

NREL Hydrogen Sensor Testing Laboratory

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DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # SCS 021

Overview

Timeline and Budget

- Project start date:
10/01/2010
- FY17 DOE funding :
\$ 315 K
- FY18 planned DOE funding:
\$ 83 K
- Total DOE funds received to date:
\$ 2,840 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, Air Liquide, Linde, AVT, First Element, SAE, NFPA 2

Government labs and agencies: JRC, DOT-NHTSA / Transport Canada / Environment Canada, CaFCP, SNL, NREL (cross-cutting programs)

Academic: Colorado School of Mines

Relevance: What is a sensor?

Sensing Element vs. Sensor vs. Analyzer

Sensing Element: Interaction with stimuli and transduction into electrical signal

- Different Platforms (CGS, TC, EC, MOX, etc.)

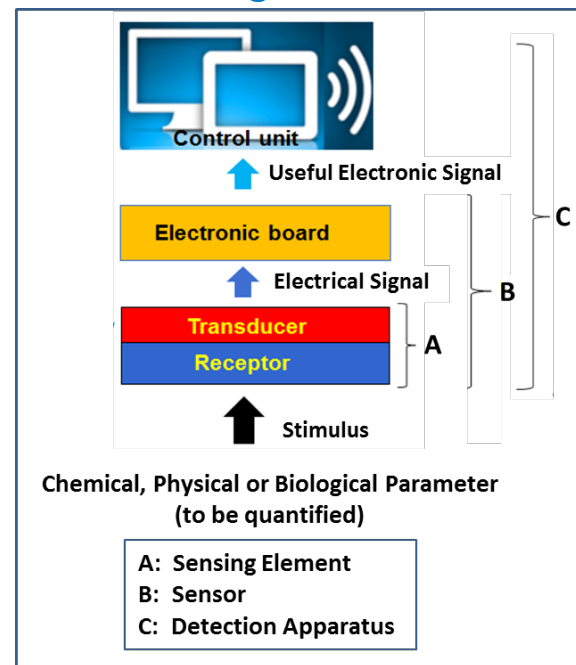
Sensor: Provides quantitative information

- Sensing Element(s) integrated with electronic circuitry (convert sensing element electrical response to useful signal)

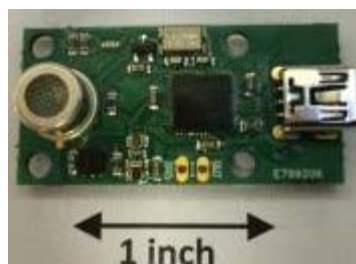
Detection Apparatus (Analyzer, etc.):

- Quantitation, Alarms, and Control Functions

Sensor vs. Sensing Element vs. Analyzer



vs.



vs.



Sensing Element (\$10 to \$100)
(analog signal)

Sensor (\$50 to \$500)
(vol% H₂)

Analyzer (>\$500)
(Control Functions)

The term “*sensor*” can have different meanings among stakeholders within the hydrogen community. Clarification is necessary to minimize confusion.

Relevance:

Why Use a Hydrogen Sensor / Detection Apparatus

- **Sensors provide indication of system status**
 - Measure hydrogen when/where it shouldn't be
 - Increase public confidence
 - Validation tools—models and facility design
- **Sensors provide critical safety factor**
 - Provide warning before unsafe conditions
 - Activate Corrective Measures (ventilation)
 - Alarm at unsafe conditions
 - System Isolation / Automatic shutdown
- **Bad things can happen when sensors are not used (properly)** [www.h2tools.org/lessons]
 - “*Gaseous Hydrogen Leak and Explosion*”
No H₂ monitoring led to fire and explosion
 - “*Two False H₂ Alarms in Research Laboratory*”
Nonspecific sensors alarmed twice (\$10,000 fine)
- **Required by code or a means to achieve SIL**
 - 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

Hydrogen Safety Sensors are an Enabling Technology for Infrastructure Implementation

