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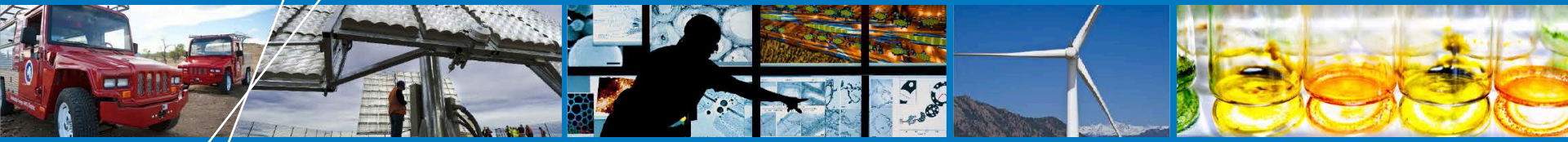
NREL Hydrogen Sensor Testing Laboratory



2013 DOE Hydrogen and Fuel Cells Program Review

William Buttner (PI), Robert Burgess, Carl Rivkin, Chad Blake

National Renewable Energy Laboratory

May 14, 2013

Project ID # SCS021

Overview

TIMELINE

- Start date: **October 1, 2012**
- End date: **10/2013***

*Project continuation and direction determined annually by DOE

BARRIERS

2012 Multiyear RD&D Plan Barriers

- **A.** Safety Data and Information: Limited Access and Availability
- **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
- **H**. "Insufficient synchronization of national codes and standards"
- **K**. No consistent codification plan and process for synchronization of R&D and code development

BUDGET

- Funding for FY12: **$500K***
- Planned FY13 funding : **$300K#**

* Combined funding for Sensor Laboratory and Component Testing

#Sensor Laboratory only

PARTNERS

- Industry: component manufacturers, automotive OEMs, station suppliers, KARCO, Battelle
- Government labs and agencies: JRC, BAM, DOT-NHTSA, NIST, NASA, TRC, CaFCP, LANL, LLNL
- Universities: CO School of Mines, UQTR
- SDOs: CSA, ISO, UL, NFPA, GTR, IEEE, FM Global

Relevance: Role of Sensors for Safe H_2 Deployment

- **Provide critical safety factor**
  - Alarm at unsafe conditions
  - Ventilation activation
  - Automatic shutdown
- **Bad things can happen when sensors are not used (properly)** [www.H2incidents.org]
  - "Gaseous Hydrogen Leak and Explosion"
    - Lack of hydrogen detection: "Hydrogen Explosion and Iron Dust Flash Fires in Powdered Metals Plant"
    - No combustible gas monitoring or training
  - "Two False Hydrogen Alarms in Research Laboratory"
    - Nonspecific sensors alarmed twice ($10K fine)
    - H_2 specific sensors are now installed

Hydrogen dispenser equipped with wall-mount and internal sensor

- **Mandated by Code**
  - **NFPA 2 10.3.19.1** Dispensing equipment shall be provided with gas detectors, leak detection, and flame detectors such that fire and gas can be detected at any point on the equipment [52,2010, 9.2.14]
  - **NFPA 2 3.3.219.2.2** Gas Detection System. One or more sensors capable of detecting hydrogen at specified concentrations and activating alarms and safety systems. [52,2010]
  - NREL C&S submitted a proposal to NFPA 2 providing guidance on sensor placement

Approach: NREL Sensor Testing Laboratory

- **Provide independent assessment of hydrogen sensor performance**
- **Interact with manufacturers to improve sensor performance to meet DOE 2012 targets**
  - Redefined at 2011 workshop (application-specific)
- **Support hydrogen sensor codes and standards development (national and international)**
- **Test/validate new sensor R&D**
- **Support end-users with information on sensor performance**
- **Client confidentiality**

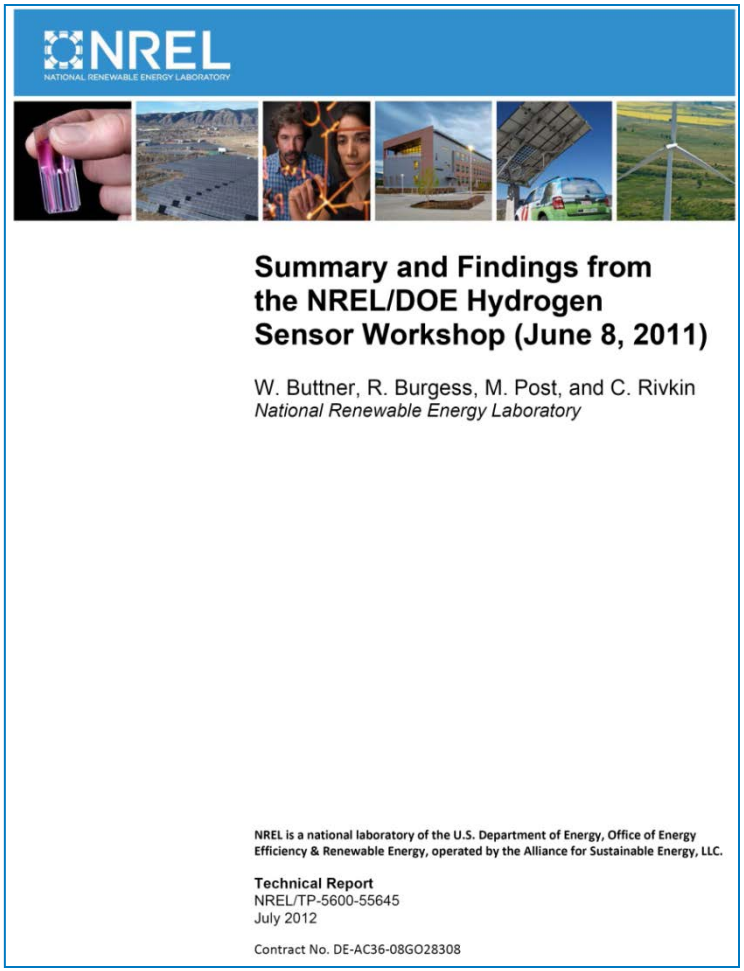
The ultimate goal of the Hydrogen Sensor Testing Laboratory is to ensure that end-users get the sensing technology they need

