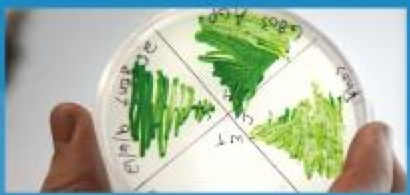




NREL Hydrogen Sensor Testing Laboratory

William Buttner, P.I.
Carl Rivkin and Robert Burgess,
H. Wright*, K. Schmidt*, K. Hartmann*
National Renewable Energy Laboratory
June 6, 2017

*Interns, Colorado School of Mines

Project ID # SC021

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project start date: 10/2010
- Project end date: 09/2017*

* Project continuation and direction determined annually by DOE

Budget

- FY16 DOE funding: $335K
- FY17 planned DOE funding : $315K
- Total DOE funds received to date: $2525 K

Barriers

C. **Safety is not always treated as a continuous process**

F. **Enabling national and international markets requires consistent RCS**

G. **Insufficient technical data to revise standards**

Partners

- **Industry:** component manufacturers, automotive OEMs, Element One, KWJ, Linde, KPA, AVT, Proton OnSite
- **Government labs and agencies:** JRC, BAM, DOT-NHTSA / Transport Canada, CaFCP, LANL, SNL, IEA-HIA, NREL (cross-cutting programs)
- **Academic:** Colorado School of Mines

Relevance: Why Use a Hydrogen Safety Sensor

- **Sensors provide critical safety factor**
  - Alarm at unsafe conditions
  - Ventilation activation
  - Automatic shutdown
- **Bad things can happen when sensors are not used (properly)** [www.h2tools.org/lessons]
  - "Gaseous Hydrogen Leak and Explosion"
    - Hydrogen explosion and iron dust flash fires in powdered metals plant
    - No combustible gas or H2 monitoring or training
  - "Two False H2 Alarms in Research Laboratory"
    - Nonspecific sensors alarmed twice ($10,000 fine)
    - H2 specific sensors are now installed
- **Mandated by code**
  - NFPA 2 (Sections 10.3.19.1 and 3.3.219.2.2)
  - IFC (repair garages, other indoor operations)
  - NFPA 2 is referenced in IFC

Hydrogen sensors in and around a hydrogen dispenser and FCEV

Relevance: Need for RD&D

"H2 Sensors Don't Work"

- Not true
- Not totally untrue
  - 1/3 of sensors tested out of spec.
  - Unacceptable failure rate in the field
  - Wrong sensor for application

Emerging Markets

- New applications (end-users)
- New sensor technology

Expectations of Performance

- Improper use/wrong sensor
- Critical gaps
  - How to properly validate sensors
  - Guidance on placement/location
  - Cost of ownership

Supports

- End-users (infrastructure and vehicle)
- Sensor manufacturers and developers
- Codes & standards

A sensor will work only if used properly

Image provided by KPA, used with permission

Vehicle Repair Facility (verification/validation)

Only one out of four sensors validated for application

Performance verification for a specific application is often necessary

Relevance

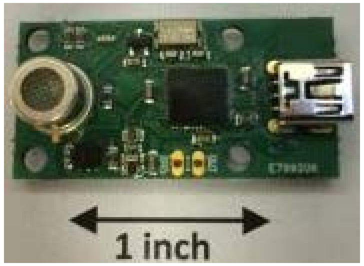
Common H_2 Sensing Elements

Features	Electro-chemical Sensors EC	Combustible Gas Sensors CGS	Thermo-conductivity sensors TC	Metal Oxide Sensors MOX	Palladium Thin Film Sensors PTF
Transduction Mechanism	Faradaic e transfer (current)	catalytic combustion (ΔR induced by ΔT)	Heat Transfer (ΔR induced by ΔT)	(ΔR) semiconductor doping	Sel. H_2 adsorption (various platforms)
Advantages	Good LDL	Robust	Fast response time	Low cost versatile sensor	Selectivity
Disadvantages	Prone to poisoning, drift	cross-sensitivity	non-selective (sensitive to $\Delta[H_2]$	Reputation for instability	Prone to poisoning; still expensive
Application	Low level detection; personal monitors; ESIF	Industry Standard; Petroleum Industry; Infrastructure	Modeling studies; controlled environ.; vehicles	General Deployment; containers	Petroleum Industry; specialized applic.

Every sensor platform is good, but none will work for every application.
The Sensing Element will control (and limit) Sensor and Analyzer performance.

Sensing Element (<$100)
(analog signal)

vs.

