet include requirements for on-site measurements.
- Expert input and guidance
  - SAE Fuel Cell Vehicle Crash Testing Safety Guidelines Task Force
  - SAE Fuel Cell Safety Task Force
  - ISO TC/158 WG 7: Fuel quality analytical methods
  - ISO TC/197 WG 27: FCEV fuel quality requirements
  - ISO TC/197 WG 28: Fuel quality verification

Strategic Partnerships and Collaborations

- DOT/Transport Canada to support FCEV crash test and tailpipe emission verification, in support of the GTR and FMVSS.
- Industrial partners to qualify sensor and validate sensor-based analytical methods.
- IET–JRC Sensor laboratory collaboration.
- Hydrogen Safety Committees including International Energy Agency Hydrogen Implementing Agreement and the International Association for Hydrogen Safety.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. NREL ROI-15-119: **"**In-Situ, Low-Cost, Low-Pressure Interface to a Fuel Contaminant Analyzer within a High Pressure Hydrogen Dispenser" (W. Buttner and K. Harrison). (undergoing NREL internal review)

FY 2016 PUBLICATIONS/PRESENTATIONS

Presentations

1. "Overview of the U.S. DOE Hydrogen Safety, Codes and Standards Program--Part 4: Hydrogen Sensors," W.J. Buttner, C. Rivkin, R. Burgess, Eric Brosha, Rangachary Mukundan, C. Will James, and Jay Keller, Sixth International Conference on Hydrogen Safety (October 19–21) Yokohama, Japan.

2. "Hydrogen Monitoring Requirements in the Global Technical Regulation on Hydrogen and Fuel Cell Vehicles," W. Buttner, C. Rivkin, R. Burgess, K. Hartmann, I. Bloomfield, M. Bubar, M. Post, L. Boon-Brett, E. Weidner, and P. Moretto, Sixth International Conference on Hydrogen Safety (October 19–21) Yokohama, Japan.

3. (Invited Talk) Hydrogen Sensor--Overview of the Sensor Laboratory; Bill Buttner, Carl Rivkin, Robert Burgess, Japanese Automotive Research Institute (JARI) (October 23, 2015), Tokyo, Japan.

4. "Sensor Testing Lab Overview," Bill Buttner, Carl Rivkin, Robert Burgess, K. Hartmann, Ian Bloomfield, M. Bubar, K. Schmidt, H. Wright, DOE Hydrogen Codes and Standards Tech Team (May 12, 2016), Telecom Meeting.

5. "NREL Hydrogen Sensor Testing Laboratory," William Buttner, C. Rivkin, R. Burgess, M. Bubar, K. Hartmann, K. Schmidt, H. Wright, U.S. Department of Energy Hydrogen and Fuel Cell Program Annual Merit Review and Peer Evaluation (June 6–10, 2015) Washington, D.C.

6. "Analyzer for FCEV Tailpipe Hydrogen Emissions as Specified in the Global Technical Regulation Number 13," William Buttner, C. Rivkin, R. Burgess, M. Bubar, K. Hartmann, and Eveline Weidner, 21st World Hydrogen Energy Conference (June 13–26, 2016) Zaragoza, Spain.

7. "Impact of Environmental Parameters on H_2 Sensor Performance," William Buttner, C. Rivkin, R. Burgess, K. Hartmann, M. Bubar, and E. Weidner, 21st World Hydrogen Energy Conference (June 13–26, 2016) Zaragoza, Spain.

8. "Sensor for hydrogen concentration in Natural Gas," E. Weidner, R. Ortiz Cebolla, C. Bonato, L. Wooninck, and W. Buttner, 21st World Hydrogen Energy Conference (June 13–26, 2016) Zaragoza, Spain.

9. "The NREL and JRC Sensor Test Laboratories Instrumentation and Methods for Hydrogen Sensor Performance Verification,"

W. Buttner, M. Post, L. Brett-Boon, G. Black, V. Palmisano, C. Rivkin, R. Burgess, E. Weidner, and R. Ortiz-Cebolla, 21st World Hydrogen Energy Conference (June 13–16, 2016) Zaragoza, Spain.

10. "NREL and JRC Sensor Test Laboratories Activity in Support of Codes, Standards, and Regulations," W. Buttner, C. Rivkin, R. Burgess, E. Weidner, and Pietro Moretto, Experts Meeting of the International Energy Agency, Hydrogen Implementation Agreement Task 37 (Safety) (June 17) San Sebastian, Spain.

11. (Invited Talk) Part I: NREL and NREL's Fuel Cell & Hydrogen Program; Part II: DOE SCS/NREL Hydrogen Sensor Technology Program, Bill Buttner, Carl Rivkin, Robert Burgess, (Matt Post), Hannah Wright, Kara Schmidt, Kevin Hartmann, Max Bubar, Ian Bloomfield, Joint Research Centre, Institute for Energy and Transport, Clean Air Divison, (June 24, 2016), Petten, the Netherlands.

12. "Hydrogen Detection in FCEV Crash Tests," William Buttner, Kara Schmidt, Matt Post, Telecom meeting of the SAE Hydrogen Fuel Cell Vehicle Crash Testing Safety Guidelines Task Force, August 17, 2016.

Journal Articles and Meeting Papers

1. "Overview of the U.S. DOE Hydrogen Safety, Codes and Standards Program--Part 4: Hydrogen Sensors," W.J. Buttner, C. Rivkin, R. Burgess, Eric Brosha, Rangachary Mukundan, C. Will James, and Jay Keller, Proceedings of the Sixth International Conference on Hydrogen Safety (October 19–21) Yokohama, Japan.