Approach:
Identification of Hydrogen Sensor Gaps and Deficiencies

Critical Gap Areas

- **Analytical parameters**
  - Signal drift (long-term stability)
  - Cross sensitivity/poisons
  - Response time (1 sec) for enclosures
- **Operational parameters**
  - Cost of maintenance and calibration
  - Alarm thresholds
- **Deployment parameters**
  - Code requirements
  - Placement and number of sensors
  - Point sensors vs. wide area monitoring

Specific DOE Targets for H_2Sensors presented in Table 3.7.6 in EERE Multiyear Plan (2012)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Summary and Findings from the NREL/DOE Hydrogen Sensor Workshop (June 8, 2011)

W. Buttner, R. Burgess, M. Post, and C. Rivkin
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

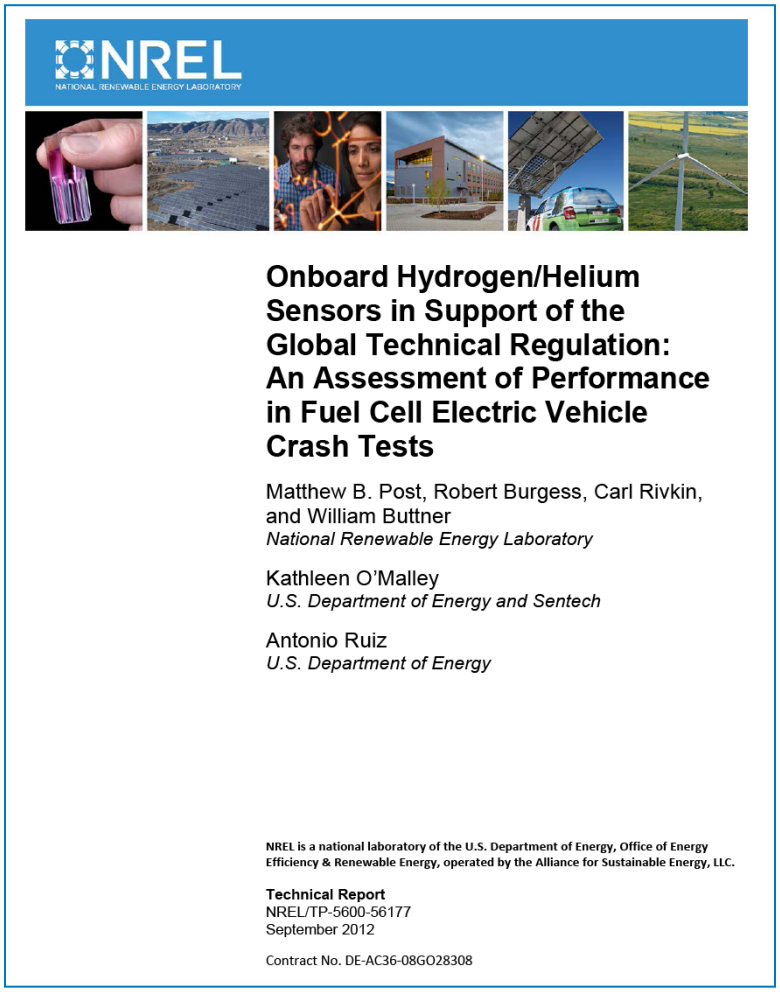
Technical Report
NREL/TP-5600-55645
July 2012

Contract No. DE-AC36-08GO28308

Follow-up Hydrogen Sensor Task Group (Quarterly WEB meetings)

Accomplishment:
Support of DOT and the GTR/Hydrogen Vehicle Crash Tests

- **GTR requirements for FCEV H_2 storage system**
  - Basis for FMVSS
  - FCEV subjected to standard crash test
  - <4 vol% H_2 for 1 hour following impact
  - Failure may result in vehicle recall
  - Actual tests may be performed with He



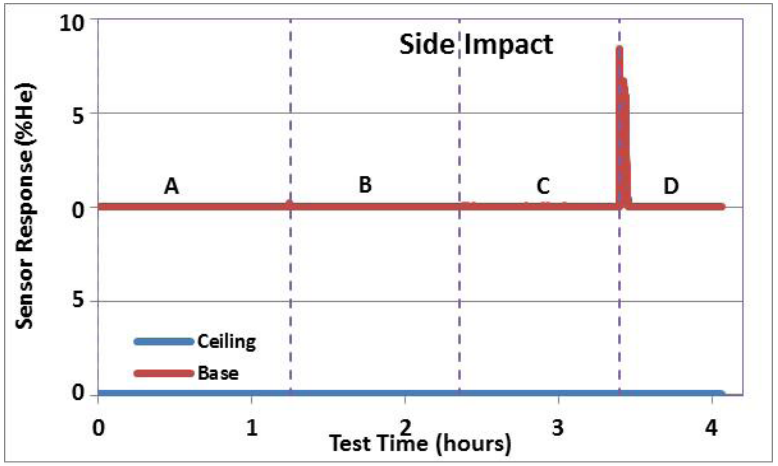
Accomplishment:
Sensor Deployment in Support of DOT and the FCEV GTR