Relevance

Need for Continued 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
 - Sensor lifetime / deployment stability
 - Cost of ownership
 - Guidance on placement/location; H₂ Wide area monitoring (HyWAM)

H₂ Sensor Research Supports

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

Distributed vertical profiling of a LH₂ Release



The NREL Sensor Laboratory developed a multipoint monitoring system for the profiling of hydrogen releases, which can be the basis for a hydrogen wide area monitor (HyWAM)
(NREL Record of Invention ROI 18-28)

Common H₂ Sensing Elements

	Electro-chemical Sensors	Combustible Gas Sensors	Thermo-conductivity sensors	Metal Oxide Sensors	Palladium Thin Film Sensors
Features	EC	CGS	TC	MOX	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.

Sensors based on various sensing element types are commercially available
Every sensor platform is good, but none will work for every application.
The Sensing Element will control (and limit) performance.
A tendency to over-generalize performance/capability still exist

Approach: Mission and Strategy of the NREL Sensor Testing Laboratory

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

- **Laboratory performance assessment**
 - Commercial and developing technologies
 - Qualification for end-users and applications
 - Not certification but validation
 - Support infrastructure and vehicle clients/applications
- **Field Deployments**
 - Verification tools for regulation requirements (e.g., GTR)
 - Validation for specific end-user applications
 - Infrastructure safety and implementation (HyWAM)
 - Indoor and outdoor facilities
 - Medium to large scale facilities
 - GH₂ and LH₂ safety research
- **Strategic partnerships to support deployment**
 - Government agencies and research institutions
 - National and International Partnerships
 - Regulators, infrastructure, and OEMs
 - Support C&S Development and safety
 - Pre-normative research and document development
 - Client Confidentiality



H₂ Sensor Testing Apparatus

The NREL Sensor Laboratory is a resource to the hydrogen community

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



Image provided by KPA, used with permission

Project Overview and Update

- KPA-Toyota service bay concept for FCEV repair facilities
- NREL validated sensor for application
 - Under CRADA CRD-14-547
- On-going deployment within multiple Toyota facilities
 - California and NE Corridor
 - No failure during deployment
- Recently recognized as an *EERE Success Story* in support of deployment



**EERE Success Story—NREL-KPA-Toyota
Collaboration Facilitates Permitting of
FCEV Repair Facilities**

FEBRUARY 15, 2018

<https://www.energy.gov/eere/success-stories/articles/eere-success-story-nrel-kpa-toyota-collaboration-facilitates>

Accomplishments and Progress

Hydrogen Sensor Workshop

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

- International hydrogen sensor workshop (Brussels, May 2017) jointly organized by NREL, JRC, FCH-JU
- Cross section of stake-holders (Infrastructure, OEMs, Manufacturers, Research, and Policy)
- Results presented at ICHS 2017 and in a Workshop Summary Report published by the JRC (Nov. 2017)
- Critical findings and Gaps
 - Sensor Lifetime
 - Cost of ownership
 - Sensor Placement / Wide Area Monitoring
 - Harmonization and simplification of C&S

H₂ Sensor Gap Analysis



Published as a JRC Technical Report
Available on-line

**Consensus gap analysis from a cross section of stakeholders.
Guidance for RD&D activity.**

Accomplishments (update): FCEV Exhaust Analyzer GTR-13 Verification

GTR 13 (overview)

