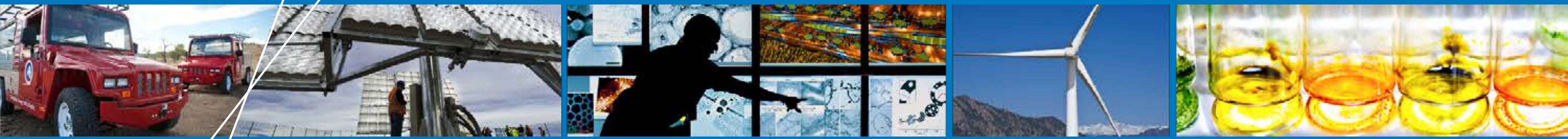
NREL

NATIONAL RENEWABLE ENERGY LABORATORY

NREL Hydrogen Sensor Testing Laboratory



William Buttner, PI

C. Rivkin and R. Burgess

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National Renewable Energy Laboratory

June 7, 2016

***Intern--Colorado School of Mines, Golden, CO**

Project ID #**SCS021**

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

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

Overview

Timeline

- **Project start date: 10/01/2010**
- **Project end date: 09/30/2016***

  * Project continuation and direction determined annually by DOE

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

Budget

- **FY15 DOE funding: $ 335K**
- **FY16 planned DOE funding: $ 335K**
- **Total DOE funds received to date: $ 2525K**

Partners

- **Industry:** component manufacturers, automotive OEMs, Parker Aerospace, Element One, Linde
- **Government labs and agencies:** JRC, BAM, DOT-NHTSA, CaFCP, LANL, LLNL, SNL, IEA-HIA. NREL (cross-cutting programs)
- **Academic:** CO School of Mines
- **Support of standards:** UL, CSA, FM Global ISO, NFPA, GTR/FMVSS, SAE, ASTM

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.h2tools.org/lessons]
  - "Gaseous Hydrogen Leak and Explosion"
    - Lack of H_2 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 is referenced in IFC

Hydrogen sensors in and around a hydrogen dispenser and FCEV

Relevance: Why Test and Evaluate Sensors

"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 (manufacturers)

Expectations of Performance
- Improper use/wrong sensor
- Critical Gaps
  - How to properly qualify sensors
  - Guidance on placement/location
  - Cost of ownership

Support of Codes & Standards
- ISO TC 197 (WG 24, 27, 28)
- ISO TC 158 (WG 7)
- UNECE GTR 13 (Hydrogen Vehicles)
- SAE FCSC Safety (TIR, in development)
- NFPA 2
- UL 2075 STP
- ASTM D03

A sensor will work only if used properly

Image provided by KPA, used with permission

Vehicle Repair Facility (qualification/demonstration study)

- One sensor qualified out of four models/platforms
- The right sensor for the application (qualification)

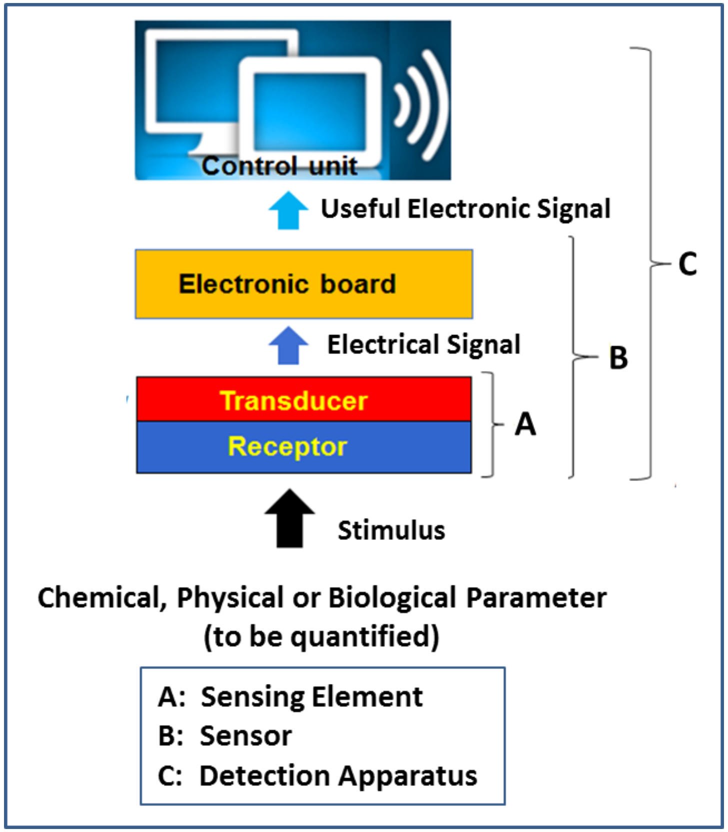
Relevance: Common Commercial H_2 Sensor Platforms

Common Sensing Element Platforms

Features	Electrochemical Sensors EC	Combustible Gas Sensors CGS	Thermo-conductivity sensors TC
Transduction Mechanism	Faradaic e^- transfer (current)	Catalytic combustion (ΔT induced by ΔT)	Heat Transfer (ΔR induced by ΔT)
Advantages	Good LDL, Linear	Robust	Fast response time
Disadvantages	Prone to poisoning, drift	cross-sensitivity	non-selective (sensitive to $\Delta[H_2]$
Applications	Low level detection; personal monitors; ESIF	Industry Standard; HRS, Repair Facilities	Modeling studies; controlled environ., vehicles

