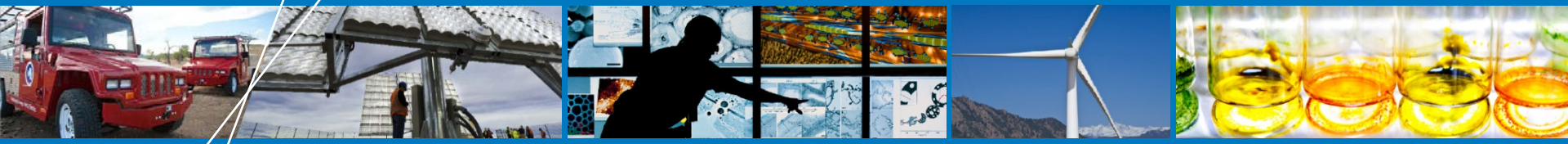
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL Hydrogen Sensor Testing Laboratory



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National Renewable Energy Laboratory
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***Intern--Colorado School of Mines, Golden, CO**

Project ID #SCS021

Overview

Timeline

Project start date: 10/1/2013
Project end date: 9/30/2014*

***Project continuation and direction determined annually by DOE**

Budget

Total project funding: $ 300K
DOE share: $ $300K

Funding received in FY13: $ 300K

Total funding planned for FY14: $325K

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

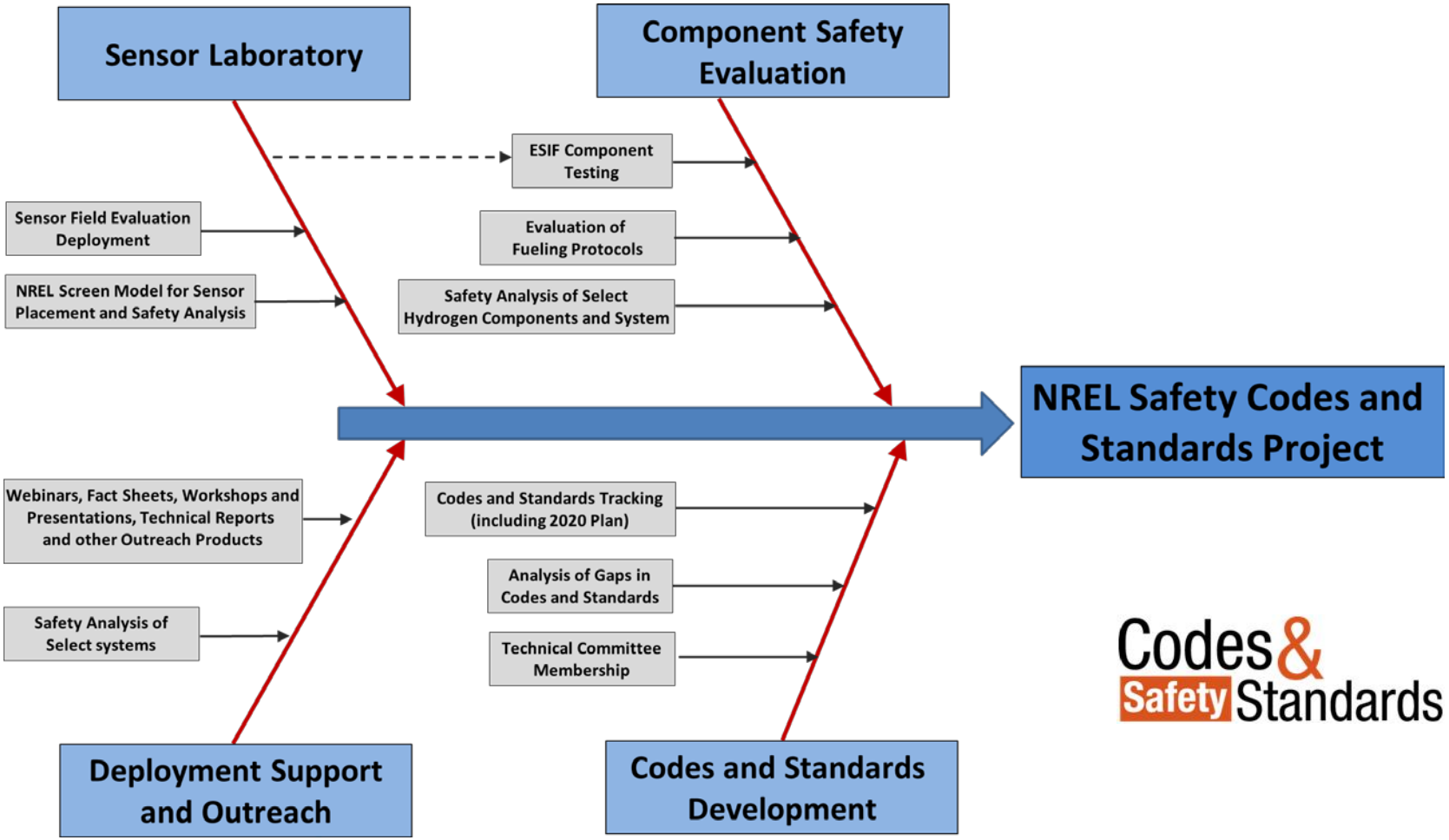
- **Industry:** component manufacturers, automotive OEMs, KPA Inc., Parker Aerospace, Element 1, Applied Nanotech
- **Government labs and agencies:** JRC, BAM, DOT-NHTSA, CaFCP, LANL, LLNL, IEA-HIA. NREL (cross-cutting programs)
- **Universities:** CO School of Mines, UQTR
- **Support of standards:** UL, CSA, FM Global ISO, NFPA, GTR/FMVSS
- **Project lead: W. Buttner**