FCEV Crash Test Deployment

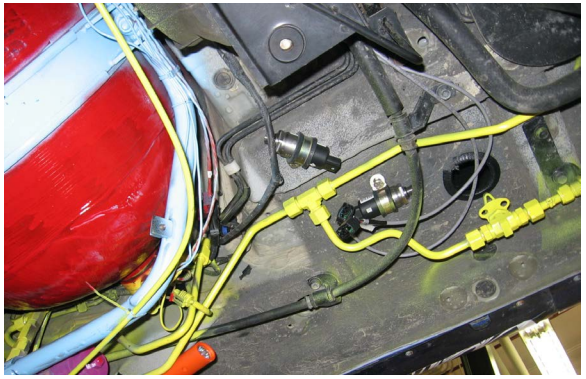
- Side impact test and rear impact test
- Passenger area and under vehicle
- Developed and deployed on-board system
  - Instrumented sensor system
  - Recommendations provided to DOT/DOE

Acknowledgement

DOT/NHTSA, KARCO, Battelle, TRC, Inc.



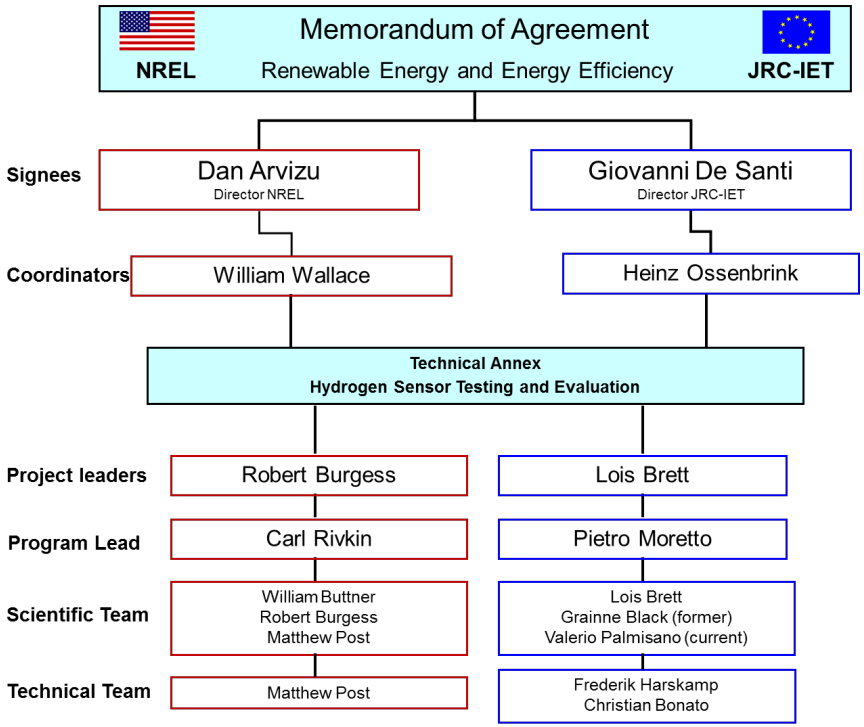
A: Final vehicle preparation
B: Fuel system pressurization
C: 1 hour post impact
D: Vehicle prep (post crash test)



Partnership: The NREL/JRC Collaboration

DOE/NREL – JRC-IET MOA since 2010
(Synergize H_2 Sensor Assessment Activity)

- Minimizing duplicated R&D efforts
- Increasing international exposure and visibility of results
- Expanding capabilities and expertise
- Facilitating implementation of the hydrogen infrastructure
- "Topical studies" to address sensor needs
- Outreach
  - Joint publications, presentations
  - Unified strategies via calls and panel participation

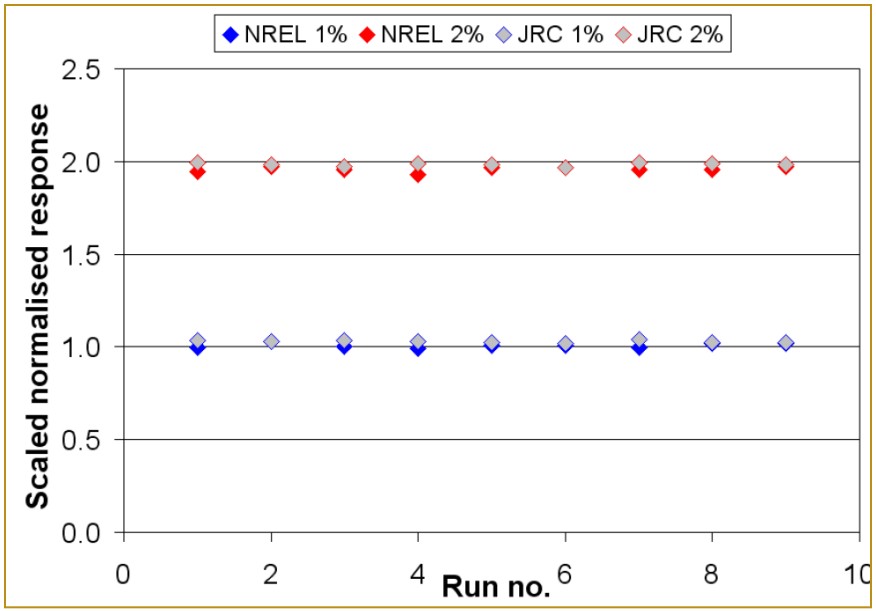


Annual Steering Committee Meetings
September 2011 and December 2012

Accomplishment:
NREL/JRC Collaboration – Round Robin Testing

Sensor INTERlaboratory Comparison (SINTERCOM)