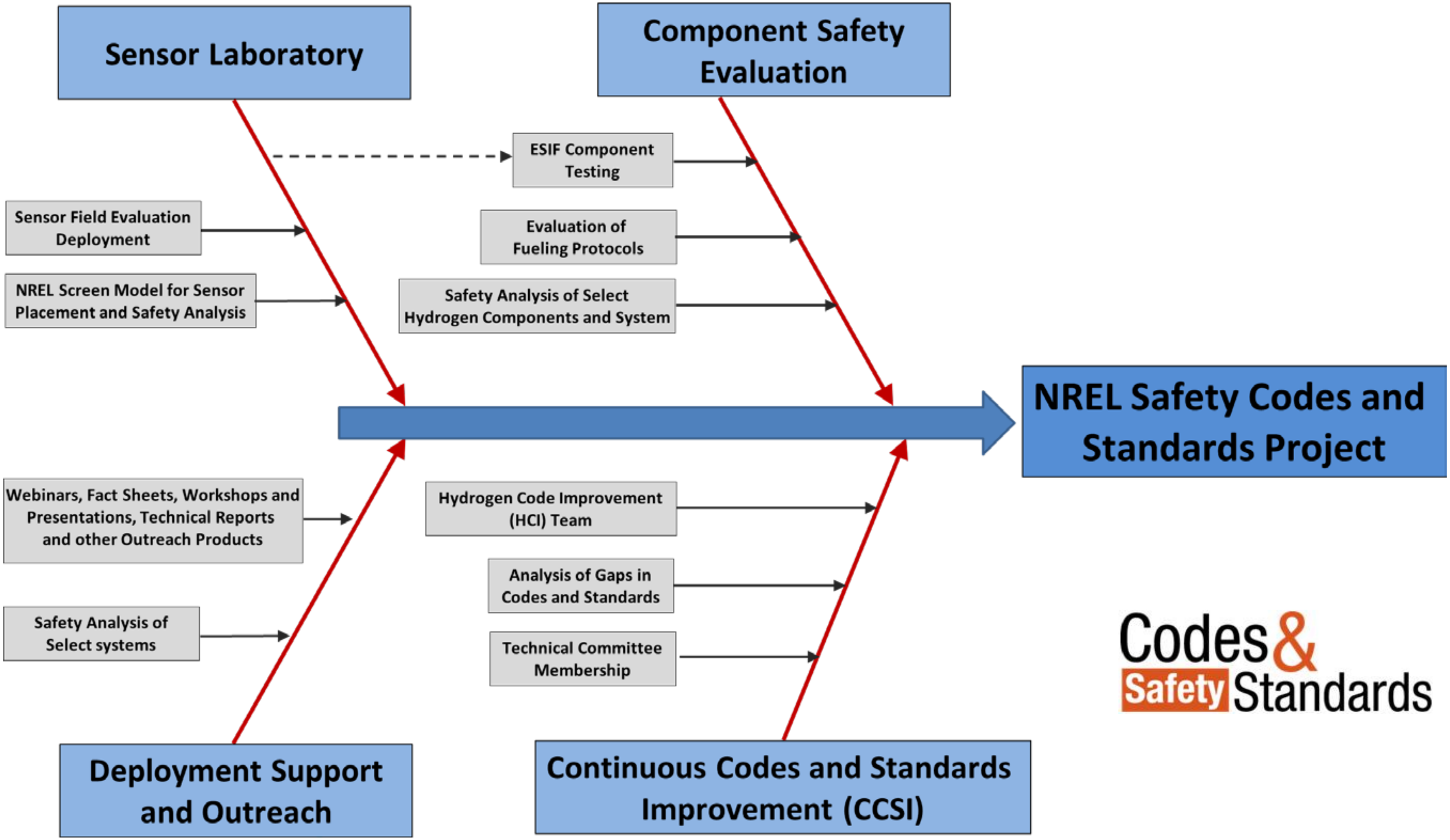
Features	Metal Oxide Sensors MOX	Palladium Thin Film Sensors PTF	Hybrid Platforms HP
Transduction Mechanism	semiconductor doping (ΔR)	Sel. H_2 adsorption; multiple platforms	Multiple platforms (integrated)
Advantages	Low cost versatile sensor	Selectivity	Broad Range (LDL and UDL)
Disadvantages	Perceived instability; cross sensitivity	Prone to poisoning; still expensive	Limited availability (market support)
Applications	General Deployment; containers	Petroleum Industry, specialized applic.	Vehicle

Sensor vs. Sensing Element



All sensor platforms are good
But none are good for all applications

Approach: NREL SCS Project Structure



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 H_2 sensing elements, sensors, or analyzers**
  - Commercial and developing technologies
  - Applications, Method Development
  - Not certification but performance verification
- **Support hydrogen sensor C&S development (national and international)**
  - Pre-normative research & document development
- **Support Deployment**
  - **Direct collaborations** with the H_2 Community
    - Regulators, Infrastructure, and OEMs
    - Research Institutions and 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 ultimate goal of the Hydrogen Sensor Testing Laboratory is to ensure that end-users get the sensing technology they need