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 ($10,000 fine)
    - H_2 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 will be referenced in IFC

Hydrogen dispenser equipped with wall-mount and internal sensor

Approach: NREL Sensor Testing Laboratory



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

Approach: NREL Sensor Testing Laboratory

- **Provide independent assessment of hydrogen sensor performance**
- **Interact with manufacturers to improve sensor performance to meet DOE 2012 targets**
- **Support deployment with information and expertise on sensor use and performance**
- **Test/validate new sensor R&D**
- **Support hydrogen sensor codes and standards development (national and international)**
- **Outreach and Education**
  - Publications, presentations, consultations
  - Student Internships
- **Client confidentiality**

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

NREL Sensor Laboratory Web Page:
http://www.nrel.gov/hydrogen/facilities_hsl.html

Accomplishments and Progress

- **Partnerships and Agreements**
  - Industrial Partnerships: implemented five formalized agreements implemented or pending; numerous informal agreements
    - Primary application: **Direct support of deployment**
    - Secondary application: Sensor technology development
  - Collaborations with Government Agencies/National Laboratories
    - US DOT-NHTSA: Ad Hoc Group-- hydrogen vehicle sensors requirements (FMVSS, GTR)
    - DOE National Laboratories (LANL, LLNL, cross cutting across NREL)
    - Joint Research Center, Institute for Energy and Transport, (JRC-IET) European Commission
    - Federal Institute for Materials Research and Testing (BAM) Berlin

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Accomplishments and Progress

