VIII.7 NREL Hydrogen Sensor Testing Laboratory

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Subcontractors:
- Element One, Boulder, CO
- Bloomfield Automation, Denver, CO
- A.V. Tchouvelev & Associates, Inc. (AVT), Mississauga, ON, 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 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) 2017 Objectives

- Support infrastructure deployment by providing sensor testing capability and guidance to stakeholders in the hydrogen energy field.
- Quantify performance metrics of commercial and developmental sensor technologies from both the private sector and government laboratories.
- Validate hydrogen safety sensors for specific infrastructure and vehicle applications.
- Support Department of Transportation (DOT) National Highway Transportation Safety Administration on the development of the Federal Motor Vehicle Safety Standard (FMVSS) for hydrogen fuel cell electric vehicles (FCEVs), especially with regards to hydrogen detection requirements identified in the Global Technical Regulation (GTR) 13 [1].
- Facilitate safe deployment of FCEVs by participation on SAE Fuel Cell Standards committees, and to lead the development of the SAE Technical Information Report J3089 “Characterization of On-board Vehicular Hydrogen Sensors.”
- Support the science of hydrogen safety by integrated theoretical-empirical profiling of hydrogen releases (indoor and outdoor).
- Support hydrogen safety code and standard development by active participation with standard and code development organizations.
- Support the deployment and implementation of hydrogen sensors and monitoring technology 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 2017 Accomplishments

- *Hydrogen Safety Sensor Gap Analysis*: Co-organized a Hydrogen Sensor Workshop entitled "Hydrogen Safety Sensors and Their Use in Applications with Hydrogen as an Alternative Fuel," in collaboration with the European Joint Research Centre (JRC) and the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), which identified critical gaps in hydrogen safety sensor performance. The resulting gap analysis is to be presented at the 7th International Conference on Hydrogen Safety (ICHS) [2].
- *FCEV Exhaust Gas Measurement Technology*: Developed a prototype analyzer for verifying that hydrogen levels in FCEV exhaust is within the regulated levels as prescribed by GTR-13 [1]. The exhaust analyzer will ultimately be used by the DOT National Highway Transportation Safety Administration for compliance verification.
- *Characterization of Outdoor Liquid Hydrogren (LH2) Releases*: Developed the Cold Hydrogen Plume Analyzer, which was designed to empirically profile hydrogen plumes generated during LH2 venting; field measurements with the analyzer supported the recommendation proposed for the upcoming edition of National Fire Protection Agency (NFPA) 2 that the hydrogen vent stacks ought to be directed up and away from ground level.
- *Characterization of Indoor Hydrogen Releases*: Profiled indoor hydrogen releases through the development of empirically verified theoretical models, in collaboration with AVT, which will be incorporated into NFPA 2 as a guidance document on sensor placement.
- *Expedited Sensor Test Methods*: Developed and verified expedited sensor test methods, in collaboration with the JRC, using an apparatus based on a flow-through design which provides results in a fraction of the time of previous designs.
- *Obtained National Renewable Energy Laboratory Record of Invention (NREL ROI 17-94)* "In-Situ, Low-Cost, Low-Pressure Interface to a Fuel Contaminant Analyzer within a High Pressure Hydrogen Dispenser." The ROI will be the basis for a provisional patent.
- *SAE Technical Information Report (TIR) J3089*: Completed the formal draft of SAE TIR J3089 "Characterization of On-board Vehicular Hydrogen Sensors," which was developed for the SAE Fuel Cell Standards Committee. The TIR will be submitted for ballot in the fall of 2017.
- *Recognition of the Sensor Laboratory Publications*: The significance of an NREL Sensor Laboratory publication was recognized in the International Association for Hydrogen Energy Newsletter, which identified the paper (An Overview of Hydrogen Sensors and Requirements, W. Buttner, et al., IJHE, 36, (2011) 2462-2470) as the fifth most cited article in the International Journal for Hydrogen Energy over the past five years.