Accomplishments and Progress

Support of Deployment/Infrastructure
NREL-KPA/Toyota (CRADA-14-547)

- **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
- **Project Overview**
  - Sensor selection with guidance from NREL
  - Simultaneous field and laboratory deployment
  - Supplemental laboratory evaluations
  - Evaluation phase end date: December 2014
- **Outcome/Significance for KPA/Toyota**
  - Qualified H2 safety sensor for repair facilities
  - 10 deployments (CA); 10 more pending (N.E.)

Image provided by KPA, used with permission

Thanks to Ian Bloomfield
Intern (former), School of Mines

Accomplishments and Progress

Support of Deployment/Detection Technology
NREL-Element One Partnership

- **Application: Hydrogen leak detection using a colorimetric indicator**
  - Workplan: Deploy on NREL Hydrogen Operations (outdoor and indoor) and evaluate with supplemental laboratory analysis
- **Project Overview**
  - Evaluated at NREL under an NCAP (16-00085)
    - Multiple small leaks identified and corrected
  - Several small but unexpected leaks identified
  - Indicators remain active for 8 months & counting
  - Commercialized and available
  - DOE Webinar: "*DetecTape® - Visual Leak Detectors for Hydrogen Equipment* " by Element One (3/14/2016)
  - NREL Technical Report: *Leak Detection Using a Commercial Hydrogen Colorimetric Indicator*, Kevin Hartmann & William Buttner (June 2016)

Thanks to Kevin Hartmann
Intern, School of Mines

Accomplishments and Progress

Analyzer for Verification of Tailpipe H_2 Emissions
Support of the GTR 13, FCEV Safety/Operation

- **Purpose**
  - Develop analytical method for GTR Requirements
- **Partners**
  - DOT/NHTSA and Transport Canada; OEMs
- **Status**
  - Low-cost sensor identified with 250 ms response time and range of 0 to 10 vol% H2
  - Basic performance demonstration in test fixtures
- **Outreach**
  - Presentations at SAE and DOT (via telecoms)
  - Formal presentation at ICHS, WHEC, and in IJHE
- **Schedule and Opportunity**
  - Prototype analyzer 4QFY16 (GOAL)
  - Goal: test in FCEV in 2016 (DOT/NHTSA – TC)
  - Adapt for broader applications/partner with OEMs

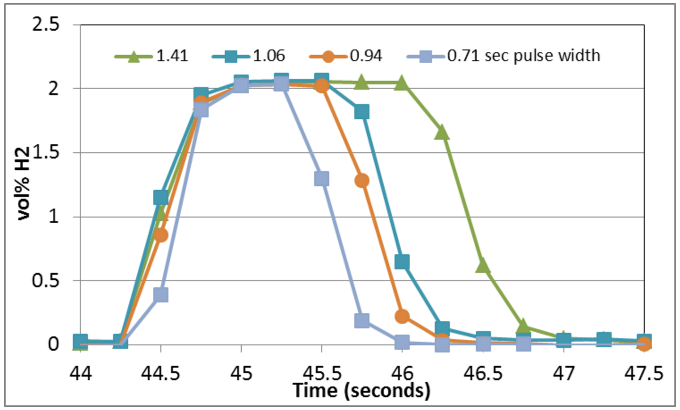


Table 3.8.2. Targets for Hydrogen Safety Sensor R&D

- Measurement Range: 0.1%-10%
- Operating Temperature: -30 to 80°C
- Response Time: under one second
- Accuracy: 5% of full scale
- Gas environment: ambient air, 10%-98% relative humidity range
- Lifetime: 10 years
- Interference resistant (e.g., hydrocarbons)

Hydrogen, FCTO Program MYPP
http://www.nrel.gov/docs/fy08osti/39146.pdf

European Commission

Thanks to Max Bubar
Intern (ret), School of Mines

Accomplishments and Progress

Support of Infrastructure
Empirical Profiling of LH2 Releases during Routine Venting

- Objective
  - Vertical profiling of LH2 during (planned) venting
  - Empirical support for modelling
  - Supports NFPA 2 and LH2 site storage safety
- Key Partners
  - Linde Group , FP2FIRE, and National Labs (LLNL, SNL)
- Approach
  - Small sensor array to cover broad range of H_2 levels
  - Extractive sampling (pump), multiplex with one analyzer
  - Low cost, simple design, easier for safety
- Status
  - Major Hardware identified, including sensors
  - Site access and testing "approved"
- Schedule
  - Build and test hardware: (ongoing)
  - Develop and Implement Control Software (ongoing)
  - Target 1st Field Deployment : Mid to late May 2016