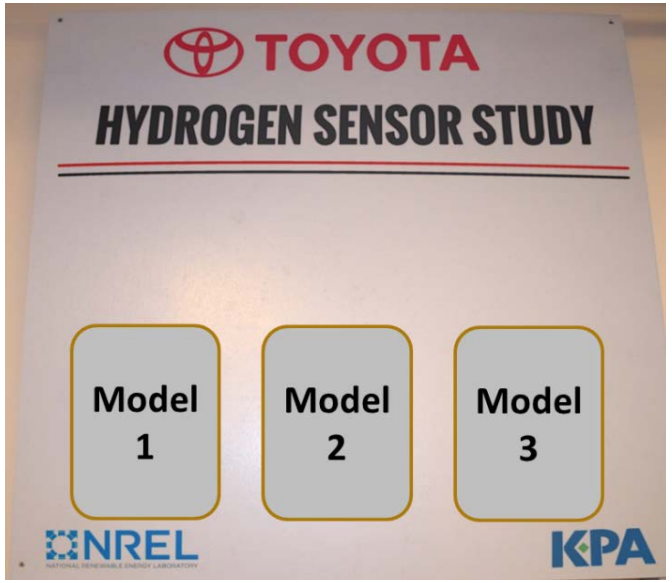
- **Overview of Operations**
  - Sensor Laboratory moved and set up in ESIF
  - SOP & RV completed and approved
- **Publications/Outreach:**
  - 6 presentations at national and international conferences/workshops
    - Includes 4 proceedings papers
    - 1 invited talk to international workshop on Hydrogen Sensors
  - 4 publications in peer-reviewed journals (published or in press)
  - 2 NREL technical reports
  - Co-organized/hosted IEA- HIA Task 31 Experts Meeting at NREL
  - Book: "Sensors for Process Monitoring and Safety in Hydrogen Technology"
    - International collaboration with JRC and BAM; projected publication date: Dec. 31, 2014

Accomplishments and Progress

Support of Deployment/Infrastructure (Industrial Partnerships)

KPA, Inc.

- **Application: Hydrogen vehicle repair facility (sensors mandated by IFC)**
  - Workplan: Define sensor requirements; identify/acquire potential sensors; laboratory assessment and multi-phase field deployments , and evaluate
  - Technical Challenge: compatibility of sensors to function in identified application
- **Status**
  - CRADA implemented March 2014
  - Sensor selection completed with guidance from NREL
  - Round 1 survey deployment completed
  - Round 2 (long term deployment) on-going
  - Project end date: December 2014
    - Results to be reviewed at CaFCP meeting (tentative)
- **Expected outcome/Significance**
  - Hydrogen Safety Sensor for turn-key safety system



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Accomplishments and Progress

Support of Market Transformation/Deployment

Parker Aerospace

- **Parker is bringing hydrogen fuel cells to the aviation market**
- **Hydrogen leakage detection is an enabling technology for ensuring safety**
  - Rigorous and verified safety and performance requirement
    - Short term performance metrics
    - Long-term performance stability
  - An aerospace certified hydrogen sensor does not exist in the market today.
  - Parker R&D project to develop such a technology is planned, in collaboration with NREL
- **Collaboration with NREL Sensor Lab formalized with TSA (pending)**
  - **Expected outcome: Fully characterized sensor validated for aerospace applications**
    - **Significance: Facilitate validation of Fuel Cell APU for aircraft deployment**
    - **Broader agreements within ESIF under negotiation**
  - **Expected outcome: Characterization of "long-term" drift, critical 1st step for mitigation**
    - **Significance: Cross cuts over many other applications**

Collaborations—government agencies

Joint Research Center, Institute for Energy and Transport

- **On-going since 2008, formalized by MOA in 2009**
  - New agreement under negotiation
  - Currently cooperating under join DOE/FCH-JU initiative
- 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
- International exposure of US technology and needs with regard to hydrogen sensors
- Outreach
  - Joint publications and presentations (over 20)
  - Unified strategies via calls and panel participation

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JRC EUROPEAN COMMISSION

iet Institute for Energy and Transport

Accomplishments and Progress

Programmatic : FCH JU (BAM, JRC) and DOE (NREL)

First EU-US common project with common objectives:

- Evaluate the capability of current sensors to detect hydrogen and to validate performance through independent laboratory tests
- Ascertain the needs of facility designers, safety engineers, product designers etc. with respect to their requirements on how hydrogen sensors should perform in different applications and under which conditions
- Identify ways to facilitate hydrogen sensor innovation by removing barriers which currently hinder sensor use and commercialization
- Facilitate the safe use and implementation of hydrogen as an alternative fuel by ensuring correct use of effective hydrogen detection devices.