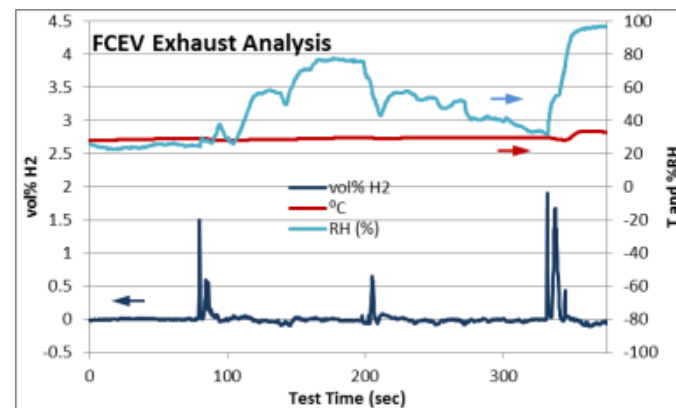
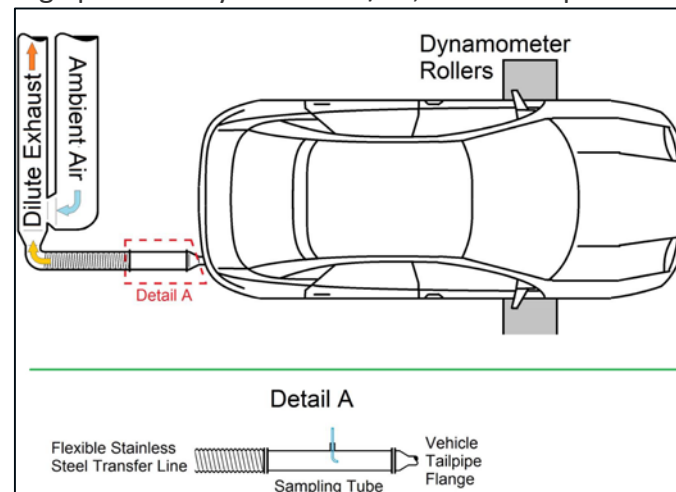
- Basis for the development of the U.S. FMVSS (and the CMVSS in Canada)
- FCEV H₂ exhaust level requirements

NREL FCEV Exhaust Analyzer (for hydrogen)

- H₂ Detection Technology for GTR-13 verification
 - Supported under DOT-NREL IAG 17-2046
 - Partners include DOT/NHTSA and Transport Canada (TC), Environment Canada (EC)
 - Performance verified in the laboratory and on vehicle
 - Field Deployment of FCEV: May/June 2018 (with EC/TC)
- OEM applications and interest



Image provided by A. Loisel/EC, used with permission




H₂ transients in FCEV exhaust, as measured by the NREL FCEV Exhaust Analyzer

Regulatory requirements need a means to verify compliance.

The NREL FCEV Exhaust Analyzer meets the GTR metrological requirements for compliance verification.

Demonstration and testing on a FCEV is scheduled for August.

Accomplishments and Progress: SAE TIR J3089

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

SAE J3089

Characterization of On-Board Vehicular Hydrogen Sensors

Background

- Developed under the auspices of the SAE Fuel Cell Standards Committee
- Supports OEM and suppliers on use of sensors in FCEV

FY 18 Updates and Accomplishments

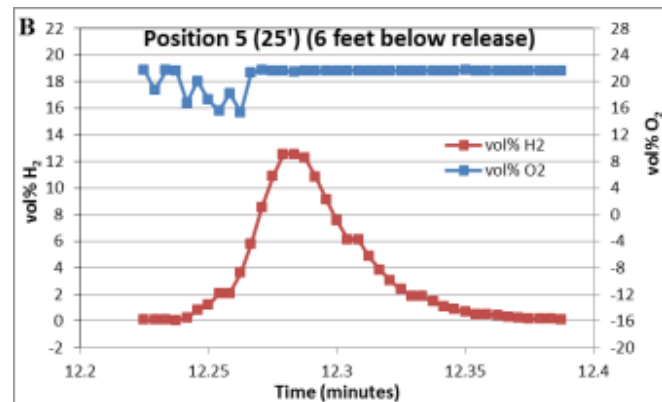
- Evolving Scope—performance and physical stress and electrical safety tests incorporated
- Ballot and Comment Submission: April 2018

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

Accomplishments and Progress: Multi-Point H₂ Detection and Profiling—Hydrogen Wide Area Monitor (HyWAM)

PROTOTYPE Analyzer Developed and Deployed (FY 17)