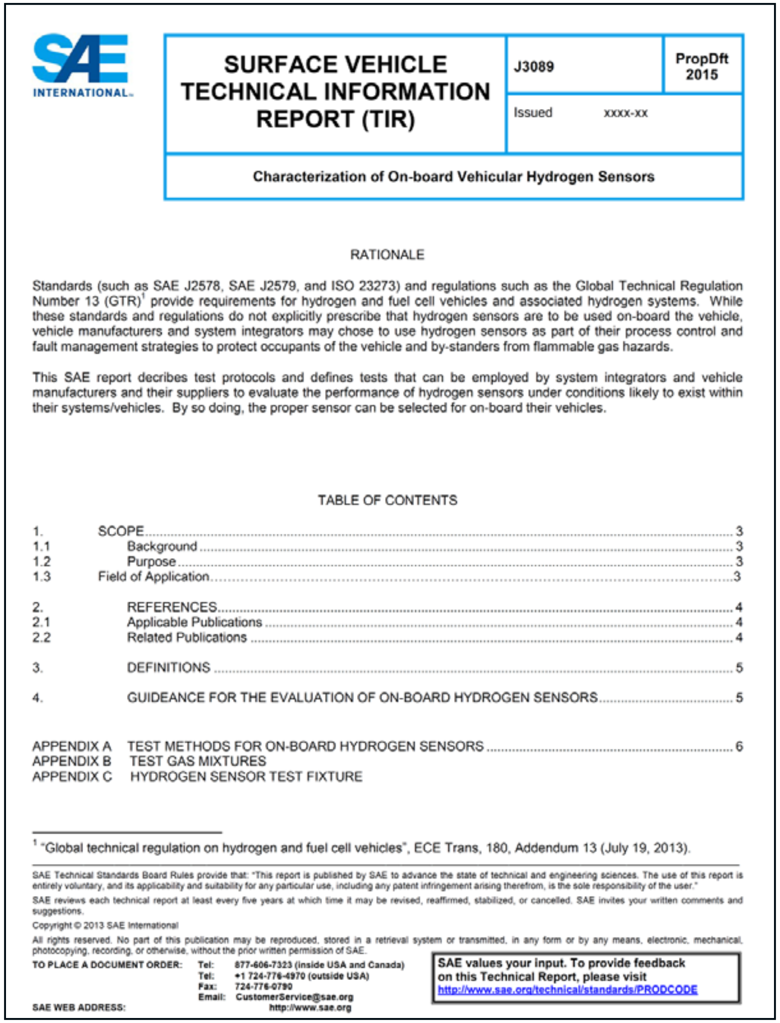
Thanks to Ian Bloomfield
Consultant, Certified LabView Developer
(former Intern, School of Mines)
Thanks to Hannah Wright and Kara Schmidt
Interns, School of Mines

Accomplishments and Progress

Support of Support of Codes and Standards Deployment

SAE Fuel Cell Standards Committee

- TIR on the characterization of hydrogen sensors
- NREL Sensor Labs (with JRC) is lead developer
- First Draft nearly completed (comment stage)
- Supplemental Input/topical studies at meetings
    - Updates on the Tailpipe Analyzer
    - Topical Study (impact of argon on sensors)
    - Topical Study: Sensor Test Methods



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. SCOPE ... 3
1.1 Background ... 3
1.2 Purpose ... 3
1.3 Field of Application ... 3

2. REFERENCES ... 4
2.1 Applicable Publications ... 4
2.2 Related Publications ... 4

3. DEFINITIONS ... 5

4. GUIDEANCE FOR THE EVALUATION OF ON-BOARD HYDROGEN SENSORS ... 5

APPENDIX A TEST METHODS FOR ON-BOARD HYDROGEN SENSORS ... 6
APPENDIX B TEST GAS MIXTURES
APPENDIX C HYDROGEN SENSOR TEST FIXTURE

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

Outreach to JARI Members

NREL Site visit to JARI (October 23, 2015)
- Review sensor technologies
- OEMs and Sensor Manufacturers

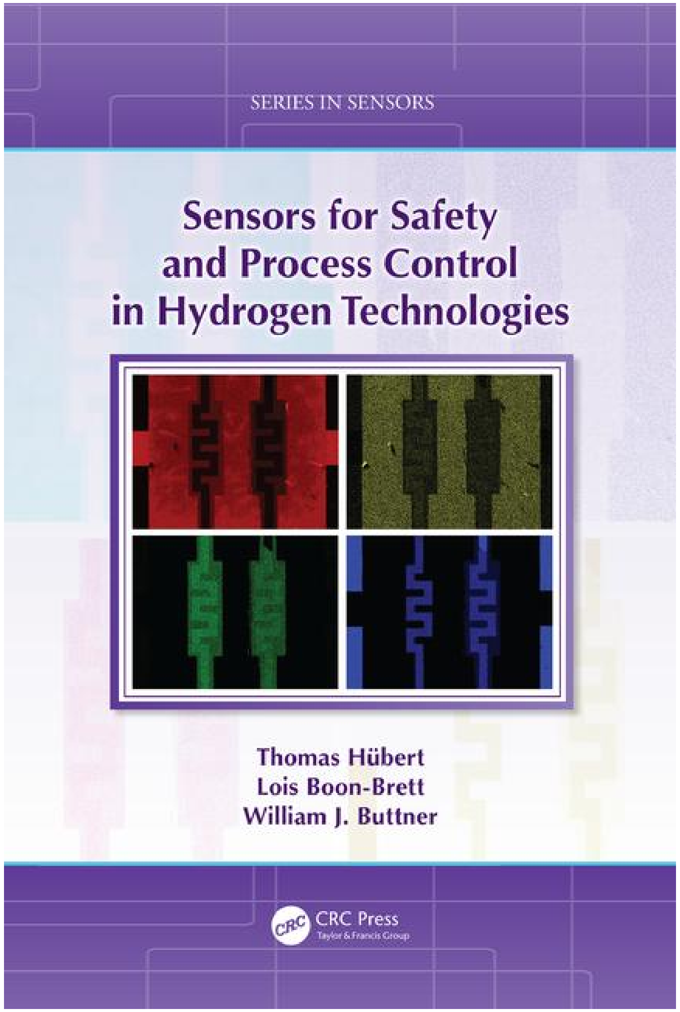
Proposed WEBINAR on Sensor Testing Apparatus
- Tentatively scheduled for May 2016
- Sensor testing methodology and analysis