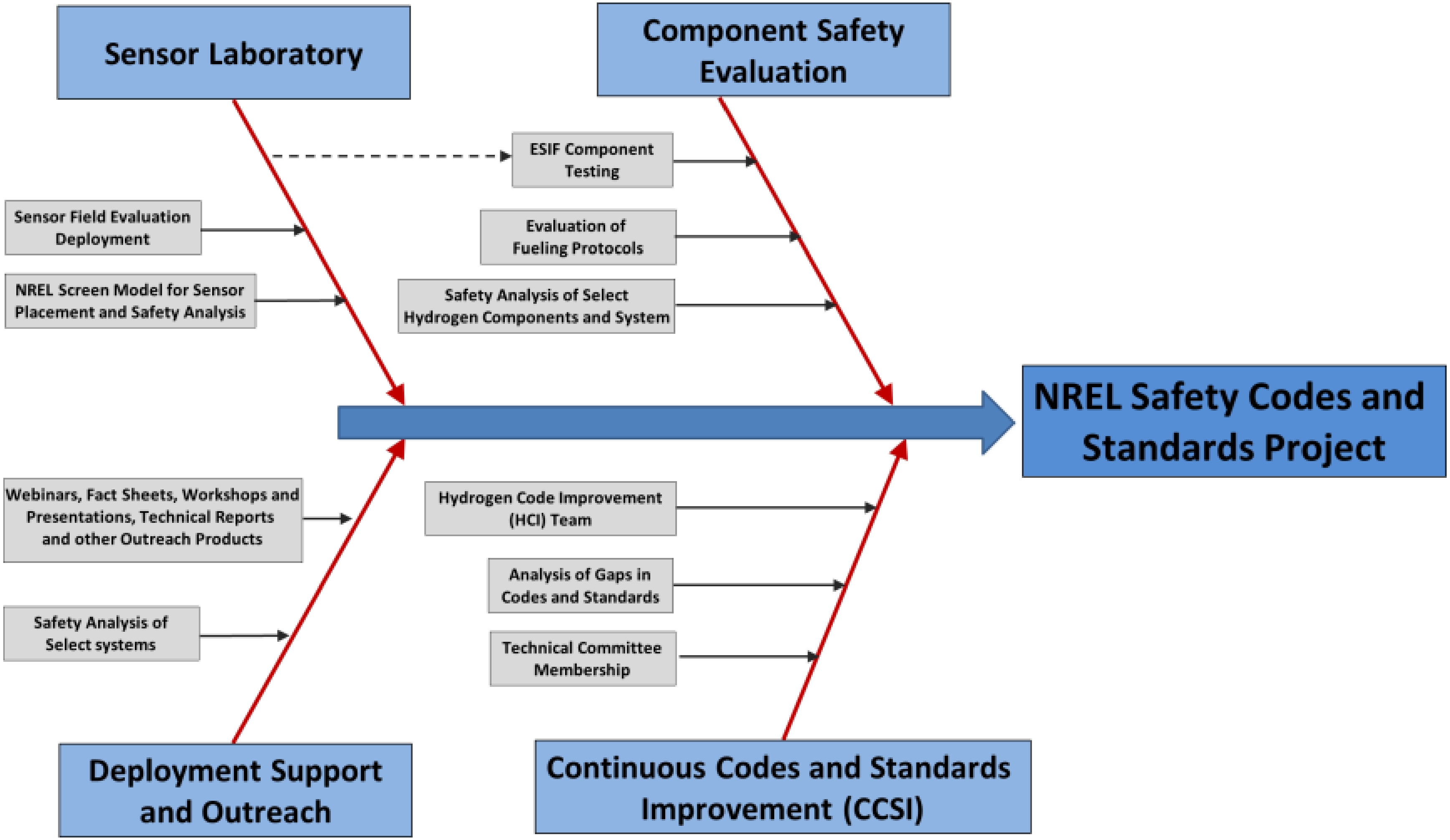


Sensor ($100 to $500)
(vol% H2)

vs.

Analyzer (>$500)
(Control Functions)

Approach



The NREL Sensor Testing Laboratory is an integral part of the NREL Safety Codes and Standards Group.

Approach: Functions of Sensor Testing Laboratory

- **Performance assessment of H2 sensing elements, sensors, or analyzers**
  - Commercial and developing technologies
  - Applications, method development
  - Not certification but performance verification/field validation
- **Support C&S development (national and international)**
  - Pre-normative research and document development
- **Support deployment**
  - **Direct collaborations** with the H2 community
    - Regulators, infrastructure, and OEMs
    - Research institutions, panels, SDO/CDO
  - "Topical Studies"—information on sensor use and case studies (Publications and Outreach)
  - Safety, FQ, and process applications
- **Client confidentiality**

The NREL Sensor Testing Apparatus

The Hydrogen Sensor Testing Laboratory RD&D effort is guided by the needs of the hydrogen community.

Approach: SDO/CDO and Safety Panel Participation

NREL and JRC Sensor Test Laboratories Support of Hydrogen Safety, Code, Standard and Regulation Development			
SDO/CDO/Regulation	**Jurisdiction**	**Lab Lead**	**Activity / Role**
GTR	International	NREL/JRC	Methodology for verification of requirements
NFPA/IFC	U.S.	NREL	Pre-normative research
CENELEC/SFEM	EU	JRC	Pre-normative research / methodology
ISO TC 197	International	JRC/NREL	Expert Support (WG 27, 28, 24)
ISO TC 158	International	JRC/NREL	Expert Support (WG 7)
CEN/CENELEC TC 6	EU	JRC	Liaison (pending)
SAE	U.S./International	NREL	Document Development, Expert Support
DOT/NHTSA	U.S.	NREL	Methodology for verification of requirements
ASTM	U.S.	NREL	Methodology for verification of requirements
UL	U.S.	NREL	Expert Support (standard technical panel)
Safety Committees	**Jurisdiction**	**Lab Lead**	**Activity / Role**
IEA-HIA	International	JRC/NREL	Methodology for verification of requirements
HySAFE	International	NREL/JRC	Expert Support

Codes and Standards ensure safety and encourage commercialization.
The H_2 Sensors Laboratories support code and standard development:

- Pre-normative research
- Document development
- Verification technology development
- Experts support/guidance/recommendations

Approach: Direct Interaction with Stakeholders

HYDROGEN SENSOR WORKSHOP

Workshop on Hydrogen Safety Sensors and Their Use in Applications with Hydrogen as an Alternative Fuel-End User Needs vs. Capability of Current Technology

Jointly organized by EC DG JRC and US DOE NREL Sensor Test facilities, and FCH 2 JU

Hydrogen Sensor Workshops

- Jointly organized: NREL-JRC Sensor Labs
- Bring together stakeholders in H2 community
  - Sensor manufacturers; infrastructure and vehicle; site safety
  - The Sensor Laboratories are a resource to the H_2 community
- Gap analysis: needs vs. capability
  - Role of Sensor Test Labs in support of the H2 community
  - Guidance document on proposed research direction
  - Summary presentation at ICHS
- Two separate venues (for international input)
  - EC: May 10, 2017 in Brussels (with the FCH JU)
  - U.S.: Technical Forum: July 18, 2017 (NREL)