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INTRODUCTION

Hydrogen sensors are an enabling technology to assure the safe use of hydrogen as an alternative, renewable fuel. Sensors facilitate the safe implementation of FCEVs and the supporting infrastructure. To assure the availability of reliable safety sensors and their proper use, the DOE Fuel Cell Technology Office established the NREL Safety Sensor Testing Laboratory. The NREL Sensor Test 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 [3] and international sensor standards [4], as well as by the sensor performance targets established by DOE [5]. In some cases, performance testing is also guided by the specific requirements of the application. In addition to laboratory assessment of sensor performance, a critical mission of the NREL Safety Sensor Testing Laboratory is to assure 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 code and standards development organizations (CDOs/SDOs), safety committees, workshops, conferences, and webinars. Furthermore, in collaboration with an international team of hydrogen sensor experts, the director of the NREL sensor laboratory (William Buttner) co-authored a book on hydrogen sensor technology, which covers a variety of sensor related topics ranging from a detailed description of the fundamentals of sensor design to practical applications and selection criteria [6]; this book represents an invaluable resource to the hydrogen community as a single source for understanding and using hydrogen sensors. The NREL sensor laboratory further facilitates deployment by partnering directly with end users to assist in the design and implementation of their sensor system.

APPROACH

The NREL sensor laboratory RD&D effort is guided by the needs of the hydrogen community. Unbiased and confidential performance evaluation of hydrogen sensors has been and remains a core activity within the NREL sensor laboratory. In this function, the Sensor Laboratory supports sensor developers, end users, as well as permitting officials and standard and code developers. Sensor evaluations are performed using a custom-built sensor test apparatus (Figure 1), which was 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. In addition, other test fixtures have been developed for lifetests and chemical poison studies, as well as for specialized applications. 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 [7], 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 [8] and by educating the hydrogen community on the proper use of hydrogen sensors.

FIGURE 1. The NREL Hydrogen Sensor Test Apparatus

The NREL sensor laboratory maximizes its impact by direct collaborations with stakeholders in the hydrogen community; this is achieved in part through numerous formal agreements with industrial partners. The NREL Sensor Laboratory was a recipient of two projects under the DOE Small Business Voucher Pilot Program [9] which facilitates access to the DOE national labs for American small businesses. Strategic partnerships have also been maintained with other government organizations, most notably with the Sensor Testing Facility at the JRC in Petten, Netherlands, under which the respective sensor test facilities collaborate on hydrogen sensor research projects of common interests. Currently, this collaboration is formalized under a DOE-JRC agreement [10]. The NREL–JRC collaboration provides a platform for the international distribution of the NREL 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, International Organization for Standardization (ISO) Technical Committee 197, SAE, UL, ASTM International, and the GTR. The type of support provided by the NREL Sensor Laboratory to safety development organizations and code development organizations include (i) pre-normative research to support code and standard requirements, (ii) document development, (iii) development and deployment of verification technology, and (iv) expert guidance and recommendations. Increasingly, the NREL sensor laboratory uses its expertise to develop sensor-based tools for the hydrogen community; currently this includes tools 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.