European Commission

Accomplishments and Progress

CRC Press Series in Sensors

- Published in December 2015!
- International Team of experts and friends!
  - Lois Brett, Scientific Officer/JRC, Lead Scientist (former) of the JRC Sensor Laboratory
  - Thomas Hűbert, Lead Scientist of the BAM Sensor Laboratory
  - **Eveline Weidner, Scientific Officer/JRC, Lead Scientist of the JRC Sensor Laboratory**



European Commission

BAM
Bundesanstalt für Materialforschung und -prüfung

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http://www.crcnetbase.com/isbn/9781466596559

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **(Collaboration and coordination with other institutions)** The project has developed excellent working relationships with industrial partners, (international) governmental bodies, and codes and standards developers. It is thus in the best position to play a reference role for this part of the safety galaxy.

The sensor laboratory views sensors as an enabling tool that allows end-users to do their job and not laboratory curiosities. Direct interaction with stakeholders is the most effective way to support the sensor needs of the hydrogen community. Partnerships and collaborations are indeed a strength of the NREL Sensor Laboratory in the "safety galaxy" as well as for other sensor applications.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **(APPROACH)** Also, it is not clear how this project interacts with the H2FIRST (Hydrogen Fueling Infrastructure Research and Station Technology) sensor project that was implemented; there was no mention of supporting or interacting with that particular project, although they were both led by NREL.
- **(Collaboration)** The project seems to work with codes and standards, testing, and commercial entities on a regular basis, and it should be part of any further H2FIRST sensor projects going forward.

Defining and verifying hydrogen fuel quality requirements is recognized as a critical issue for the success of FCEV and is being addressed through several avenues. Under our AOP, the sensor lab is active and at the forefront of FQ verification through ISO TC197 WG 27, ISO WG 28, ISO 158 TC 7, SAE Fuel Cell Safety Group, ASTM D03 and though my direct collaboration with JRC. We are coordinating with a major gas producer on the development of support hardware for gas measurements (NREL ROI 15-119) designed to directly interface to (most) field deployable gas analyzers.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **(Recommendations)** While this work is good, there is a need for more guidance on the installation of sensors—where to place them, how many are needed, maintenance recommendations, etc. Because this project already works with industry, it should be an "easy" next step.
- **(Recommendations)** Perhaps it is possible to couple sensor performance indicators with risk assessment tools to be able to answer the question of where to more effectively install safety sensors to ensure capture of all possible hazards related to hydrogen accidental releases.

I agree the work of the sensor laboratory is good.

Published guidelines for hydrogen safety sensor placement is a critical cap and needs to be addressed. The NREL and JRC Sensor Laboratories (Eveline Weidner and Daniele Baraldi) along with Sandia (Chris Lafleur) agreed in principle to form an "EXPERTS GROUP" that included CFD modelers and risk assessments experts to provided guidance on sensor placement. Good intentions collided with realities of limited time and resources, coupled with an internal restructuring. Developing a path forward on this topic will be explored under the auspices of the NREL-JRC collaborations.

Collaborations

Joint Research Centre, Institute for Energy and Transport

- **On-going collaborations since 2008**
  - Formalized with an MOA (2010-2012), DOE/JRC Common Call (2014-2015)
  - NDA and CRA pending
- **Extensive collaborative outreach and publications**
  - Over 25 formal talks at international conferences and workshops
  - Over 25 formal written publications (journal articles, reports, proceedings, book)
  - Joint participation standards and safety committees (IEA-HIA, HySafe, SAE, ISO etc.)
- **Current Activity—Partial List**
  - "Analyzer for FCEV tailpipe hydrogen emissions as specified in the GTR # 13"-WHEC
  - "Sensors for hydrogen concentration measurements in natural gas"-WHEC
  - "Impact of Environmental Parameters on H_2 Sensor Performance"-WHEC
  - "The NREL and JRC Sensor Test Laboratories Instrumentation and Methods for Hydrogen Sensor Performance Verification" (POSTER)-"WHEC"
  - Sensor Placement Guidance Document via Experts Group (with SNL)
  - Gap Analyses on Sensor Technologies for safety and FQ (in development for *ACS Sensors*)