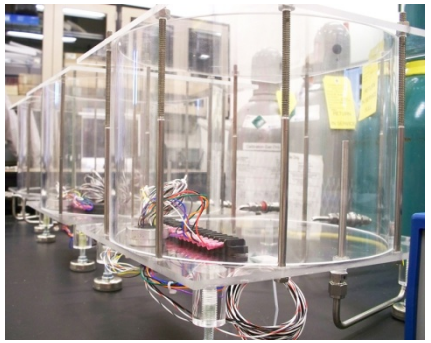
- **JRC-IET and DOE/NREL collaboration**
  - RRT of COTS sensors
  - Validated laboratories and test protocols
  - Data and assessment to stakeholders
- **Outcomes and significance**
  - Cross validation of laboratories
  - Survey of sensor platform types
    - Interim report published
    - Comprehensive report under development (survey of platforms to meet requirements)
    - **1/3 of sensor models did not meet manufacturer accuracy specification**
  - Expanded scope (more "topical studies")
  - **No duplication of effort**



SINTERCOM short-term stability results
- MOS sensor platform
- 1 vol% H_2 and 2 vol% H_2
- JRC and NREL data

Accomplishment:
NREL/JRC Collaboration – Long Term Exposure Results

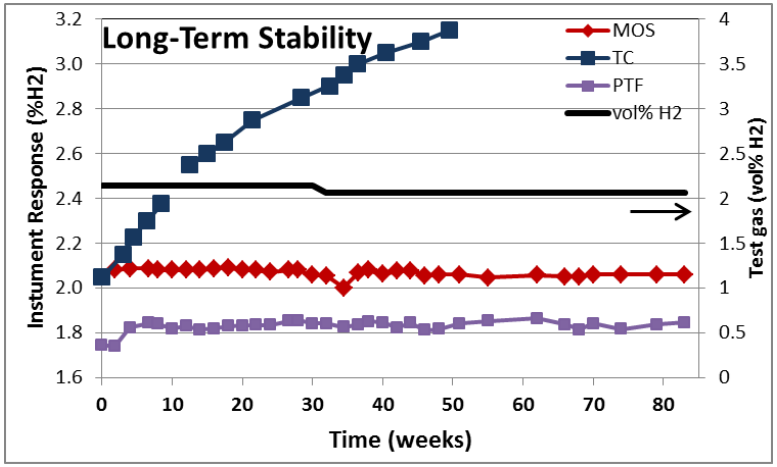
Purpose: *To determine sensor capability through at end of life*



Life test fixture

Sensor Long-Term Stability

- Stored in air at ambient T, P, with RH regulated to 45% ± 2%
- Periodic challenged to 2.0% ± 0.2% H_2
- Sensor Platforms: MOS, TC, PTF
- Additional technologies will be subjected to the life test protocol



Accomplishments: NREL/JRC Collaboration – Topical Studies

Sensor performance in inert matrix

- Inert gas purges may alleviate risks but may deactivate sensors
- O_2 requirement depends on technology
- Initiated to educate end-users
- **Significance: potentially dangerous situations arise using wrong sensor**
- Presented: ICHS 2011; IJHE 2012

Sensor miniaturization via micromachining

- Promises: economy, fast kinetics, small size
- Pitfalls: compromised performance, fragile
- Collaboration with UQTR/H2Canada
- Post-graduate student support
- **Significance: "reality check" on over-emphasis of a single parameter**
- Presented: WHEC 2012; IJHE (2013)

Impacts of interferents and poisons

- Interferents can lead to false alarms
  - Target interferents (CO, CO_2, CH_4, NH_3)
- Poisons permanently damage sensor
  - Sulfur, silicones, WD-40®
- Platform dependent
- **Significance: addresses false alarms, premature sensor failure**
- To be presented: ICHS 2013; IJHE 2013

H_2 determination via O_2 displacement

- Advantages: COTS, diluent independent
- Pitfalls: poor LDL, large T&P impacts, insensitive for closed systems, poor lifetime
- **Significance: inappropriate for H_2 safety; poor accuracy for other applications**
- **Approach referenced in GTR**
  - **Alternative: use TCD for release studies**
- To be presented: ICHS 2013; IJHE 2013

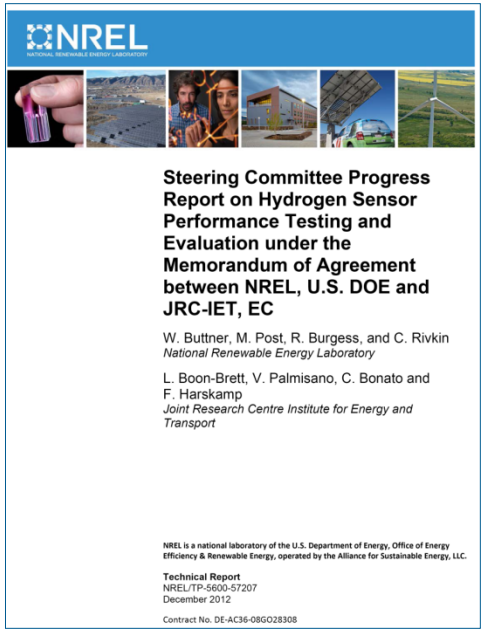
Future Work: NREL and JRC Collaboration

Sensor Evaluation (2013)

- Sensor testing (ongoing)
- WAM (to be initiated)
- Interferent and poisons testing
- Infrastructure support
- Topical studies (tbd)

Outreach (2013)

- Joint presentations at ICHS 2013 (2)
- Joint peer reviewed papers (3)
- Joint technical reports (1 completed)
- Common input into Hydrogen Safety Panels (IEA Task 31), International SDOs
- EU Hydrogen Sensor Workshop (September 2013)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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

W. Buttner, M. Post, R. Burgess, and C. Rivkin
National Renewable Energy Laboratory

L. Boon-Brett, V. Palmisano, C. Bonato and F. Harskamp
Joint Research Centre Institute for Energy and Transport

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-57207
December 2012

Contract No. DE-AC36-08GO28308


JRC Technical Notes

Interim Report of the SINTERCOM Project

Black, G.[1], Boon-Brett, L.[1], Harskamp, F.[1], Moretto, P.[1]
Buttner, W. J.[2], Post, M. B.[2], Burgess, R.[2], Rivkin, C.[2]

[1] European Commission, DG Joint Research Centre, Institute for Energy – Cleaner Energy Unit, P.O. Box 2, 1755 ZG Petten, The Netherlands.
[2] Hydrogen Technologies & Systems Center, National Renewable Energy Laboratory, Golden CO 80401, USA.