EU Team Headed by BAM, JRC, working with industry under auspices of **H2Sense**

US Team headed primarily from NREL with support from DOE

- NREL supported H2Sense as a Keynote Speaker at H2Sense Sensor workshop, and through telecoms, program reviews, sensor evaluations, final report (pending), and future work plans.

Accomplishments and Progress

JRC EUROPEAN COMMISSION

Topical Studies (in collaboration with JRC)

- **"An Assessment on the Quantification of Hydrogen Releases through Oxygen Displacement Using Oxygen Sensors"**
  - Initiated 2013, completed 2014--performed under auspices of an MOA
  - Presented and published at the 5th International Conference on Hydrogen Safety
  - Published in the International Journal on Hydrogen Energy
  - **Significance: although endorsed in GTR, approach will not work for vehicles (inadequate LDL, partial pressure vs. vol% dependence, non-selective for H2 vs. air bag releases)**
  - **Significance: approach is inappropriate for H_2 safety and may false alarm**
  - **Significance: NREL support of DOT-NHTSA on FMVSS sensor requirements**

From the GTR (Hydrogen Fueled Vehicles)

(Section 6.1.2: Post-Crash Concentration Test for Enclosed Spaces)

"Sensors are selected to measure either the build-up of the hydrogen or helium gas or the reduction in oxygen (due to displacement of air by leaking hydrogen/helium)"

Based on this work, NREL has formally recommended that the text of the GTR be modified to remove the text "or the reduction in oxygen of air by leaking hydrogen/helium"

Accomplishments and Progress

Topical Studies (in Collaboration with JRC)

- **"Assessment of Commercial Micro-Machined Hydrogen Sensors Performance"**
  - Initiated 2012 under auspices of an MOA, Completed,
    - with Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada
  - Published in the International Journal on Hydrogen Energy (2014)
  - **Significance: addressed positive attributes and potential pitfalls associated with micro-fabricated of hydrogen sensors.**
- **Impact of poisons and interferents**
  - Initiated 2012 under auspices of an MOA, on-going,
  - Presented and published at the 5th International Conference on Hydrogen Safety
  - International Journal on Hydrogen Energy (in Press)
  - Updated for presentation at the 2014 WHEC
  - **Significance: addresses false alarms, premature sensor failure**
  - **Significance: Identify specific chemical causes of sensor failures.**
- **Wide Area Monitoring**
  - Initiated 2014 on-going
  - Reviewed LIDAR method; ultrasonic initiated
  - **Significance:** Unbiased assessment of strengths/weaknesses of WAM for deployment

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Project # SCS-021: NREL Hydrogen Sensor Testing Laboratory

Accomplishment:

The ability to assess sensors with a vehicle crash test is nice. Whether there is a need to include a sensor on a vehicle is still open to debate.

At this moment sensors are the only means to detect hydrogen in vehicle compartments. Alternative means to guarantee safety could be allowed, if developed and demonstrated. However, presently, such means or methods have not been demonstrated. Thus, as of now it remains necessary to have appropriate hydrogen sensors available in vehicles and available for infrastructure. It is also unlikely that a alternative other than sensors will be developed that meets the GTR crash test requirements.

Approach:

The approach is sound. However, direct detection of leaks may not be appropriate in many applications. Currently, sensors are costly, require maintenance, and are often unsuitable for a number of applications. The results are often spurious alarms or no detection—both are issues. Sensors might become an issue and not a solution.

Similar to the previous reply, alternative means to demonstrate safety do not yet always exist. It remains important to have appropriate hydrogen sensors available for infrastructure. The use of safety sensors in the infrastructure is a facilitator for its implementation. With that said, addressing long-term stability issues of sensors is a critical subject, and the Sensor Laboratory is exploring mitigation strategies to alleviate the current long-term sensor stability issues.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Project # SCS-021: NREL Hydrogen Sensor Testing Laboratory

Accomplishment:

This project features an excellent mix of accomplishments. The collaboration with the Joint Research Centre (JRC) seems especially valuable and produced some very interesting outcomes, including the lack of accuracy of sensors tested in the round-robin testing and the inappropriateness of oxygen displacement sensors for hydrogen measurements. Also significant was the gap analysis result that sensor maintenance is a large cost and that sensors need to be calibrated often (the researchers suggest no less often than semi-annually). In the past, some sensor manufacturers would claim that their sensors could be calibrated every couple of years.