Accomplishments and Progress (update): H2 Sensors for FCEV Repair Facilities

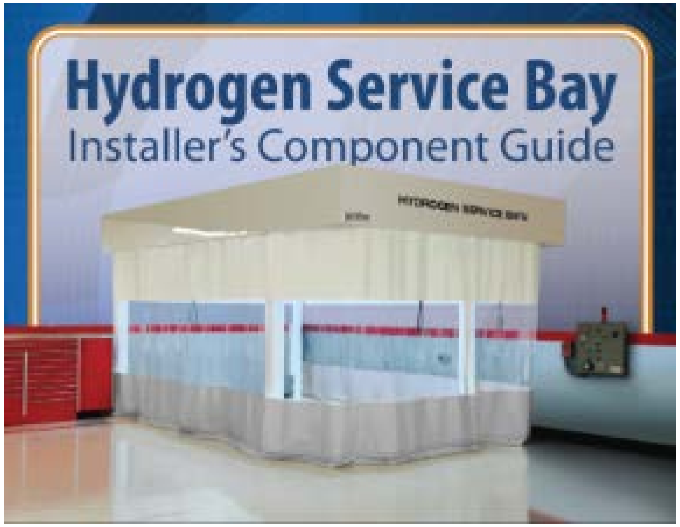


Image provided by KPA, used with permission

Project Overview and Update

- KPA-Toyota developed H_2 FCEV service bay
- NREL validated sensor for application
  - Under CRADA CRD-14-547
- Deployed within 9 Toyota facilities in CA
  - No failure in field for qualified sensor
- N.E. corridor deployment proceeding
  - 1 completed, 5-7 pending
- Technical Note for KPA web page (KPA request)
  - Summarize project (sensor validation for application), hydrogen as a safe fuel
  - http://www.kpaonline.com

The NREL Sensor Laboratory supports deployment by collaboration with stakeholders.
NREL successfully qualified sensor for application, facilitating AHJ acceptance.
On-going support to assure continued success.

Accomplishments and Progress: FCEV Exhaust Analyzer for Verification of GTR-13 Requirements

GTR 13 (overview)

- Basis for the development of the U.S. FMVSS and CMVSS
- FCEV exhaust composition verification is one H_2 monitoring requirements (general application, post-crash test)

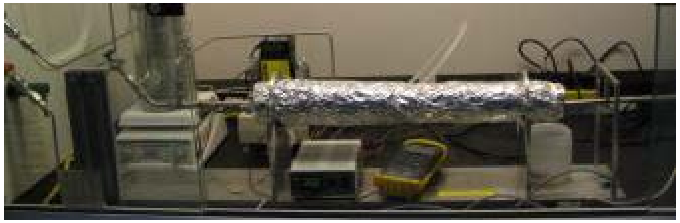
Transport Canada

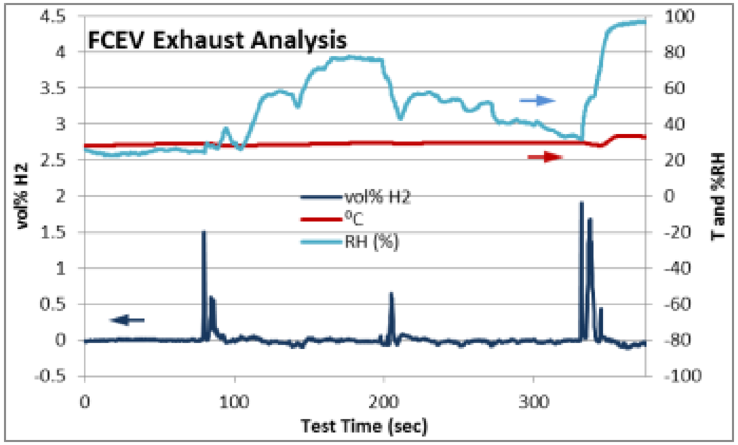
NHTSA

www.nhtsa.gov

NREL FCEV Exhaust Analyzer (for hydrogen)

- The GTR-13 exhaust requirement assures FCEV operational safety
- Performance verified in the laboratory
- Field tested on FCEV; detected hydrogen (Nov and Feb)
- Modified probe is being built
- Support DOT/NHTSA-TC FCEV exhaust tests
  - DOT-TC-NREL team for FCEV testing
- OEM applications and interest





Regulatory requirements need a means to verify compliance.
The NREL FCEV Exhaust Analyzer meets the GTR requirements for compliance verification.

Accomplishments and Progress:
Cold H2 Plume Analyzer – Field Deployment and Results

PROTOTYPE Cold Hydrogen Plume Analyzer

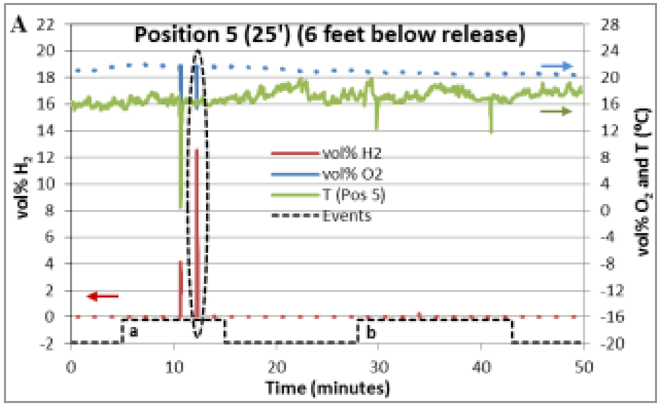
- In response to NFPA 2 H_2 Storage Task Group
- Address questions in Low-Cost Analyzer
  - 10 vertical measurement points on support structure with remote analyzer box with a single set of gas sensors
  - Multiplex vol% H_2, vol% O_2, T, RH measurements

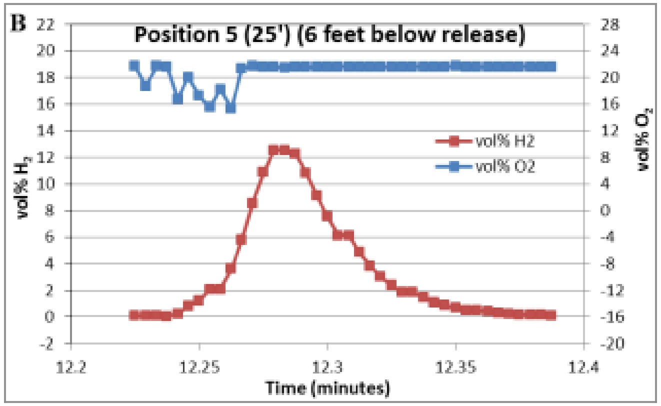
Field Demonstration Oct 25, 2016

- H_2 (> LFL) was observed up to 8' below release point
- Plume not totally dominated by buoyancy (wind effects)
- Vol% O_2 was not rigorously correlated to vol% H_2
- T was near constant (except low T transients)
- Vapor cloud did not seem to correlate to vol% H_2