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Clean Energies

National Renewable Energy Laboratory
A laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
operated by the Alliance for Sustainable Energy, LLC
1617 Cole Blvd.
Golden, CO 80401-3305

EUR 24854 EN - 2011

JRC EUROPEAN COMMISSION

Collaborations

Developmental Activity

- LANL/LLNL – third round of testing on prototype sensor
- Element One, Memorandum of Understanding
- Colorado School of Mines

Infrastructure Support (Repair Facilities, Fueling Stations, etc.)

- NREL EHS (ESIF chemical detection)
- Vehicle OEMs
- CaFCP

NREL Sensor Laboratory Outreach

Feedback to Manufacturers/Sensor Developers and End-Users

- Written performance summaries and recommendations
- Telecom option to review test results

Site Visits to Hydrogen Facilities

- Industrial and government
  - Indoor: repair facilities, dispensing, forklift
  - Outdoor: storage, dispensing

Sensor Workshop (2011)/Hydrogen Sensor Task Group (on-going)

- Quarterly Web meetings with topical talks and open discussions
  - Open venue for all stakeholders in the hydrogen community
- Sub-group: Hydrogen Standards Group

Working Groups and Technical Panels

- STP member on Sensor Standard Committees
- IEA Task 31 (formerly Task 19) Hydrogen Safety

NREL Sensor Laboratory Web Page

- http://www.nrel.gov/hydrogen/facilities_hsl.html

NREL Sensor Laboratory Publications*

Talks and Presentations (conferences, workshops, and technical panels)

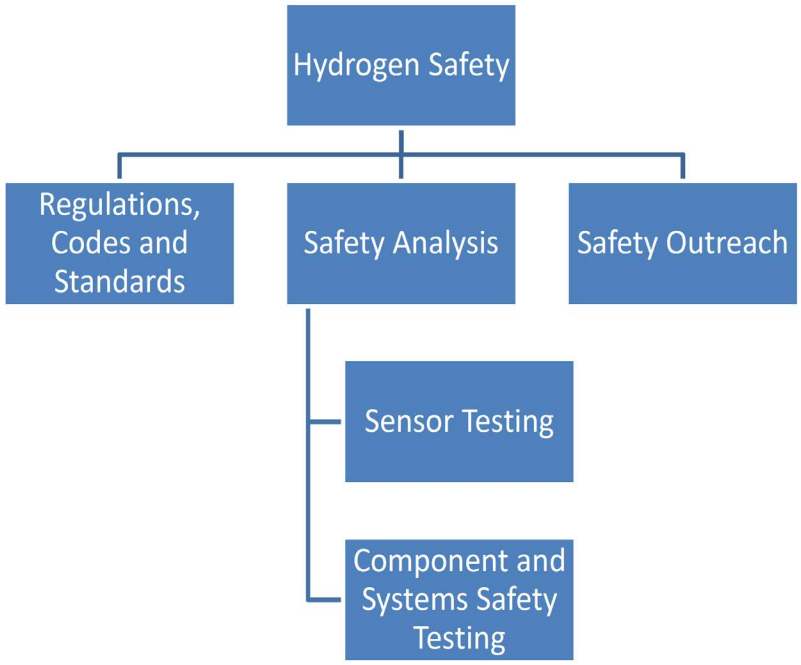
- NHA/FCHEA, IEA Task 19/Task 31, ICHS (2013, 2011, 2009), DOE AMR, Telcordia, DOE Sensor Workshops, NREL Sensor Task Group, IEEE, ISO, UL ECS, WHEC, JRC-NREL MOA Steering Committee Meeting, Clients
  - ~35 presentations since 2008; 7 in 2012, 7 (projected) in 2013
  - The NREL Sensor Laboratory, W. Buttner, R. Burgess, M. Post, C. Rivkin, Presented at DOE Sensor Workshop, Chicago, IL (September 24-25, 2012).

Publications (technical reports, peer review papers, conference papers, book)

- ~25 publications since 2008; 5 in 2012, 8 (projected) in 2013
- Book: **Sensors for Process Control and Safety in Hydrogen Technologies**
  - With T. Hübert, L. Brett-Boon, W. Buttner, U. Schmidtchen and B. Fellmuth
  - CRC Press (1st Draft due 12/31/2013)

***Funded in part under AOP Task 7.3 Outreach**

Future Work: The NREL Hydrogen Sensor Multiyear Plan



Manufacture/Developer Support

- Sensor performance validation
- Developmental technologies support
- Wide area monitoring/distributed sensors
- Process control/hydrogen
- Process control/fuel quality sensors
- Field deployment test

End-User Support to Support Deployment

- Auto-calibration
- Guidance on deployment
- DOT and the GTR on hydrogen vehicles
- Barriers to sensor certification and impacts
- Delivery
- Support of NREL component testing