The claim of sensors operating for two years without calibration is still made by some manufacturers. We recently tested such an instrument; it did not fare too well. With that said, we have found excellent short to mid-term stability for some sensor models; data does not yet exist for long term stability. Further, we have found that sensor stability is often affected by the deployment scenario. Some sensors worked well (for up to 2 years) in a clean atmosphere, but such conditions are not necessarily prevalent in the "real world". Thus empirical calibration/validation remains necessary. The inability of sensors to maintain stability over specified calibration cycles is the biggest concern we hear from end-users working with the NREL sensor laboratory. As previously stated , addressing long-term stability issues of sensors is a critical subject, and the Sensor Laboratory is exploring mitigation strategies to alleviate the current long-term sensor stability issues.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Project # SCS-001: National Codes and Standards Deployment and Outreach

Recommendations for additions/deletions to project scope:

The hydrogen sensor work is obsolete because the industry has sensor solutions available in its production vehicles and stations. It is recommended to halt this project.

First off, it is noted that this comment was not made in response to the presentation on the sensor project, but was a comment provided for the National Codes and Standards Deployment and Outreach presentation.

The statement that sensor solutions are available for production vehicles is misleading if not wrong. Cost and long-term stability remain an issue. Gaps also remain in the technical performance of the sensor mounted in vehicle exhaust, as per, for example, the response time requirement. The recommendation in the above review reflects a myopic view of the emerging infrastructure needs. Sensor technology may be available that works for many (not all!) infrastructure, but concerns remain about cost and reliability, and even about how to identify and set up sensors within hydrogen facilities. The NREL Sensor Laboratory's collaborations with private industry (including infrastructure, OEM, SDOs) to support deployment demonstrates the need for the sensor laboratory as a facilitator for deployment.

Collaborations—government agencies

- **Government Agencies**
  - JRC-IET: Topical studies, outreach, deployment, FQ
  - BAM: Outreach, codes and standards
  - DOT: Development and implementation of hydrogen sensor requirements in national (FMVSS) and international (GTR) standards
- **National Laboratories**
  - LANL-LLNL: Proposed deployment study within real-world (NREL) hydrogen application
  - NREL (cross-cutting programs): Support of NREL component testing and facility upgrades
- **Informal Consultations (sensitive applications)**
  - DOD
  - NASA
  - Argonne National Laboratory

Collaborations—Private Organizations

Deployment (Hydrogen Safety)

- **KPA:** (CRADA) NREL provided expert guidance on hydrogen sensor technology in support of KPA integrated safety system
- **Parker Aerospace:** (TSA) NREL activity to include quantitative assessment of hydrogen sensors; investigate failure modes; develop mitigation strategies
- **Other**: (NDA signed, TSA proposed)--proprietary customer

Technology Development/verification

- **Element 1:** (MOU, Subcontract) Colorimetric indicator be tested on NREL operations (deployment)
- **Applied Nanotech:** (letter of collaboration): Hydrogen based on a physical transduction proposed to be tested within NREL hydrogen operations (deployment)