Findings and Analyzer Upgrades

- Incorporate wind speed and direction sensor
- Use dedicated sensor for each measurement point (τ_{90} ≈250 ms)
- Amenable for H_2 Wide Area Monitoring with multiple support structures (low-cost and for use by untrained personnel)



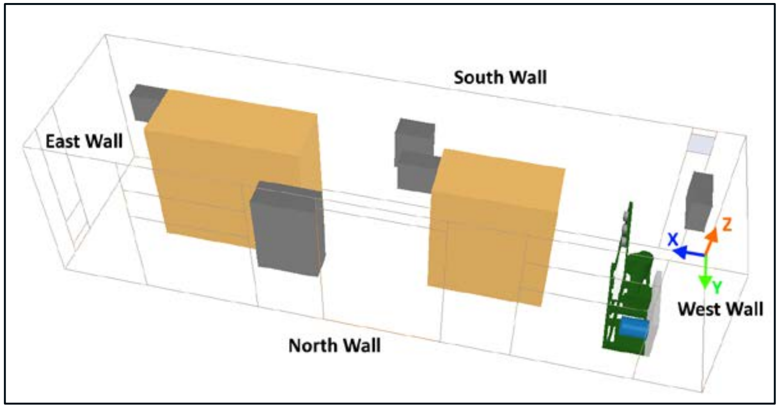


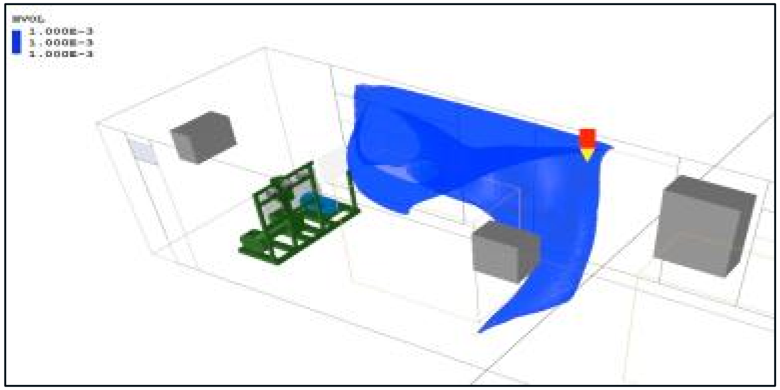
Research in support of C&S development
Safe use of LH2 is critical for hydrogen infrastructure scale up.
Behavior of releases is poorly understood.
Empirical work supports modelling and NFPA 2 set backs.

Accomplishments and Progress: Guidance on Sensor Placement
CFD modelling and empirical verification of indoor hydrogen releases

Guidance on H_2 Sensor Placement

- Identified in 2016 AMR as a GAP
- Test system: ISO container (hydrogen production with internal electrolysis production units)
- CFD modelling completed by A. V. Tchouvelev & Associates Inc. and by JRC
- Empirical verification at NREL within the ISO container using helium as a hydrogen surrogate
    - The Cold Hydrogen Plume Analyzer will be used
- Other operations/configurations to be studied
- In support of NFPA 2 (proposed Technical Annex)





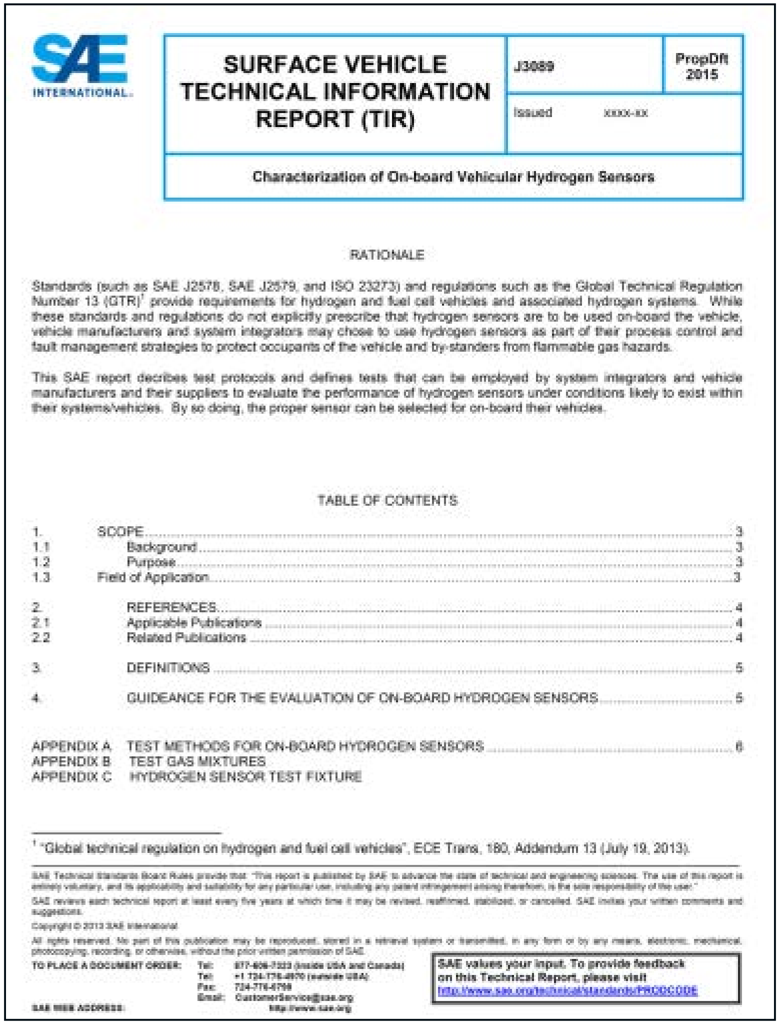
H_2 sensors are mandated by NFPA 2 and IFC, but without guidance on deployment.
Understanding hydrogen plume behavior will guide sensor placement for optimized safety.
A Sensor Placement Guidance Document will be developed as a Technical Annex in NFPA 2.