- Address gaps identified by NFPA 2 H₂ Storage Task Group
 - H₂ (> LFL) was observed up to 8' below release point of LH₂
 - H₂ (< LFL, but near warning level) was at ground level
 - Plume not totally dominated by buoyancy
 - vol% O₂ did not rigorously correlated to vol% H₂
 - Temperature was near constant (except low T transients)
 - Vapor cloud did not correlate to vol% H₂
- Presented at the ICHS 2017 and to NPFA Subgroup
- Gaps and questions on H₂ dispersion behavior remain



Analyzer Upgrades and Advancements (FY 18)

- Dedicated sensor for each measurement point ($\tau_{90} \approx 300$ ms)
- Amenable for low-cost, automated H₂ Wide Area Monitoring
 - NREL Record of Invention ROI 18-28: Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)
 - R&D tool for release modelling and site safety monitor
 - Active monitoring tool to alleviate NFPA LH₂ Setbacks
 - Partners identified for development, demonstration, and deployment (through the DOE TCF, CRADA, NDAs)
- Recent deployment: quantitative indoor H₂ profiling and model verification (see next slide)



Research in support of C&S development and LH₂ Safety
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 (Indoor HyWAM Application)

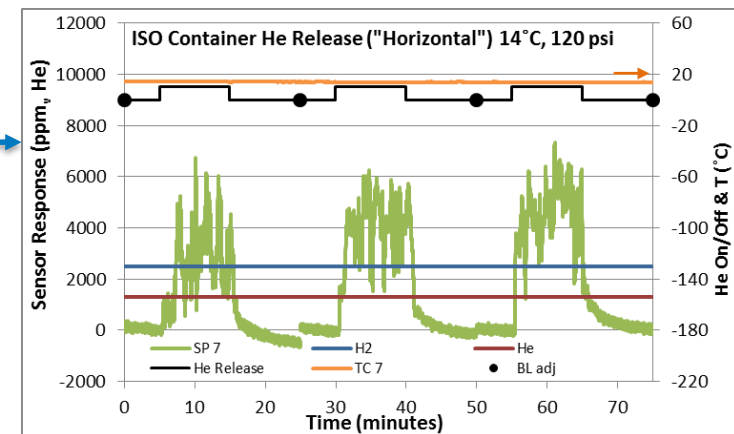
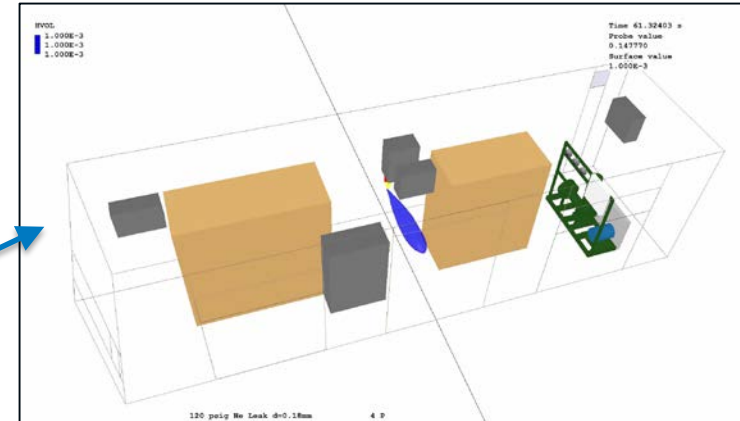
CFD modelling and empirical verification of indoor hydrogen releases

Guidance on H₂ Sensor Placement

- Identified in as a GAP (AMR, Sensor Workshop)
- Test system: ISO container (hydrogen production units with internal compressor)
- CFD modelling completed by A. V. Tchouvelev & Associates Inc. (video simulation by AVT)

FY 2018 Update

- Empirical verification using the NREL HyWAM
 - 10 sensor points for spatial and temporal profiling
- Good agreement between model (AVT, red line) and measurement (NREL, green trace)
- Independent CFD verification by JRC (on-going)
 - Excellent temporal and spatial correlation
 - Guidance document is under development with AVT
- Other HyWAM applications/uses are on-going