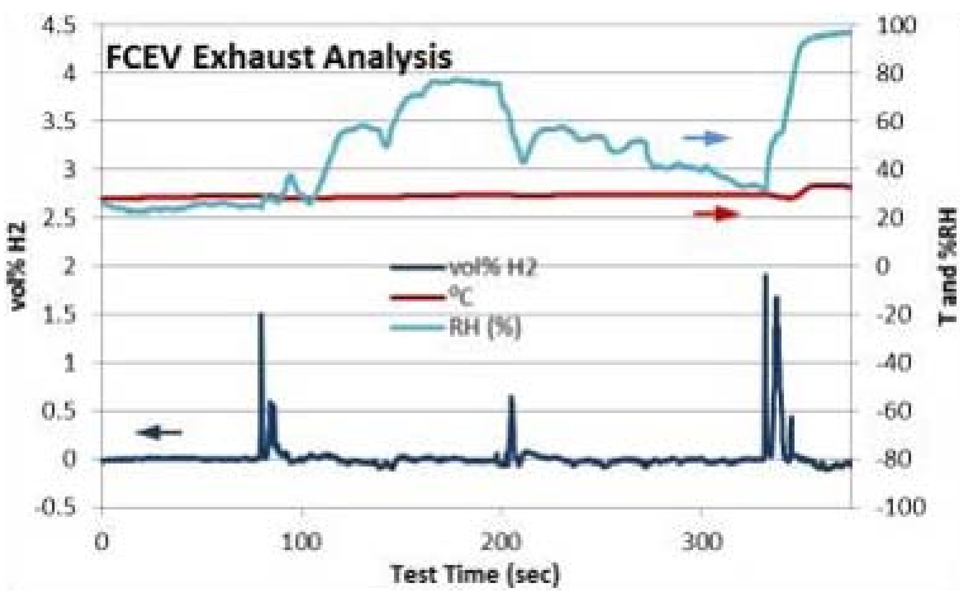
Finally, it is noted that the NREL Sensor Laboratory has an on-going commitment for training young scientists and engineers in the field of renewable energy. Accordingly, the Sensor Laboratory has for several years provided internship opportunities to undergraduate engineering majors. While supervised by the Director of the NREL Sensor Laboratory, interns are assigned and thus responsible for a specific project (or several projects). Responsibilities include experimental design and data analysis, as well as interaction (under supervision) with clients. Interns have made significant contributions to numerous projects within the NREL Sensor Laboratory, including several described in this report. Accordingly they have been included as co-authors on numerous presentations and papers. Upon graduation, several interns have remained at NREL as entry-level engineers or consultants.

RESULTS

Hydrogen Sensor Workshop—Sensor Gap Analysis: A workshop on hydrogen sensors was held on May 10, 2017, at the headquarters of the European FCH JU in Brussels, Belgium (*Hydrogen Safety Sensors and Their Use in Applications with Hydrogen as an Alternative Fuel*). A primary purpose of the workshop was to get input from a cross-section of stakeholders on hydrogen sensor needs and experiences. The workshop was jointly organized by the JRC and NREL sensor laboratories and the FCH JU. The focus was on the ability of existing hydrogen sensor technology to meet end-user needs in applications pertaining to hydrogen as alternative fuel. With over twenty participants that included program administrators, sensor manufacturers, end-users, facility managers, and experts from sensor test laboratories, the workshop identified critical gaps in hydrogen safety sensor performance. Critical metrological gaps include sensor lifetime and stability, the need for capital and maintenance cost reduction, and improved response time, especially for specialized applications such as the FCEV exhaust gas analyzer. There also exists a need for the reduction in complexity of Regulations, Codes and Standards, especially with regards to international acceptance and harmonization because many countries or regions require their own national standards. A thorough gap analysis is being prepared and will be presented at the ICHS [2].

FCEV Exhaust Gas Measurement Technology and support of the GTR and FMVSS: GTR 13 [1] is the defining document regulating hydrogen vehicle safety requirements. GTR-13 has been formally implemented, and accordingly, 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 emission levels in FCEVs. The NREL Safety Sensor Testing 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. The analyzer has been developed for use by regulatory agencies such as DOT to verify compliance to this GTR specification, although vehicle manufacturers have also expressed a need and interest in the technology. A laboratory bench top prototype analyzer was previously demonstrated [11]. The prototype analyzer with gas collection probe was field tested on an FCEV to measure hydrogen in the exhaust gas stream. 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. Based upon the field results, a modified gas collection system for the probe has been developed.

Characterization of Outdoor LH2 Releases: Cold hydrogen plumes formed during LH2 releases are currently not well understood because field data is essentially non-existent. This lack of understanding leads to overly



RH – relative humidity

FIGURE 2. Hydrogen concentrations as measured from an actual FCEV using the NREL Exhaust Gas Analyzer. Physical parameters (temperature and humidity) are plotted relative to the right ordinate.