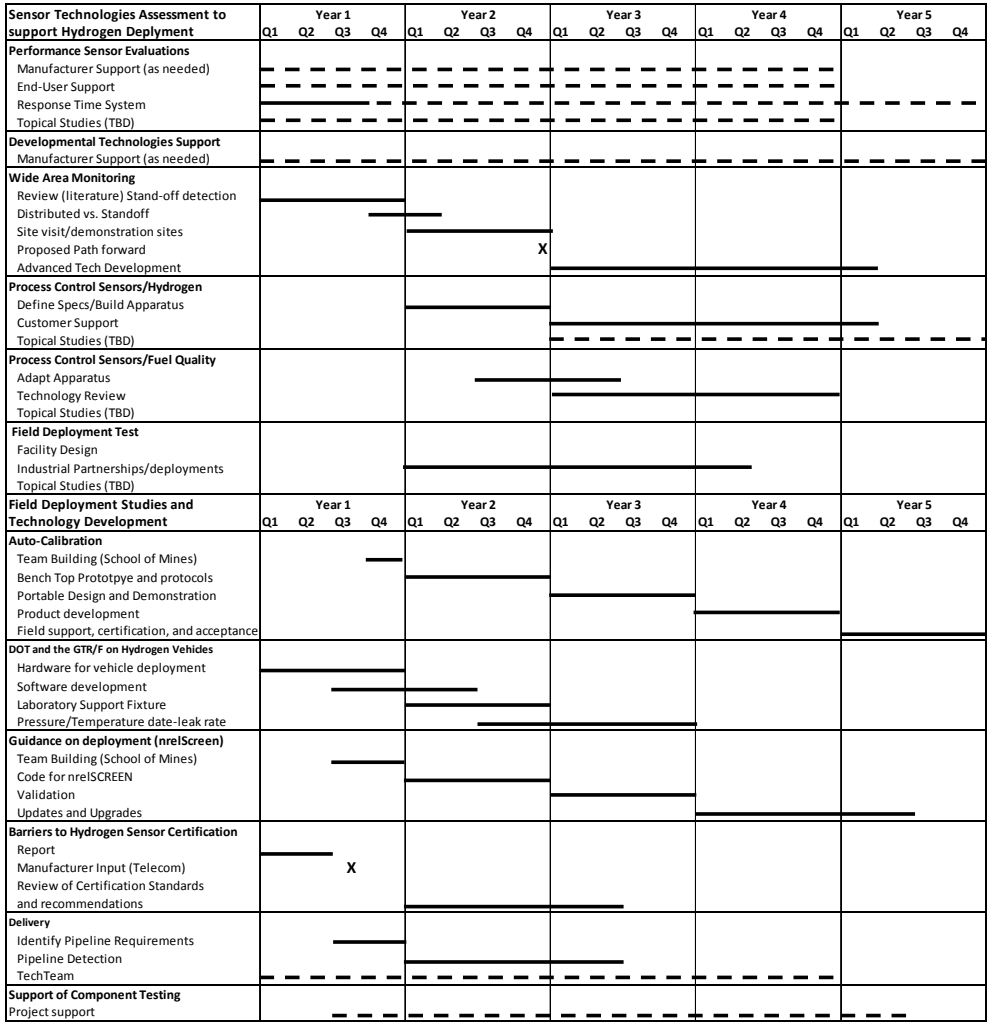
ESIF – Energy Systems Integration Facility

Completion of new NREL facility scheduled for early FY13, to include sensor lab, components lab, and high pressure test lab

NREL Sensor Laboratory Schedule

Priority

- **Sensor assessment**
  - WAM
  - Developmental technologies
- **Field deployment/ technology development**
  - AutoCalibration
  - Guidance on deployment



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 & 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) has leveraged NREL's success in advancing hydrogen safety sensors.

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.

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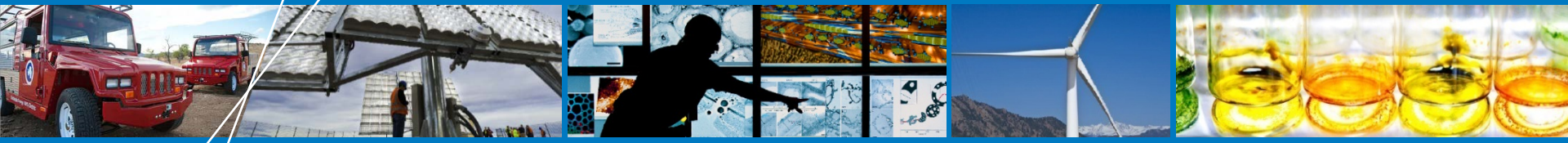