2. "Hydrogen Monitoring Requirements in the Global Technical Regulation on Hydrogen and Fuel Cell Vehicles," W. Buttner, C. Rivkin, R. Burgess, K. Hartmann, I. Bloomfield, M. Bubar, M. Post, L. Boon-Brett, E. Weidner, and P. Moretto, Sixth International Conference on Hydrogen Safety (October 19–21), Yokohama, Japan.

3. "Analyzer for FCEV Tailpipe Hydrogen Emissions as Specified in the Global Technical Regulation Number 13," William Buttner, C. Rivkin, and R. Burgess, M. Bubar, K. Hartmann, and Eveline Weidner, International Journal of Hydrogen Energy (2016) in press.

4. "Analyzer for FCEV Tailpipe Hydrogen Emissions as Specified in the Global Technical Regulation Number 13," William Buttner, C. Rivkin, R. Burgess, M. Bubar, K. Hartmann, and Eveline Weidner, Extended Abstract, 21st World Hydrogen Energy Conference (June 13–26, 2016), Zaragoza, Spain.

5. "Impact of Environmental Parameters on H_2 Sensor Performance," William Buttner, C. Rivkin, R. Burgess, K. Hartmann, M. Bubar, and E. Weidner, Extended Abstract, 21st World Hydrogen Energy Conference (June 13–26, 2016), Zaragoza, Spain.

6. "Sensor for Hydrogen Concentration in Natural Gas" E. Weidner, R. Ortiz Cebolla, C. Bonato, L. Wooninck, and W. Buttner, Extended Abstract, 21st World Hydrogen Energy Conference (June 13–26, 2016), Zaragoza, Spain.

7. The NREL and JRC Sensor Test Laboratories Instrumentation and Methods for Hydrogen Sensor Performance Verification," W. Buttner, M. Post, L. Brett-Boon, G. Black, V. Palmisano, C. Rivkin, R. Burgess, E. Weidner, and R. Ortiz-Cebolla, Extended Abstract, 21st World Hydrogen Energy Conference (June 13–26, 2016), Zaragoza, Spain.

Technical Reports

1. "Passive Leak Detection Using Commercial Hydrogen Colorimetric Indicator," Kevin Hartmann, William Buttner, Robert Burgess, and Carl Rivkin, NREL Technical Report (2016).

Book

1. "Sensors for Safety and Process Control in Hydrogen Technology," Thomas Hűbert, Lois Boon-Brett, and William J. Buttner, CRC Press, Taylor and Francis Group, Boca Raton, ISBN 13-978-1-4665-9654-2 (2016).

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2. "ISO 26142 Hydrogen Detector for Stationary Apparatus"

3. 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 (EERE), 2005. http://www.nrel.gov/docs/fy08osti/39146.pdf

4. "Standard Hydrogen Test Protocols for the NREL Sensor Testing Laboratory," NREL Brochure (see http://www.nrel.gov/hydrogen/pdfs/53079.pdf, accessed July 22, 2016).

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7. "Impact of Environmental Parameters on H_2 Sensor Performance," William Buttner, C. Rivkin, R. Burgess, K. Hartmann, M. Bubar, and E. Weidner, Extended Abstract, 21st World Hydrogen Energy Conference (June 13–26, 2016) Zaragoza, Spain.

8. Onboard Hydrogen/Helium Sensors in Support of the Global Technical Regulation: An Assessment of Performance in Fuel Cell Electric Vehicle Crash Tests, Matthew B. Post, Robert Burgess, Carl Rivkin, William Buttner, Kathleen O'Malley, and Antonio Ruiz, Technical Report NREL/TP-5600-56177 (September 2012).

9. "Analyzer for FCEV Tailpipe Hydrogen Emissions as Specified in the Global Technical Regulation Number 13," William Buttner, C. Rivkin, R. Burgess, M. Bubar, K. Hartmann, and Eveline Weidner, International Journal of Hydrogen Energy (2016) in press.

10. Memorandum of Understanding, Alliance for Sustainable Energy, LLC (National Renewable Energy Laboratory) with Element One, Inc., MOU Number MOU-14-334 (February 28, 2014).

11. "Performance of a Hydrogen Colorimetric Indicator, NREL Commercialization Assistance Program, NCAP Project Number: NCAP16-00085.

12. "Passive Leak Detection Using Commercial Hydrogen Colorimetric Indicator," Kevin Hartmann, William Buttner, Robert Burgess, and Carl Rivkin, NREL Technical Report, in press (2016).

13. Buttner, W., et al., *Steering Committee Progress Report on Hydrogen Sensor Performance Testing and Evaluation under the Memorandum of Agreement between NREL, U.S. DOE and JRC-IET, EC,* NREL Technical Report: NREL/TP-5600-57207 (2012).

14. "Sensors for Safety and Process Control in Hydrogen Technology," Thomas Hűbert, Lois Boon-Brett, and William J. Buttner, CRC Press, Taylor and Francis Group, Boca Raton, ISBN 13-978-1-4665-9654-2 (2016). (see https://www.crcpress.com/Sensors-for-Safety-and-Process-Control-in-Hydrogen-Technologies/Hubert-Boon-Brett-Buttner/p/book/9781466596542, accessed July 22)

15. DOE EERE Small Business Voucher Award. (see https://www.sbv.org; accessed July 22, 2016)