Remaining Challenges and Barriers

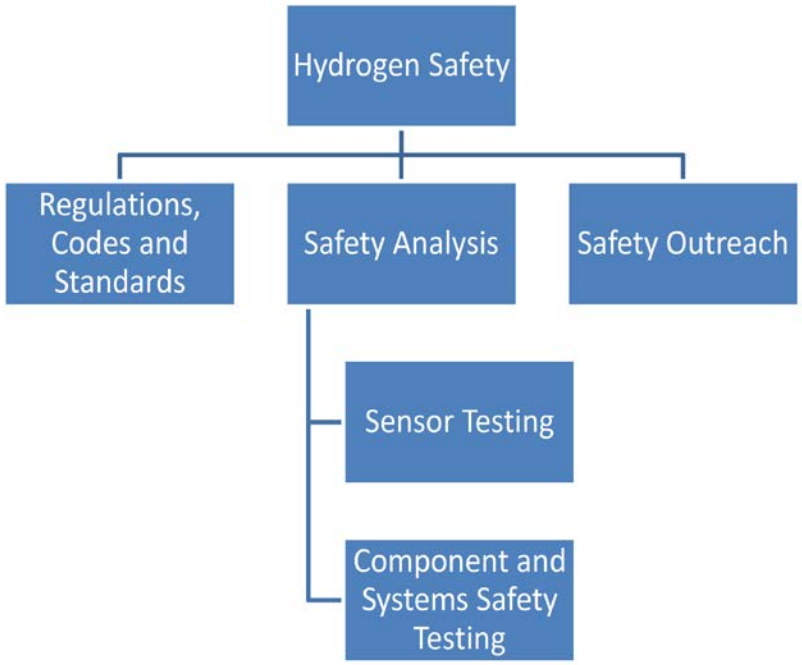
Hydrogen Safety Sensors:

- **Stakeholder acceptance/perception:** Although less now than in the past, there remains a lack of acceptance on the use of safety sensors, but often coupled with the hypothetical caveat "or alternate means".
- **Low maintenance sensors/lifetime:** 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.
- **Response time:** Some application of safety sensors require a response time of 1 sec; this remains elusive. A standardize RT does not exist

System Operations

- **Fuel quality:** Real-time sensors could verify fuel quality (just) prior to dispensing. **This application has been identified as critical**, although the nature of the monitoring system needs to be defined.
- **Process control:** Potential for hydrogen system operations (e.g., intelligent control of anode gas streams) via real-time monitoring.

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 (nrelScreen)
- 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

Proposed Future Work

FY14

- Finish sensor field deployment (KPA)
- Laboratory assessment of Applied Nanotech Sensor
- Sensor support of NREL Component testing
- Continued assessment, with DOT-NHTSS of H2 vehicle FMVSS sensor requirements, update text of GTR
- “Sensors for Process Monitoring and Safety in Hydrogen Technology”