conservative safety distances at LH2 facilities. To address this need, the NREL sensor laboratory, in collaboration with NFPA 2 hydrogen storage task group, developed the prototype Cold 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 environmental (e.g., temperature and humidity) sensors, was deployed during an actual LH2 venting operation. Critical findings included the detection of hydrogen above the lower flammable limit more than two meters below the horizontal release point. The venting process is shown in Figure 3, which clearly shows the downward momentum of the vapor cloud (formed from chilled water vapor) during the LH2 venting. Although the measured hydrogen concentration did not correlate to the vapor cloud, the field measurements did verify that hydrogen would be observed below the horizontal release point, an observation that was not predicted by models existing at the time. Thus, hydrogen buoyancy would not necessarily dominate the dispersion process. The demonstration that the hydrogen plume would be observed below the horizontal release point contributed significantly to the ready acceptance by the NFPA Hydrogen Storage Task Group to support incorporation into the upcoming edition of NFPA 2 the proposal that the hydrogen vent stacks ought to be directed up and away from ground level. The outcome of this study and proposed future applications will be presented at the ICHS [12].

Although developed for LH2 facilities, the Analyzer is amenable to gaseous hydrogen as well. The Analyzer has been upgraded for enhanced metrological capabilities including improved spatial and temporal profiling of hydrogen plumes and tracking of prevailing weather conditions. The system can be readily adapted for hydrogen wide area monitoring of small to large-scale gaseous hydrogen and LH2 facilities.

Characterization of Indoor Hydrogen Releases: Sensors are mandated by both the International Fire Code and NFPA 2 for numerous indoor hydrogen infrastructure applications. However, no guidance is provided on the selection or use of sensor technology. The NREL Sensor Laboratory and AVT (Mississauga, Ontario, Canada) collaborated to profile indoor hydrogen releases. As a model system, AVT performed computational fluid dynamics modeling of a leak scenario associated with an electrolyzer system housed within a 20 foot ISO container. Figure 4 illustrates the hydrogen dispersion following a release. In this modelling, a leak scenario was identified that would otherwise be undetected by other methods, such as the inability of a small leak to be detector by a pressure loss within a flowing pneumatic line. The theoretical dispersion profile is to be validated by NREL using the hydrogen wide area monitoring Analyzer developed for the LH2 release and consists of an array of hydrogen and physical sensors to temporally and spatially profile hydrogen releases. The outcome of this work will be incorporated into NFPA 2 as a guidance document on sensor placement.

Expedited Sensor Performance Test Protocols: In collaboration with the JRC, expedited sensor test methods were developed and verified using an apparatus based on a flow-through design that provides results similar to chamber methods, such as those prescribed in performance standards (e.g., UL 2075 [3], ISO 26142 [4]), but in only a fraction of the time. This work was performed under an international collaborative agreement between DOE and the JRC [10].

FIGURE 3. The NREL Hydrogen Plume Analyzer deployed during a planned LH2 venting process. The observation of hydrogen below the horizontal release point facilitated the recommendation proposed for future editions of NFPA 2 that the vent stack be designed to direct the release up away from ground level.

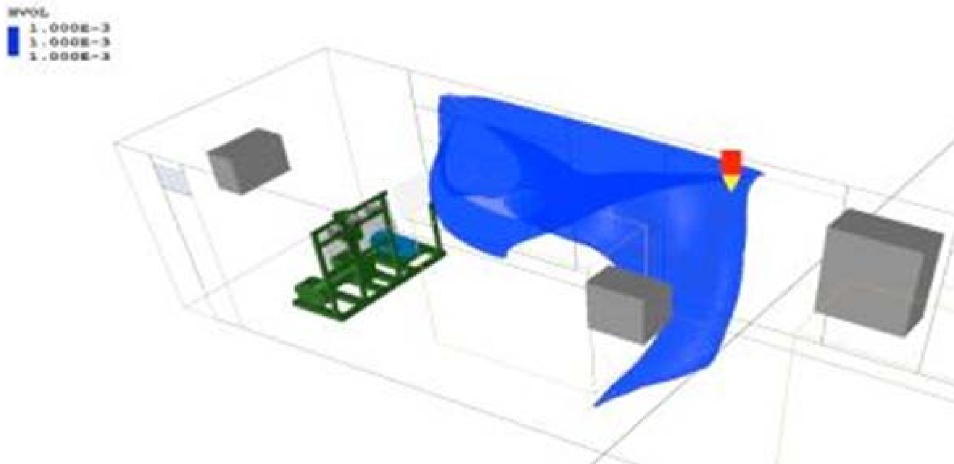


FIGURE 4. Hydrogen concentration contour as predicted from computational fluid dynamics modeling formed following an indoor release

The outcome of this study on the use of the expedited test methods will be presented at the ICHS [13].