Collaborations: Industrial Partnerships

Performance & Qualification (Safety)

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

Infrastructure Support
- KPA (on-going support)

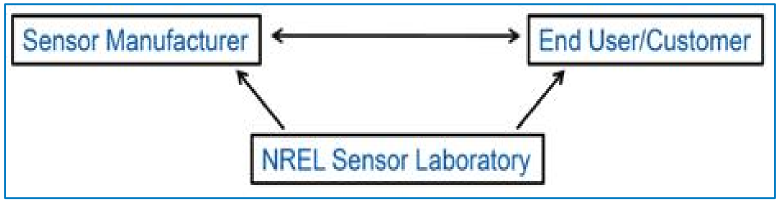
Vehicle Support
- Ford Motor Company (NDA)
- JARI (through the SAE FCSC)
  - OEMs & sensor suppliers

New Markets
- Parker Aerospace (**TSA)**

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 H2 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 Nat. Lab.
  - Direct business to lab collaboration
  - Not a funding source
- Simple, easy application protocol
- Tiered application deadline (Rd 1 and Rd 2 are closed; but other are pending)
- **https://www.sbv.org/**
  Google “Small Business Voucher”

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

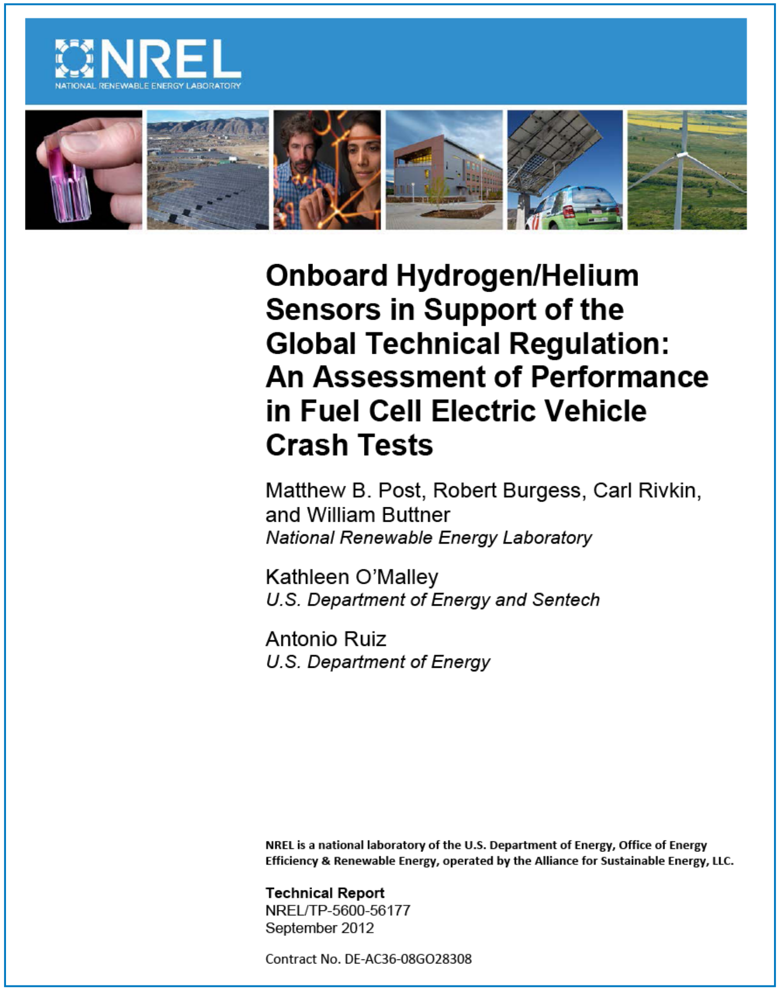
Process Control/FQ ("specialized" application):

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

Remaining Challenges and Barriers

Market Sustainability (example):

- **Sensor "qualified" for FCEV crash test**
  - Range, survivability
  - Compatible for H_2 and He
  - Commercially available, but product discontinued
  - Lack of Market Demand
- **Upcoming crash test (2016)**
  - Old new stock sensor will be used for deployment
  - Identify and qualify new technology
  - Upgrade measurement protocol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Onboard Hydrogen/Helium Sensors in Support of the Global Technical Regulation: An Assessment of Performance in Fuel Cell Electric Vehicle Crash Tests

Matthew B. Post, Robert Burgess, Carl Rivkin, and William Buttner
National Renewable Energy Laboratory