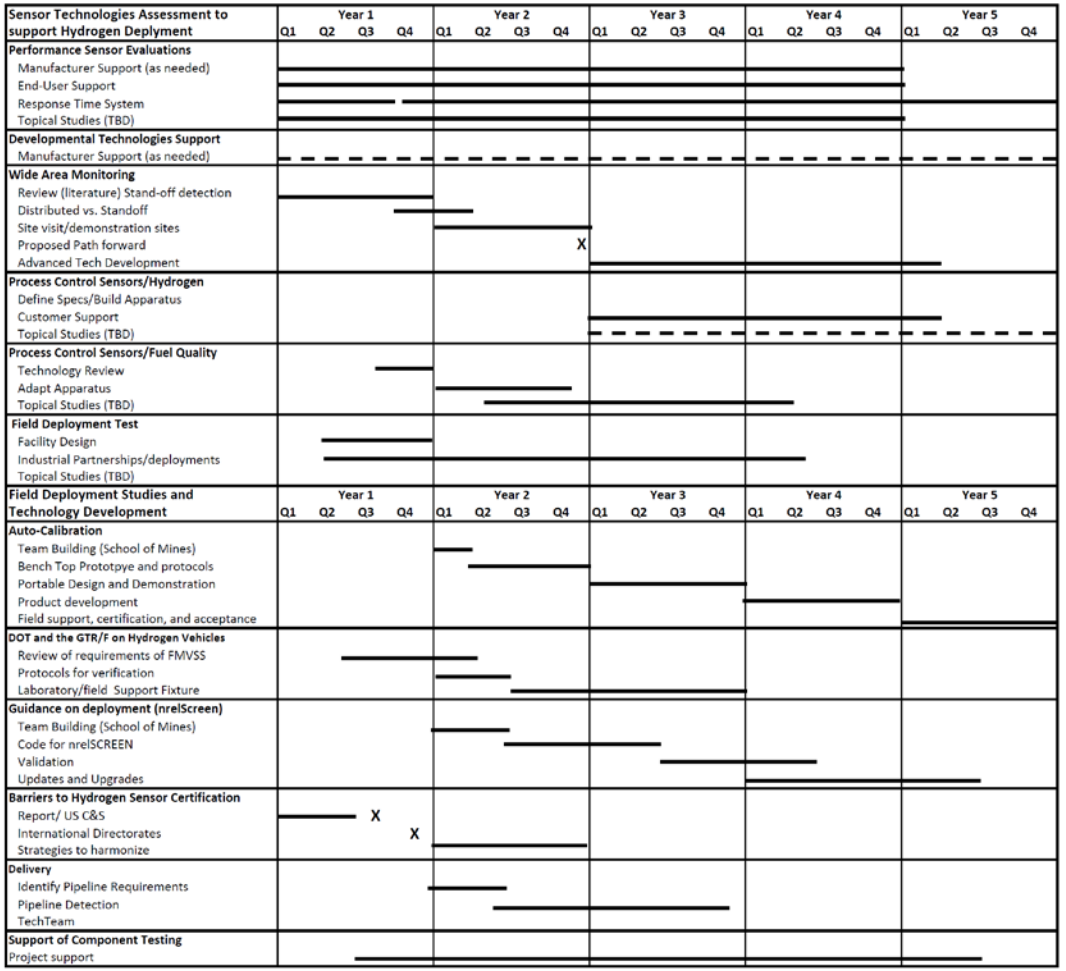
FY15

- Continued support for deployment
- Sensor lifetime studies and mitigation strategies
- Fuel Quality detector/strategies
- FMVSS requirements
- Complete review and update on WAM

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, private industry) 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 support the development of improved methods to verify fuel quality. NREL will continue to work with SDOs to revise documents, when required.

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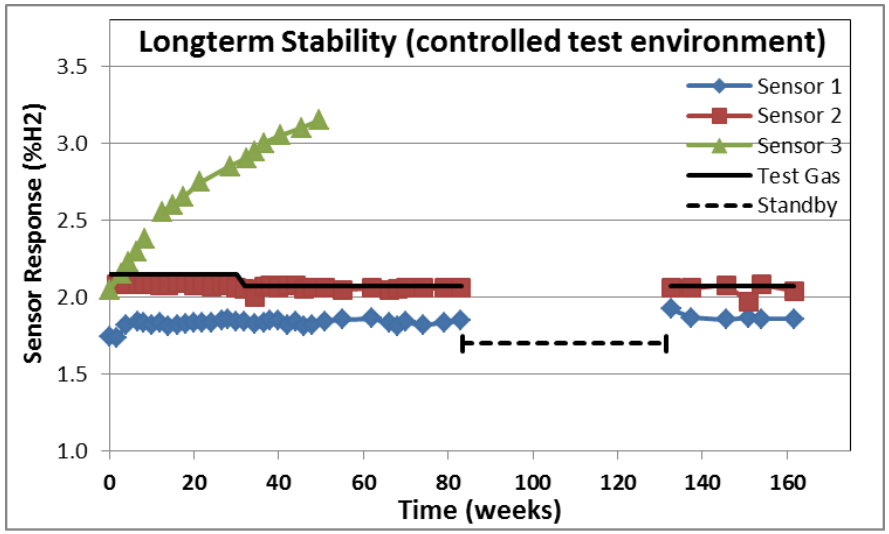
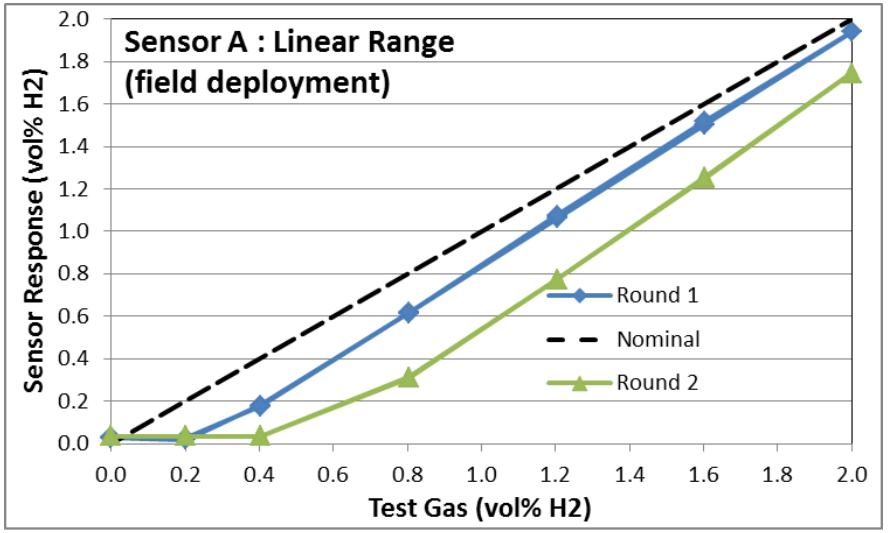
Technical Back-Up Slides