Record of Invention (NREL ROI 17-94): There are two aspects necessary for practical on-site chemical analysis for verification of hydrogen fuel purity, the availability of the appropriate analytical technology (e.g., the hydrogen contaminant detector) and an interface to allow transfer of hydrogen from the high pressure dispenser to the (low pressure) analytical instrument. The NREL Sensor Laboratory recently submitted an ROI "In-Situ, Low-Cost, Low-Pressure Interface to a Fuel Contaminant Analyzer within a High Pressure Hydrogen Dispenser." This invention provides an automated interface to support the onsite analysis of hydrogen at commercial fueling facilities and is compatible with almost any existing or proposed field deployable gas detection technology. A bench-scale model has been developed for prototype testing of hydrogen contaminant detector technology. The bench-scale model will also serve as the design guideline for the in-dispenser system, which will be used for real-world deployment of hydrogen contaminant detectors at hydrogen fueling facilities. A provisional patent on this concept is to be filed.

SAE Technical Information Report J3089: SAE TIR J3089 "Characterization of On-board Vehicular Hydrogen Sensors" was prepared under the auspices of SAE Fuel Cell Standards Committee. The purpose of the TIR was to provide a uniform performance assessment guide for FCEV manufacturers and their sensor suppliers. The finish draft of TIR will be submitted for ballot in the fall of 2017.

CONCLUSIONS AND UPCOMING ACTIVITIES

The Hydrogen Plume Analyzer (Cold Hydrogen Plume Analyzer) was developed for outdoor empirical measurements during LH2 releases. The initial deployment demonstrated that hydrogen buoyancy will not always dominate the dispersion process, and that hydrogen will often be observed below the horizontal release point. The analyzer is amenable to both LH2 and gaseous hydrogen and can form the basis of a hydrogen wide area monitor. Although future direction of this work is pending appropriations the sensor laboratory is in discussion with industrial partners to support further characterizations of hydrogen releases which will provide empirical correlations of environmental and physical parameters to hydrogen dispersions. These empirical studies will ultimately integrate with theoretical dispersions models to provide predictive capabilities.

The analytical performance of the NREL FCEV Exhaust Analyzer has been demonstrated. Currently a probe design that integrates to the analyzer is being developed to provide better measurement integrity. The DOT has provided support to the NREL FCEV to perform real-world measurements on an FCEV. This testing is in support of DOT mission to demonstrate vehicle safety, in part by developing test protocols per regulatory requirements. Currently the proposed requirements are those prescribed in GTR 13, which may be directly incorporated into the FMVSS.

While funding for continued sensor performance testing is pending appropriations, the NREL Sensor Laboratory will endeavor to continue to support FCEV and infrastructure implementation. This will be through addressing the gaps identified in the workshop [2]. In addition to sensor testing, this support will be in the form of expert guidance provided by, for example, topical Webinars. Presently, the NREL Sensor Laboratory is soliciting topics from members of the SAE Fuel Cell Standards Committee.

FY 2017 PUBLICATIONS/PRESENTATIONS

Talks and Presentations

1. "Sensor Testing Overview (The NREL Hydrogen Sensor Test Laboratory)," W. Buttner, R. Burgess, C. Rivkin, K. Schmitt, H. Wright, K. Hartmann, Joint CSTT-HDTT Meeting Agenda, National Renewable Energy Laboratory, Golden, CO, November 1–2, 2016.

2. "NREL and JRC Sensor Testing Laboratory Programs-H2 Safety Sensor Gap Analysis-Support of Safety Codes and Standards," W. Buttner, E. Weidner, R. Burgess, C. Rivkin, R. Ortiz Cebolla, C. Bonato, P. Moretto, K. Schmidt, H. Wright, K. Hartmann, IEA-HIA Task 37 Experts Meeting, Bethesda, MD, November 28–29, 2016.