Kathleen O'Malley
U.S. Department of Energy and Sentech

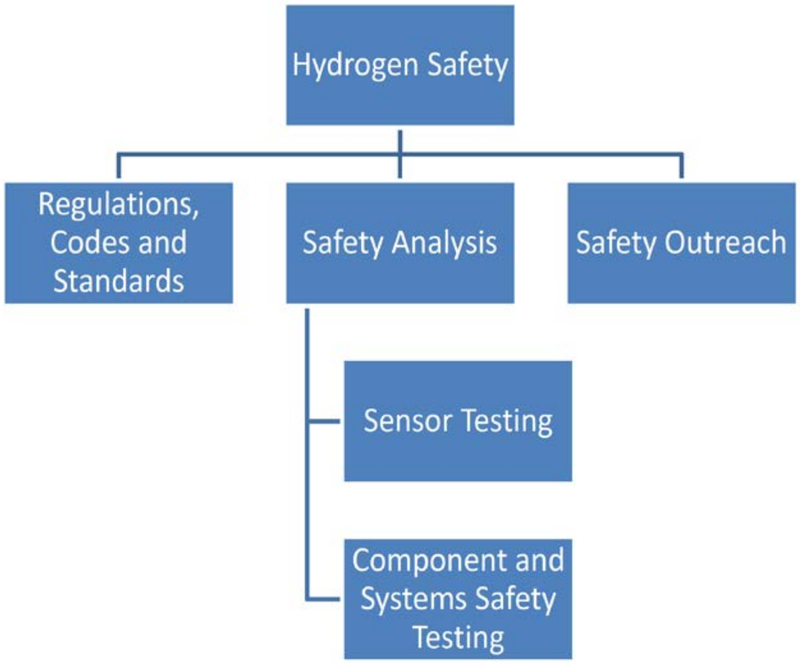
Antonio Ruiz
U.S. Department of Energy

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-5600-56177
September 2012

Contract No. DE-AC36-08GO28308

Future Work: The NREL Hydrogen Sensor Multiyear Plan



Manufacture/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

ESIF – Energy Systems Integration Facility
New 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 & 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 support the development of improved methods to verify fuel quality. NREL will continue to work with SDOs to revise documents, when required.

Acknowledgements

Support for the NREL Hydrogen Sensor laboratory provided through the EERE's Fuel Cells Technologies Office, Hydrogen Safety Codes and Standards Program, Will James Manager

Special Thanks to NREL Interns from the Colorado School of Mines

- Ian Bloomfield (June 2013- December 2014): KPA, GTR, Component Support
- Max Bubar (June 2014 – December 2015): GTR
- Kevin Hartmann (June 2014 to present) KPA, NCAP, Topical Studies (impact of background gases), component support
- Kara Schmidt (April 2016 to present): LH2, GTR (crash test)
- Hannah Wright (April 2016 to present): LH2, GTR (tailpipe)

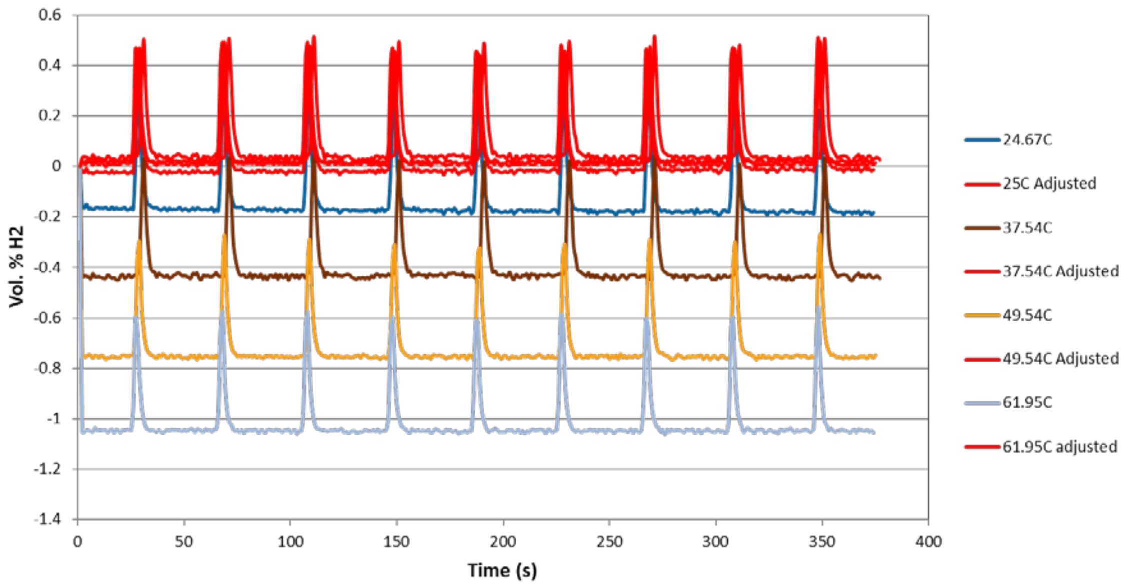
JRC Intern, Technical University of Vienna

- Laila Wooninck (October 2015 – February 2016), Impact of interferents and poisons

Technical Back-Up Slides

(Include this "separator" slide if you are including back-up technical slides **[maximum of five]**. These back-up technical slides will be available for your presentation and will be included in the electronic media and Web PDF files released to the public.)