Technical Backup Slides

Acronyms and Abbreviations

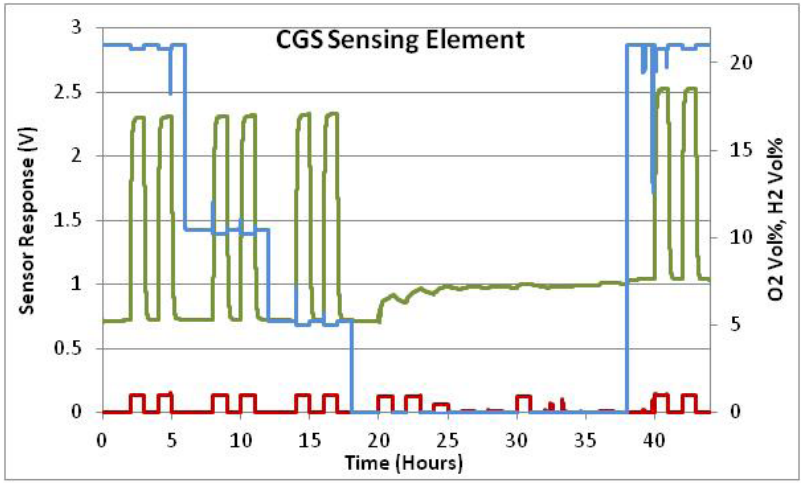
BAM: Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing)
CaFCP: California Fuel Cell Partnership
COTS: Commercial Off The Shelf
CSA: Formerly Canadian Standards Association
DOE: Department of Energy (US)
DOT: Department of Transportation (US)
EHS: Environmental Health and Safety
EU: European Union
FCEV: Fuel Cell Electric Vehicle
FMVSS: Federal Motor Vehicle Safety Standard
GTR: Global Technology Regulation—Hydrogen Fueled Vehicle (Draft)
ICHS: International Conference on Hydrogen Safety
IEA: International Energy Agency
IEEE: Institute of Electrical and Electronics Engineers
IET: Institute for Energy and Transport (Europe)
IJHE: International Journal of Hydrogen Energy
ISO: international organization for standardization
JRC: Joint Research Centre (Europe)
LANL: Los Alamos National Laboratory
LLNL: Lawrence Livermore National Laboratory
NASA: National Aeronautics and Space Administration
NFPA: National Fire Protection Association
NHTAS: National Highway Transportation Safety Administration
NIST: National Institute for Standards and Technology
NREL: National Renewable Energy Laboratory
Mines: Colorado School of Mines
MOS: Metal Oxide Semiconductor
OEM: Original Equipment Manufacturer
P: Pressure
PTF: Palladium Thin Film
RCS Regulations Codes and Standard
RH: Relative Humidity
RRT: Round Robin Testing
SDOs Standards Development Organizations
STP: Standards technical Panel
T: Temperature
TC: Themoconductivity
TRC Transportation Research Center, Inc.
UL: underwriters laboratories
UQTR: Universite du Quebec c à Trois-Rivières
WAM: Wide Area Monitoring
WHEC World Hydrogen Energy Conference

Results: NREL-JRC Collaboration

Performance under anaerobic conditions

O_2 requirements for H_2 sensors

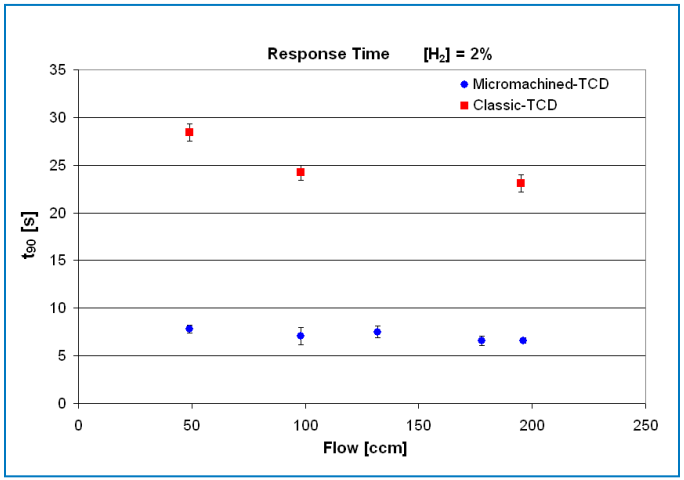
- **H_2 sensor operation in inert atmospheres**
  - Inert gas purges may alleviate risks, but may deactivate sensors/permanently alter
  - O_2 requirement depends on technology
  - Initiated to educate end-users
    - Proposed operation of CGS in nitrogen
  - Assessment of three platform types (presented at ICHS 2011 and published in IJHE 2012)
    - Comprehensive evaluation (CGS, MOX, MOS, PTF-resistive film, EC, TC) in preparation for publication

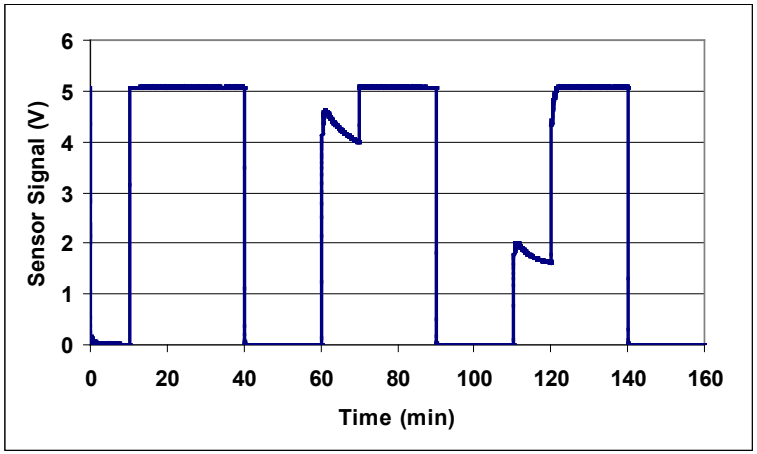


Results: NREL-JRC Collaboration

Promises and drawbacks of sensor miniaturization

- **Potential**
  - Economy of scale
  - Small size
  - Device to device repeatability
  - Improved kinetic
- **Pitfalls**
  - Focused on manufacturing not performance
    - Especially response time!
  - Degradation of critical metrics (linear range, lifetime, robustness to stresses)
    - 1 sec response time is elusive
- **Presented at WHEC (2012) and to be submitted to IJHE (April 2013)**
  - Performed with UQTR/H2 Can