3. "The NREL Analyzer For Profiling Cold Hydrogen Plume Release," W. Buttner, C. Rivkin, K. Schmitt, H. Wright, K. Hartmann, NFPA 2 Hydrogen Storage Task Group, Sandia National Laboratories, Livermore, CA, March 1, 2017.

4. "Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH2 Storage Vessels," W. Buttner, C. Rivkin, K. Schmidt, K. Hartmann, H. Schmidt, E. Weidner, 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–13, 2017.

5. "Flow-through method validation for hydrogen sensors testing," R. Ortiz-Cebolla, E. Weidner, C. Bonato, W. Buttner, K. Hartmann, K. Schmidt, 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–13, 2017.

Publications

1. "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, P. Moretto, *International Journal of Hydrogen Energy* (http://doi.org/10.1016/j.ijhydene.2016.06.053).

2. "Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH2 Storage Vessels," W. Buttner, C. Rivkin, K. Schmidt, K. Hartmann, H. Schmidt, E. Weidner, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017.

3. "Flow-through method validation for hydrogen sensors testing," R. Ortiz-Cebolla, E. Weidner, C. Bonato, W. Buttner, K. Hartmann, K. Schmidt, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017.

4. "Hydrogen Safety Sensor Performance and Use Gap Analysis," W. Buttner, R. Burgess, K. Schmidt, K. Hartmann, H. Schmidt, E. Weidner, R. Ortiz Cebolla, C. Bonato, P. Moretto, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017.

5. High Pressure Hydrogen Pressure Relief Devices: Accelerated Life Testing and Application Best Practices, R. Burgess, M. Post, W. Buttner, C. Rivkin, NREL Technical Report, in press.

6. *FY 2016 DOE Hydrogen and Fuel Cells Program Annual Report*, "VIII.7 NREL Hydrogen Sensor Testing Laboratory," W. Buttner, R. Burgess, C. Rivkin.

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1. Addendum 13: Global technical regulation No. 13 Global technical regulation on hydrogen and fuel cell vehicles ECE/TRANS/180/Add.13, July 19, 2013). (see http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a13e.pdf, accessed July 22, 2015)

2. "Hydrogen Safety Sensor Performance and Use Gap Analysis," W. Buttner, R. Burgess, K. Schmidt, K. Hartmann, H. Schmidt, E. Weidner, R. Ortiz Cebolla, C. Bonato, P. Moretto, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017).

3. "UL 2075 Gas and Vapor Detectors and Sensors."

4. "ISO 26142 Hydrogen Detector for Stationary Apparatus."

5. 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

6. "Sensors for Safety and Process Control in Hydrogen Technologies", Thomas Hűbert, Lois Boon-Brett, William Buttner, CRC Press ISBN 9781466596542 (2015).

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

8. "Hydrogen-Powered Vehicles–A Safe Alternative to Traditional Gasoline Internal Combustion Engines" William Buttner (March 2017). (see https://www.kpaonline.com/ehs/hydrogen-powered-vehicles-safe-alternative-traditional-gasoline-internal-combustion-engines/)

9. DOE Small Business Voucher Pilot (see https://www.sbv.org/).

10. Collaboration Arrangement for Research and Development in Energy-Related Fields DOE-JRC signed June 2, 2016. (see: https://eeas.europa.eu/headquarters/headquarters-homepage/2817/node/2817_nl).

11. "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, P. Moretto, *International Journal of Hydrogen Energy* (http://doi.org/10.1016/j.ijhydene.2016.06.053).

12. "Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH2 Storage Vessels," W. Buttner, C. Rivkin, K. Schmidt, K. Hartmann, H. Schmidt, E. Weidner, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017.

13. "Flow-through method validation for hydrogen sensors testing," R. Ortiz-Cebolla, E. Weidner, C. Bonato, W. Buttner, K. Hartmann, K. Schmidt, To be published in the proceedings of the 7th International Conference on Hydrogen Safety, Hamburg, Germany, September 11–17, 2017.