Accomplishments and Progress: SAE TIR J3089

SAE J3089

Characterization of On-Board Vehicular Hydrogen Sensors

- NREL is lead (with help from JRC, JARI, and FCSC)
- Technical information report (not a standard)
- Scope evolving—performance and physical operational testing
- Non-specific application
- Ready for comment: June 2017
- Topical studies:
  - Sensor Test Methods (Chamber vs. Flow Through)
  - FCEV Exhaust Analyzer
  - Stress testing to protect / assure against failure (on-going)
    - Chemical stresses
    - Physical stress



SAE INTERNATIONAL

SURFACE VEHICLE TECHNICAL INFORMATION REPORT (TIR)	J3089	PropDft 2015
	Issued XXXX-XX	
Characterization of On-board Vehicular Hydrogen Sensors		

RATIONALE

Standards (such as SAE J2578, SAE J2579, and ISO 23273) and regulations such as the Global Technical Regulation Number 13 (GTR)[1] provide requirements for hydrogen and fuel cell vehicles and associated hydrogen systems. While these standards and regulations do not explicitly prescribe that hydrogen sensors are to be used on-board the vehicle, vehicle manufacturers and system integrators may chose to use hydrogen sensors as part of their process control and fault management strategies to protect occupants of the vehicle and by-standers from flammable gas hazards.

This SAE report decribes test protocols and defines tests that can be employed by system integrators and vehicle manufacturers and their suppliers to evaluate the performance of hydrogen sensors under conditions likely to exist within their systems/vehicles. By so doing, the proper sensor can be selected for on-board their vehicles.

TABLE OF CONTENTS

[1] "Global technical regulation on hydrogen and fuel cell vehicles", ECE Trans, 180, Addendum 13 (July 19, 2013).

Codes and standards enhance safety and facilitate commercialization.
The TIR provides a uniform performance assessment guide for sensor suppliers and OEMs.

Accomplishments and Progress

NREL-JRC Collaboration—Joint Presentations for the ICHS 2017

Hydrogen Safety Sensor Performance and Use Gap Analysis

- Compare end-user needs to sensor capability
- Identify advances in performance in past 5 years
- Provide guidance document for manufacturers and proposed research directions
- To summarize Hydrogen Sensor Workshops (May 10, Brussels; July 18 at NREL)

Flow-Through Method Validation for Hydrogen Sensors Testing

- In response to SAE FCSC for cost-effective sensor qualification testing (supports TIR J3089)
- "Chamber Method" prescribed by standards is slow, hence expensive; flow through can be done in <20% of the time with less test gas
- Potential pitfall: pneumatic and sensor cross talk

Empirical Profiling of Cold Hydrogen Plumes Formed from Venting of LH2 Storage Vessels

- One of the first empirical measurement of LH2 venting
- Demonstrated critical LH2 release behavior (buoyancy not always dominant)
- Adaptable to GH2 releases
- Amenable for WAM of facilities

Hydrogen Safety Sensor Stability Testing—Impact of the Chemical Environment

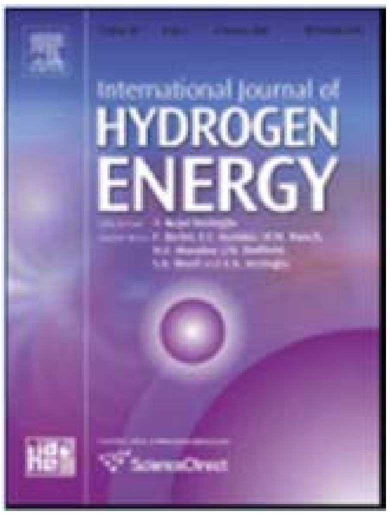
- Root cause of sensor failure is a gap (and premature failure in the field a concern)
- Chemical stresses are one critical factor impacting sensor performance
- Need to verify that sensor will not be poisoned or false alarm due to ambient contaminants

Hydrogen sensors assure the safe use of hydrogen.
The Sensor Laboratories facilitate proper use of sensors by outreach and partnerships.
The ICHS is the premier venue for the dissemination of hydrogen safety RD&D.

Accomplishments and Progress: Program Update

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

international association for hydrogen energy
Clean and Abundant Energy for Sustainability

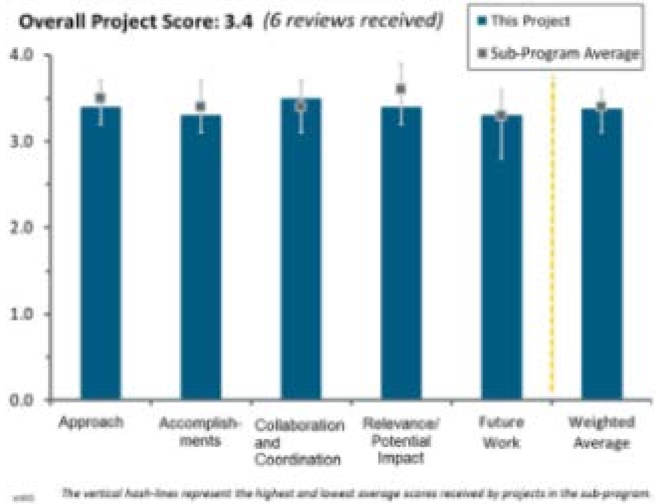


Most Cited IJHE Articles (past 5 years)

1. A comprehensive review on PEM water electrolysis
   Carmo M, Fritz DL, Mergel J, Stolten D. Int J Hydrogen Energy 2013;38(12):4901–34.
2. Nanoscale and nano-structured electrodes of solid oxide fuel cells by infiltration: Advances and challenges
   Jiang SP. Int J Hydrogen Energy 2012;37(1):449–70.
3. Non precious metal catalysts for the PEM fuel cell cathode
   Othman R, Dicks AL, Zhu Z. Int J Hydrogen Energy 2012;37(1):357–72.
4. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications
   Gahleitner G. Int J Hydrogen Energy 2013;38(5):2039–61.
5. An overview of hydrogen safety sensors and requirements
   Buttner WJ, Post MB, Burgess R, Rivkin C. Int J Hydrogen Energy 2011;36(3):2462–70.
6. Pd-Ni electrocatalysts for efficient ethanol oxidation reaction in alkaline electrolyte
   Zhang Z, Xin L, Sun K, Li W. Int J Hydrogen Energy 2011;36(20):12686–97.
7. Ammonia and related chemicals as potential indirect hydrogen storage materials
   Lan, R, Irvine, J.T.S., Tao, S. Int J Hydrogen Energy 2012;37(2):1482–94.