H₂ 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: Internships within the NREL Sensor Laboratory

On-going Mentoring of Junior Scientists and Engineers within the NREL Sensor Laboratory

Student Interns within the NREL Sensor Laboratory

- Mutually beneficial
- Real-world research experience in H₂
- Assigned as “technical lead” on a topical project
 - Interactions with clients
 - Allowed to present on their own work
 - Good publication record (co-authorship on talks, reports, and journal articles)
- Successful post-graduation careers in technical area of study
 - Several have hired on at NREL



**Sensor Laboratory Interns
(past and present)**

M. Bubar, H. Wright, K. Schmidt, I. Bloomfield

**An NREL Internship provides real world experience in renewable energy.
Several Sensor Laboratory Interns have been hired by NREL**

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Overall, the approach and achievements of the NREL Sensor Laboratory rated high.

(ACCOMPLISHMENTS) This project has made solid accomplishments that directly address specific data and technology needs for immediate commercial applications and for developing, implementing, and testing C&S. These are great examples of the benefit of DOE projects executed by the national laboratories.

- Positive reviewer's comments on the NREL Sensor Laboratory Accomplishments and Collaborations stood out as successful attributes in 2017

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Proposed Future Work had constructive suggestions

The review/statement of future work was pretty generic. It is unclear whether there are specific projects that still need to be started and whether specific work and deliverables remain on the project as it winds down this year (September 2017 end date). It seems like there is still some work going on with the cold plume analyzer, though it is unclear what needs to be finished there.

- The activity and accomplishments of Sensor Laboratory required more time than allocated to properly discuss (see Accomplishments). There was simply no time remaining to properly discuss Future Work.
- The Cold Hydrogen Plume Project is on-going and the Prototype Analyzer used therein has been recognized as the basis for a low-cost Hydrogen Wide Area Monitor (HyWAM)
- There is still activity planned for using the NREL HyWAM for LH₂ releases, but the system has been used to support indoor release activity as well.

Project Weakness

The comment that "...if the U.S. hydrogen sensor workshop happens, it will be in September rather than July 2017" was disappointing

- Regrettably, the budget and other issues were realities that affected the strategy and activity of the NREL Sensor Laboratory
- Things are looking better
- However, interactions with stakeholders outside the formalities of a Workshop are on-going.

Collaborations: Private and Government Partnerships

Performance & Qualification (Safety)

Sensing Element Development

- Element One, Inc. (MOU; SBV/CRADA)
- KWJ, Engineering (SBV/CRADA)
- Nitto, Panasonic (NDAs)

Infrastructure Support

- KPA (on-going support on sensors)
- AVT (Contract for release modeling)
- First Element

Vehicle Support

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

New Markets

- HyWAM Development and Applications
 - CRADA (Toyota)
 - TCF Proposal (KWJ, First Element)

Process Monitoring and Methods

Infrastructure Support

- NFPA 2 H₂ Storage Safety Task Group

Vehicle Support (GTR)

- SAE Fuel Cell Standards Committee
- GTR: Ford Motor Company/Daimler

Government Partnerships

- DOT/NHTSA (IAG) with Transport Canada/Environment Canada
- Joint Research Centre, Clean Energy Group
- HSL (LH₂ behavior/HyWAM), pending