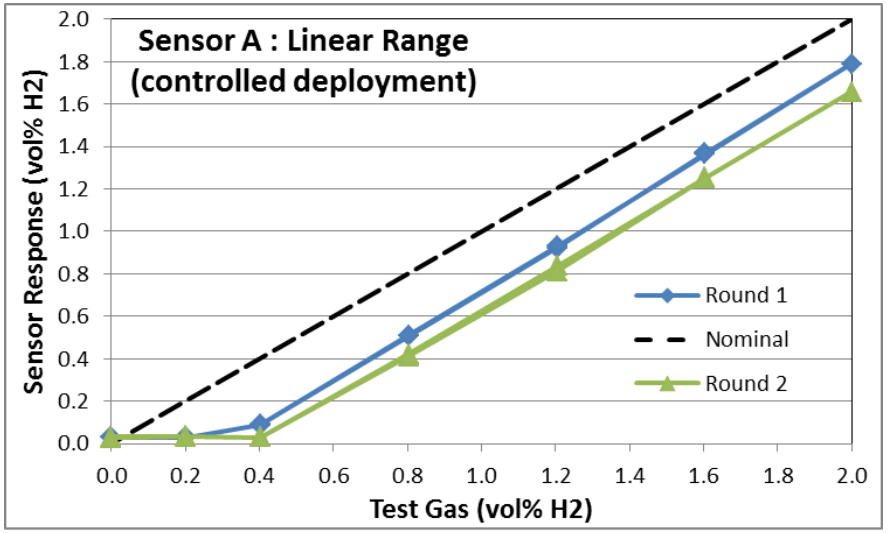
Accomplishment:– Long Term Exposure Sensor Stability

Sensor Long-Term Stability

- Stored in air at ambient T, P, with RH regulated to 45% ± 2%
- Periodic challenged to 2.0% H_2
- Multiple Sensor Platforms
- Issue: Laboratory performance ≠ (always) field deployment performance







Long-term sensor stability affected by deployment conditions

- **Field validation per application requirements remains necessary**

Acronyms and Abbreviations

BAM:	Bundesanstalt für Materialforschung und –prüfung (Federal Institute for Materials Research and Testing)
CaFCP:	California Fuel Cell Partnership
CSA:	Formerly Canadian Standards Association
DOE:	Department of Energy (US)
DOT:	Department of Transportation (US)
EU:	European Union
FCHJU	Fuel Cells and Hydrogen Joint Undertaking
FMVSS:	Federal Motor Vehicle Safety Standard
GTR:	Global
ICHS:	International Conference on Hydrogen Safety
IEA:	International Energy Agency
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
NREL:	National Renewable Energy Laboratory
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
T:	Temperature
TC:	Themoconductivity
UL:	underwriters laboratories
UQTR:	Universite du Quebec c à Trois-Rivières
WAM:	Wide Area Monitoring
WHEC	World Hydrogen Energy Conference