From the December 2016 IAHE Newsletter
Demonstration of the on-going relevance of the Sensor Laboratory

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments



Reviewers Comments (Accomplishment and Progress Category)

Developing sensor function test facilities and methods is very important to the next step of developing better application information. It seems like many sensor problems are really application or misapplication problems, so having this foundation to start to address those issues is good. The tailpipe sensor selection/assessment work is also very valuable. Perhaps that work can now be coordinated with the component research and development to make sure the durability/reliability of a specific sensor in a specific application is well understood.

This comment alludes to a gap in hydrogen sensors that is identified below, namely the stability of a sensor in deployment. The underlying cause of sensor failures needs to be better elucidated. Degradation may be due to chemical stresses, which is a topic of study for the ICHS, but in some applications, physical stressors (mechanical, T, RH, P fluctuations) can be critical but their impact has not been properly elucidated. An investigation into impact of these stressors is being initiated.

Reviewers Comments (Accomplishment and Progress Category)

"Support of Infrastructure Empirical Profiling of LH2Releases during Routine Venting"

The reviewer provided a rather lengthy, multifaceted "critique" of the approach and perceptions of likely outcomes.

General comment/reply

At the 2016 AMR, the design of the Cold Hydrogen Plume Analyzer was introduced as an accomplishment.

- *The description was in fact for a **PROTOTYPE** design, configured for flexibility and upgradeable*
- *Flexibility was necessary to get a understanding of where the H_2 would be*
  - *Near-total lack of field data (and understanding) on LH2 releases*
  - *An uncertainty existed within the NFPA H_2 Storage Task Group to the extent that buoyancy of H_2 would dominate (e.g., would H_2 exist below the release point).*
  - *Little information on release process and behavior was available (e.g., the depressurization following the LH2 transfer releases 50 to 75 kg of hydrogen out of a 30-foot tall vent over a 1 hour period)*
  - *There was also a very limited budget.*

The reply continues on the next few slides

Reply to some specifics

… However, what is being executed is an array of vertical pointwise measurements taken about 10 s apart… …There are 10 ports, 10 s apart, which means that each port is sampled every 100 s.

- *This is only true for the **PROTOTYPE** design.*
- *Response time for current design is 250 ms.*

… The pointwise-in-time and space measurement of anything will yield useless information… … Point measurements in this situation are a waste of time and money because nothing of meaning can be expected from this effort. …

- *Not true. The **PROTOTYPE** analyzer already demonstrated that buoyancy is not the totally dominant factor in the release (H_2 will be observed below the release point).*
- *A proper array of analyzers can provide low-cost and simple WAM and perimeter monitoring for assurance of safety and, with a real-world measurement capability, will test validity of models.*
- *The (updated) analyzer is being used to validate indoor release model (with AVT).*

Reply to some specifics

..the next-best option is a line-of-sight integrated volumetric time-resolved movie (such as schlieren or shadow graph)…

- *Stand off methods, such as Schlieren proposed in this comment are challenging and most likely will not work in an outdoor environment at the level needed*

…Except for the noted sub-project, this project continues to have an outstanding outreach/publication record. The project contributes to appropriate technical symposia, journals, reports, books, etc., which is excellent...

- *Thank you—I try.*

Collaborations: Joint Research Centre

NREL-JRC Sensor Laboratory Collaboration

- Since 2008 (various agreements)
  - Collaboration Arrangement for Research and Development in Energy-Related Fields DOE-JRC (June 2, 2016)
- Exchange of personnel (W. Buttner's 2 month assignment at the JRC)
- Coordinated research and outreach
  - 4 papers to ICHS (2017)
  - Over 30 joint talks and presentations
  - Over 25 joint publications (reports, articles, book)
- Coordinated participation on Safety Committees (HySafe, IEA-HIA Task 37)
- Hydrogen Sensor Workshops (identify gaps)
  - EC: Brussels (with FCH2 JU) May 10, 2017
  - US: NREL (July 18, 2017)

Invitation letter for 8-week JRC assignment

From:	Marc.STEEN@ec.europa.eu
Sent:	Friday, October 21, 2016 5:57 AM
To:	Buttner, William
Cc:	James Jr, Charles (HQ); Hill, Laura (FELLOW) (HQ); Satyapal, Sunita (HQ); Pietro.MORETTO@ec.europa.eu; Eveline.WEIDNER@ec.europa.eu; Tanya.ARABADZHIEVA@ec.europa.eu
Subject:	Invitation to Petten

Dear Dr. Buttner,

It is my great pleasure to invite you to the JRC Institute for Energy and Transport for an extended visit for a period of 6-8 weeks in the 1st or 2nd quarter of 2017.

This invitation relates to the exchange of scientists foreseen in the Collaboration Arrangement between the US Department of Energy and the Directorate General Joint Research Centre.

The NREL and JRC sensor laboratories collaboration on impartially evaluating hydrogen sensor performance and verifying compatibility of sensors for use in specific applications will benefit from an extended scientist exchange. A main aim of the planned work during your visit would be the development of test instrumentation and procedures, both of which can be adapted to address performance requirements as defined by emerging applications. The work on characterizing the effect of contaminants on the performance and lifetime of sensors should be continued in 2017, in particular with the elaboration of testing protocols for exposure to contaminants likely to occur in the transport sector. The tests prescribed in ISO 26142 have been found to not sufficiently reproduce the use environment of sensors for automotive applications. The effect of temperature cycles and other stressors on the lifetime of sensors has been investigated, and further work is planned on analysing sensor degradation. In addition, support to the hydrogen community should be provided by work on the proper choice and placement of hydrogen sensors.