The NREL Sensor Laboratory

A resource to the H₂ community

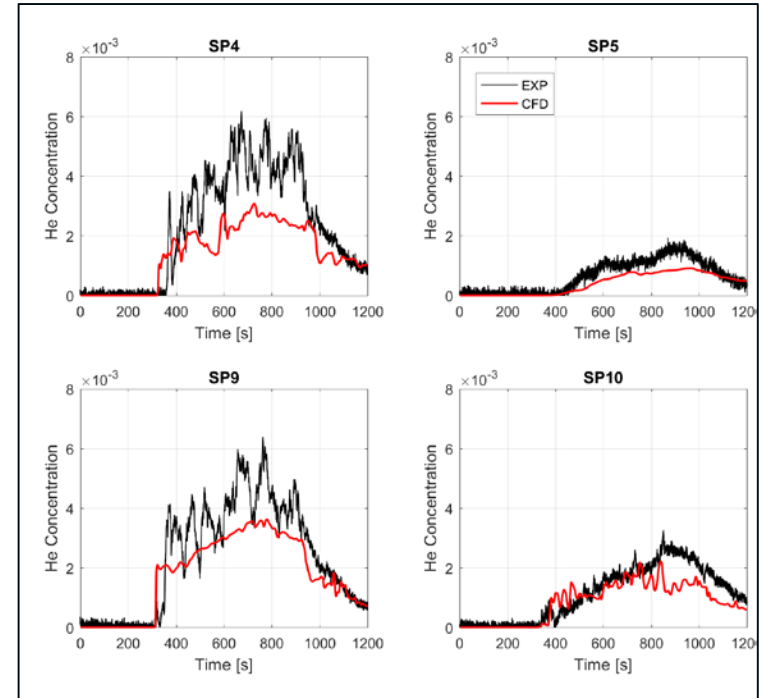
- Infrastructure, vehicle, and new markets
- Sensor developers and end-users
- Formal and informal agreements
- Available for WFO

NREL Sensor Laboratory - JRC Collaboration

(on-going since 2008)*

NREL-JRC 2018 Collaborative Research Activity

- Hydrogen Sensor Gap Analysis
 - Presented at ICHS (preliminary) and JRC Report
- Sensor Test Apparatus Design and Methods Comparison
 - Presented at ICHS and incorporated into SAE TIR 3089
- Impact of Chemical Stresses (Interferents)
 - Presented at the European Hydrogen Energy Commission
- Behavior of hydrogen releases
 - Preliminary study on LH₂ release behavior presented at ICHS and to be published in IJHE
 - Independent modelling of Helium releases in ISO Container (ongoing)
 - Support of LH₂ (cold hydrogen) dispersion modelling (proposed)



Indoor helium release behavior. Comparison of empirical behavior (—) and simulations (—) for 4 of 10 NREL HyWAM sampling points. (He is a common surrogate for H₂ release modeling)

The NREL-JRC Partnership synergized the resources and activities of the respective laboratories. The collaboration fosters international exposure of U.S. technology and expertise.

*Currently under “Collaboration Arrangement for Research and Development in Energy-Related Fields between the U.S. Department of Energy and the Joint Research Centre of the European Commission”, signed June 2, 2016

Remaining Challenges and Barriers

Hydrogen Sensors for Safety Applications

- **Low maintenance sensors/lifetime (cost of ownership):** Sensor maintenance (calibration, replacement, and even out-of-the box out-of-spec performance) remains an issue. Validated ALT technology for lifetime predictions does not exist.
- **Sensor Placement:** Sensor placement strategies are primarily by intuition. Guidance documents are lacking. Cost-effective sensor technology is necessary for large facilities (e.g., H₂@scale); validated alternative strategies may be needed.
- **HyWAM:** An economical HyWAM with the necessary metrological characteristics does not exist, especially for routine use. Active monitoring, coupled with CFD may be required to economically meet compliance requirements of NFPA 2
- **Complex Standards Requirements:** Strategies for meeting safety requirements require complex testing and validation; standards and safety strategies are not internationally harmonized

Process Control/FQ (“specialized” applications):

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

Proposed Future Work: Hydrogen Sensors and the NREL Sensor Laboratory

FY 18

- **Technical assessment of WAM Technologies for Hydrogen (HyWAM):** Perform an assessment of different WAM strategies (stand-off detection vs. array of point measurements), with an emphasis on H2@Scale applications. Highlight strengths, weaknesses, and applicability of various approaches for different scenarios.
- **Sensor Placement:** Utilizing the empirically validated models for indoor hydrogen dispersion, a guidance document on sensor placement is under development.
- **FCEV Exhaust Gas Analysis:** Field deploy the NREL FCEV Exhaust Gas Analyzer under working conditions (in collaboration with Transport Canada/Environment Canada, and support from DOT). This will also supports DOT on the GTR documentation.