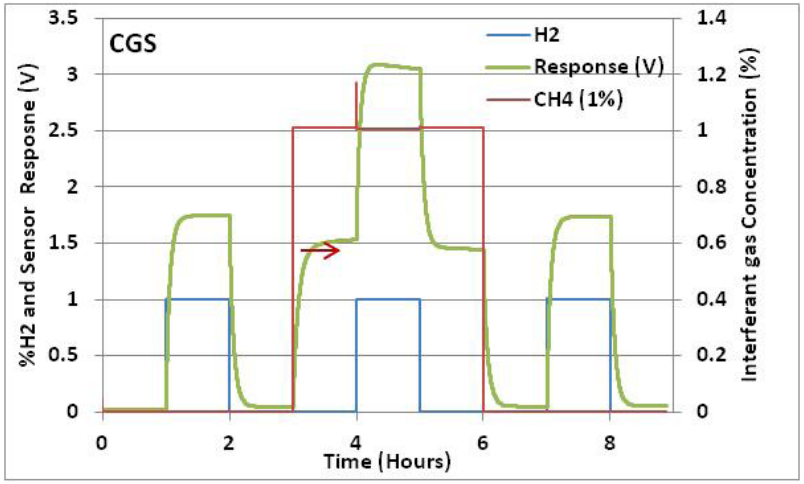


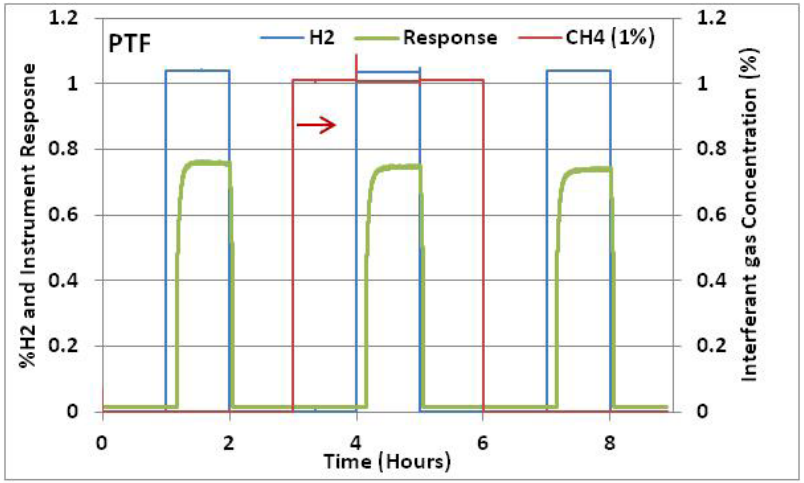
Results: NREL-JRC Collaboration

Impact of interferents and poisons

Cross Sensitivity

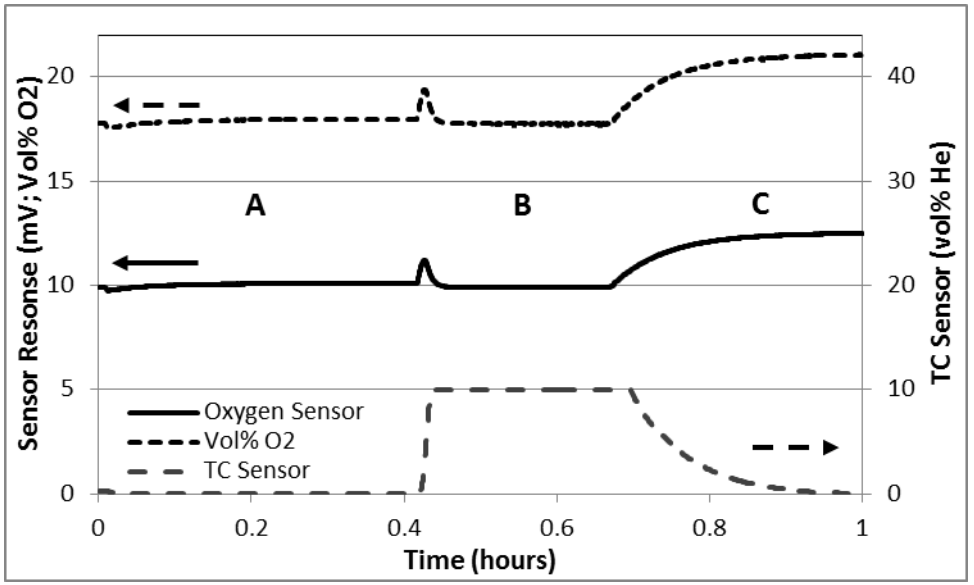
- Impact of interferents and poisons
  - Critical performance specification
    - Interferents can lead to false alarms
    - Poisons can permanently damage sensor
  - Interferent: reversible impact
    - CO, NO_2, NH_3, CO_2, etc.
    - Screening study complete, systematic on-going
  - Poison: irreversible impact
    - Silicone, sulfur, “WD-40”
    - Poison may not affect all platforms
    - Ongoing at JRC, nearing completion
- Outcomes
  - Interim results to be presented at 2013 ICHS and in preparation for IJHE





Results: NREL-JRC Collaboration
H_2 determination via O_2 displacement

- **Advantages**
  - O_2 Sensors (COTs, low-cost, simple)
  - Applicable for H_2, He, (other)
- **Pitfalls (indirect method)**
  - Diluent ambiguity
  - Poor detection limit, resolution, a concern for H_2 safety applications
  - No response for H_2/He release into close system
  - Strong T and P dependence
  - Not perfectly linear
  - O_2 sensors are "expendable"
- **Alternative**
  - Use TCD (for H_2/He releases)
  - Other platforms as per application requirements
- **To be published IJHE and ICHS**
  - Collaboration with JRC



Legend

A: Air at 0.8 bar (P_{O2} = 0.17 bar)

B: Air with 20% He at 1.0 bar (P_{O2} = 17 bar)

C: Air at 1.0 bar (P_{O2} = 0.21 bar)

Oxygen displacement measurements **CANNOT** be used to (reliably) measure hydrogen