This email does not constitute the official invitation, which you will receive from our Director. With the official invitation, you will also receive information on the administrative procedure to be followed from your side to prepare for the visit.

I very much hope that you are able to accept the invitation, and I am looking forward to welcoming you in Petten.

Best regards,

Marc STEEN
Head of Unit

European Commission
Joint Research Centre
Directorate for Energy, Transport and Climate
Energy Storage Unit

The NREL-JRC sensor collaboration synergizes the effort of each laboratory:
Minimized duplicated R&D efforts while exploiting the range of respective expertise and capability
Increased international exposure and visibility of results to facilitate deployment

Collaborations: Private and Government Partnerships

Performance & Qualification (Safety)

Technology Development

- Element One, Inc. (MOU/NCAP; SBV)
- LANL/KWJ, Engineering (SBV)
- LANL

Infrastructure Support

- KPA (on-going support)
- Proton Onsite
- AVT (sensor placement guideline)

Vehicle Support

- Ford Motor Company (NDA)
- JARI (through the SAE FCSC)
  - OEMs & sensor suppliers

New Markets

- Fuel Quality Verification

Process Monitoring and Methods

Infrastructure Support

- The Linde Group(NDA, pending)
- Xensor, Inc (NDA, pending)

Vehicle Support (GTR)

- GTR: Ford Motor Company/Daimler
- DOT/NHTSA, Transport Canada

The NREL Sensor Laboratory
A resource to the H_2 community

- **Infrastructure, vehicle, and new markets**
- **Sensor developers and end-users**
- **Formal and informal agreements**
- **Available for WFO**

Collaborations: The DOE Small Business Voucher Program

Element One, Inc.

Development and Testing of Low-Cost Hydrogen Leak Detection

Lead DOE Laboratory: NREL, William Buttner, PI

- Provide NREL/DOE resources for fabrication and characterization of thin film colorimetric/electrical indicators
- Correlation between performance, fabrication parameters, and morphology
- Application development

KWJ Engineering, Inc.

Advanced Characterization of Printed Hydrogen Sensors

Lead DOE Laboratory: LANL, E. Brosha and R. Mukundan

- Develop fabrication protocols

Support Laboratory: NREL, William Buttner, Lead

- Performance assessment

Small Business Vouchers Pilot
U.S. DEPARTMENT OF ENERGY

Technical assistance from national lab

- **Direct business to lab collaboration**
- **Not a funding source**

Simple, easy application protocol

Tiered application deadline

https://www.sbv.org/
Google "Small Business Voucher"

Collaborations: Education and Outreach

Student Internships in the Sensor Laboratory

The NREL Sensor Laboratory has mentored student interns since 2014 (summer and year-round predicated on class schedule)

- **Ian Bloomfield** (June 2013–December 2015): KPA Project; "Bloomfield Automation" Consultant NREL Cold Plume Analyzer
- **Kevin Hartmann** (June 2014–January 2017): NCAP-Element One DetecTape®, Cold Plume Analyzer, HCD-I
- **Max Bubar** (June 2014–December 2015): GTR Tailpipe Analyzer
- **Kara Schmidt** (April 2016–present): Cold Hydrogen Plume Analyzer
- **Hannah Wright** (April 2016–present): Cold Hydrogen Plume Analyzer, GTR Tailpipe

The interns have presented and co-authored technical talks and publications.

Interns (past and present), Colorado School of Mines
Max Bubar (graduated); Hannah Wright, Kara Schmidt; Ian Bloomfield (graduated , now a consultant); Kevin Hartmann (not shown)

SCHOOL OF MINES 1874 COLORADO

Remaining Challenges and Barriers

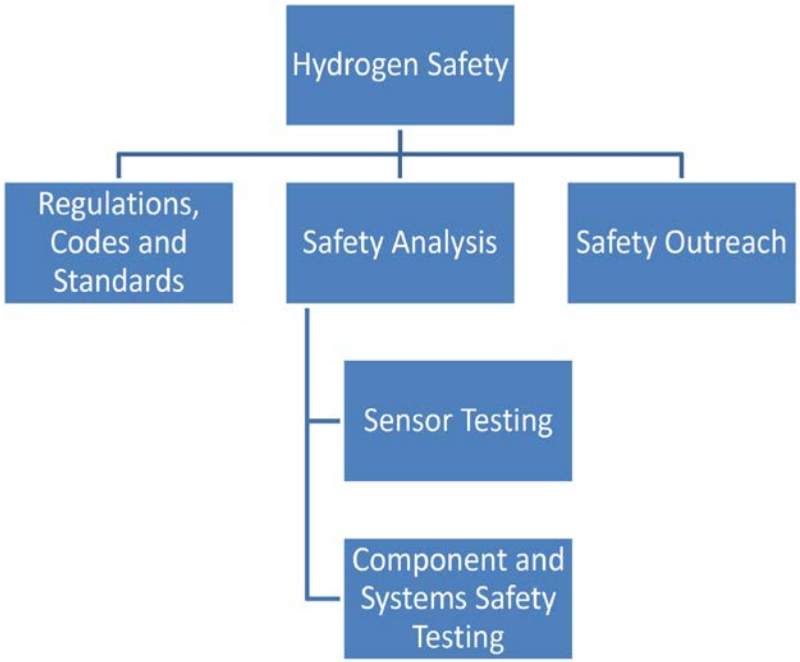
Hydrogen Safety Sensors:

- **Low maintenance sensors/lifetime (cost of ownership):** Sensor maintenance (calibration, replacement, and even out-of-the box in spec performance) remains an issue. Mitigating impact of poisons and lengthening calibration duty cycles is essential to improve end-user acceptance. Proper sensor selection and an understanding of failure mechanisms and rates is critical to support deployment.
- **Sensor Placement:** Sensor placement strategies are informal and often by intuition. Guidance documents are lacking. As a corollary, sensor placement and number guidance is necessary for large indoor hydrogen facilities (e.g., warehouses); alternative/supplemental strategies may be needed for cost
- **Response time:** Some sensor applications require a fast response time (1 s or less); this has remains elusive, although a TC platform can meet this requirement under certain conditions. Standardize RT methodology does not exist