Technical Backup Slides—GTR Sensor Performance

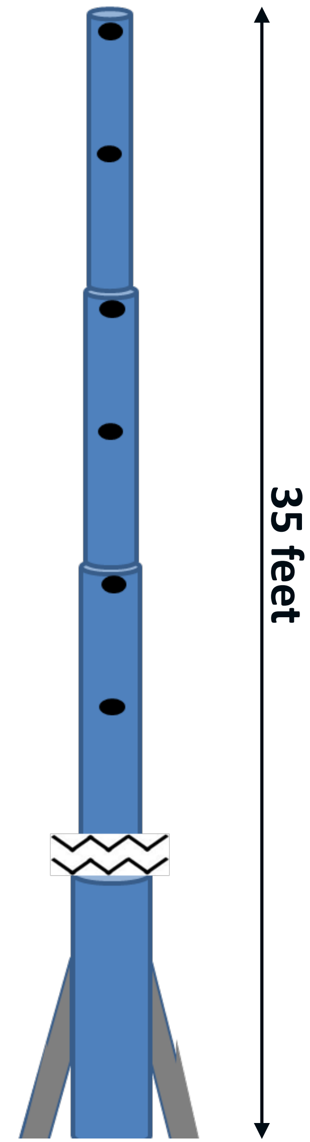


- **TC Sensor Response: SR = F(H_2, Matrix, I, T, RH, P)**
- **SR ≈ SRo + SR(H_2) + SR(I) + SR(T) + SR(RH) + SR(P)**
- **Sensor “background” (SRo) depends on matrix**
- **Empirical compensation for T and RH**
  - T compensation completed; RH compensation underway
- **Minimal impact with interferences (I)**

Technical Backup Slides—LH2 Venting Project: Profiling

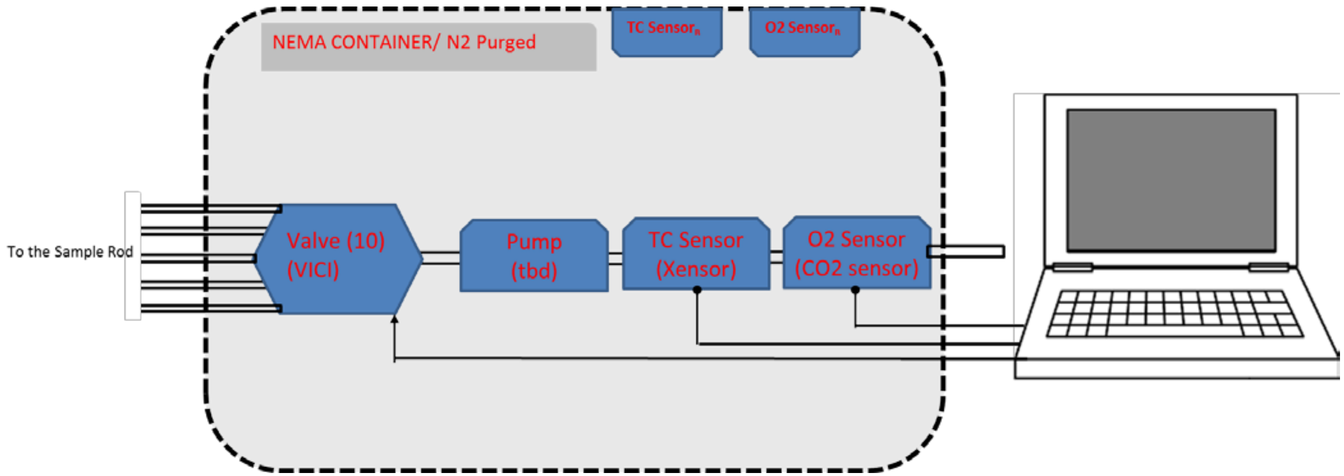
Field fixture

- **Assembled on commercial "telescoping" pole (35 feet)**
  - Install 10 gas sampling pneumatic lines (6 shown) spaced every 2.5 feet (nominal) from the top height.
  - Install 8 thermocouples spaced every 2.5 feet from the top.
  - "Analyzer" box at base of pole
  - Thermocouples and "indicator tape" will be mounted on pole.
- **Tasks:**
  - Construction of TC and Pneumatic Lines on Pole
  - Verification of functionality (Thermocouples, TC & O2 sensors)
  - Mock field test at NREL (May 15)
  - Deployment



Pneumatic System					Thermocouples			
Port #	color	Height	"tail"	total	Channel	Height	"tail"	total
1		35	15	50	1	35	15	50
2		32.5	15	47.5	2	32.5	15	47.5
3		30	15	45	3	30	15	45
4		27.5	15	42.5	4	27.5	15	42.5
5		25	15	40	5	25	15	40
6		22.5	15	37.5	6	22.5	15	37.5
7		20	15	35	7	20	15	35
8		17.5	15	32.5	8	17.5	15	32.5
9		15	15	30				
10		12.5	15	27.5				

NREL Sensor Laboratory
Empirical Profiling of LH2 Releases during Routine Venting



- **Pole design**
  - Pneumatic Line (10 points) with Thermocouples (8 points) interfaced to Analyzer Box
- **Analyzer Box Design**
  - Deployed at base of Sampler Pole
  - Thermo-conductivity sensor (H_2; 0 to 10 vol%) and O_2 Sensor
- **System Integration**
  - Goal: Sample each point 1/min
  - Integrated software (control, data logging, signal management) under development
  - Mock Field Deployment