FY 19

- **HyWAM:** An economical HyWAM with the necessary metrological characteristics does not exist, especially for routine use. Active monitoring, coupled with CFD may be required to economically meet compliance requirements for safe use of LH₂. NREL will develop a validated HyWAM for use in support of H2@scale.
- **Process Control/FQ (“specialized” application):** Emerging and specialized applications have unique and challenging metrological requirements (detection limits, harsh environments). Integration of advanced detection technology with creative sampling methods will be necessary to achieve these challenging requirements.

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

Technology Transfer Activities

- **NREL Provisional Patent 17-94:** Interface for High Pressure Dispensers
 - A universal low-pressure interface to any commercial/developing HCD.
- **NREL Record of Invention 18-28:** Wide Area Monitor for Hydrogen Releases within Hydrogen Facilities (HyWAM)
 - Based on the prototype NREL multipoint hydrogen analyzer used at an LH₂ facility
- **Technology Commercialization Proposal** with industrial partner to develop a cost effective HyWAM based upon NREL Technology
 - Partners include hydrogen fueling station operator and chemical instrument manufacturer.
 - Requirements guided in part by the NFPA Hydrogen Storage Task Group
- **Small Business Voucher** projects to facilitate technology development from U.S. small business.
 - KWJ: Advanced Characterization of Printed Hydrogen Sensors for Fuel Cell and Vehicle Applications
 - Element One (CRADA 16-613): Development and Testing of Low-Cost Hydrogen Leak Detection

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

Summary: Advancement from 2017 of on-going projects and activity

Project/Activity	FY 17 Status	FY 18 Advancements
SAE TIR 3089	Completed 1st draft, but scope expanded during reviews	Completed document, submitted for ballot (April 2018)
HyWAM (Outdoor, LH2)	Prototype analyzer developed and deployed, ICHS paper, results reported to NFPA 2 subgroup, potential for HyWAM Identified	Upgraded analyzer for HyWAM, IJHE paper on LH2 releases, ROI, active NFPA 2 subgroup participation, expanded applications, new partners (industrial, gov.)
HyWAM (Indoor, GH2/He)	CFD Modelling by AVT completed, facility instrumented with the NREL HyWAM	Empirical verification by NREL, complementary CFD modeling ongoing by JRC, reported to DOE C&S Tech Team, Guidance Document under development
FCEV Exhaust Analyzer, support of GTR 13	Laboratory testing to validate metrological requirements meet GTR requirements	IAG with DOT to deploy and validate the NREL Exhaust Analyzer, new probe design, preliminary measurements on FCEV, Field Test at TC/EC planned for June
H2 Sensors in Repair Facilities	With KPA and Toyota, successful initial deployment of the NREL-qualified sensor in multiple repair facilities, thereby facilitating permitting	On-going utilization of the qualified at all repair facilities without failure; recognized as an EERE Success Story
Sensor Testing and Evaluation	General testing in support of deployment, primarily under AOP	Performance evaluation remains a core capability of the NREL Sensor Lab, but more focused under NDAs and TSAs with sensor developers and end-users.
CDO/SDO Committees	Document development (TIR J3089), expert input on hydrogen sensors and gas detection, prenornantive R&D investigations	Prenornantive research on hydrogen release behavior, on-going verification technology development

Much of the NREL Sensor laboratory FY18 activity is ongoing and naturally builds off the past work

Thank You

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Publication Number

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Technical Back-Up Slides

(Include this “divider” 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 Web PDF files released to the public.)

Technical Back-Up Slides

- Technical back-up slides WILL be included in the published meeting proceedings but are intended primarily to answer questions or provide supplemental information.
 - Maximum five slides
 - Must be placed after main presentation and before reviewer-only slides
- Technical back-up slides are optional.