Process Control/FQ ("specialized" application):

- **Metrologic performance:** Emerging applications have unique and challenging analytical requirements (detection limits, harsh environments)

Proposed Future Work: NREL Hydrogen Sensor Multiyear Plan



Manufacturer/Developer Support

- Sensor performance validation (e.g., SBV)
- Developmental technologies support
- Process control/fuel quality sensors
- Sensor deployment/infrastructure support
- Wide area monitoring/distributed sensors

End-User Support to Support Deployment

- Auto-calibration
- Guidance on deployment / placement
- DOT/NHTSA and the GTR on hydrogen vehicles
- C&S support (NFPA 2/LH2 profiling; ISO, SAE)
- Barriers to sensor certification and impacts
- Support of NREL component testing

Any proposed future work is subject to change based on funding levels.

ESIF – Energy Systems Integration Facility
NREL facility includes the sensor lab, components lab, high pressure test lab, and infrastructure test sites (e.g., fueling station, Energy Systems Integration Laboratory, ESIL)

Summary

Relevance: Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure.

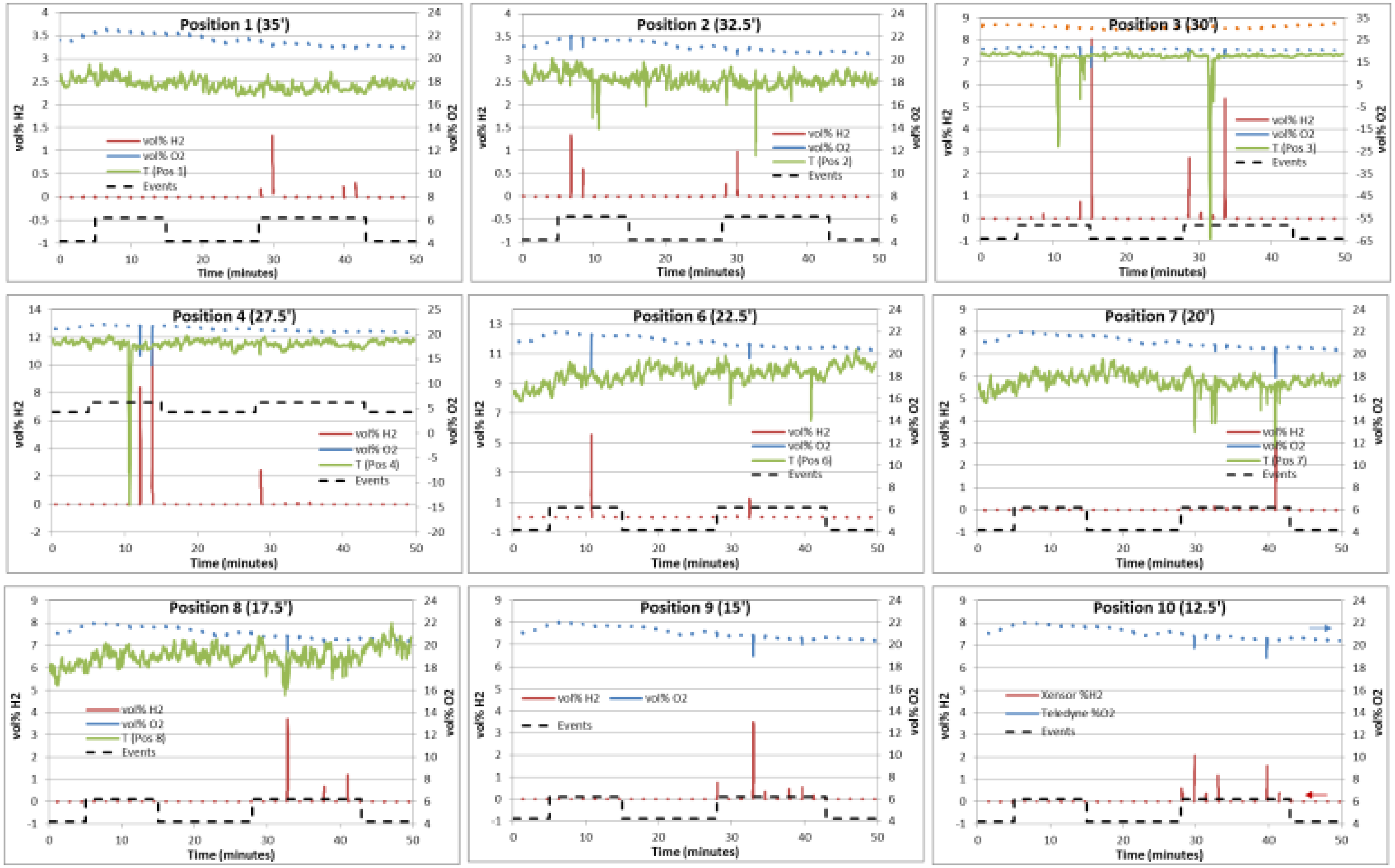
Approach: NREL Sensor Laboratory tests and verifies sensor performance for manufacturers, developers, end-users, and SDOs.

Accomplishments and Progress: NREL's R&D accomplishments have supported developers, industry, and SDOs by providing independent third party assessment of performance.

Collaborations: Collaboration with other laboratories (JRC, universities, private industry) has leveraged NREL's success in advancing hydrogen safety sensors and process control.

Proposed Future Work: NREL will support hydrogen deployment and the proper use of hydrogen sensors. NREL will continue to work with SDOs to revise documents, when required. NREL will support the development of improved methods to verify fuel quality.

Technical Back-Up Slides



- Field data for the Cold Hydrogen Plume Analyzer: vol% H_2, vol% O_2, and T measurements for nine measurement positions from the Cold Hydrogen Plume Analyzer
- To be presented at ICHS 2017