NREL Hydrogen Sensor Testing Laboratory

William Buttner, M. Post, K. Hartman,
D. Pearman, I. Palin, K. Lee
Presenter Name: William Buttner
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Project Goal
Hydrogen Sensor Testing Laboratory

The NREL Sensor Laboratory supports the HFTO's mission for the safe and efficient implementation of hydrogen as an energy carrier:

- Facilitate the development and use of hydrogen detection technology for safety, process control, and emissions quantification applications for existing and emerging applications
- Provide end-users with an unbiased resource to validate sensor performance to application requirements.
- Support hydrogen codes and standards development and safety research.
- Support development of advanced hydrogen detection methodologies for early leak detection.

The NREL Sensor Testing Laboratory was established to assure that stakeholders have the hydrogen detection technology they need.

Overview

Timeline and Budget

- Project start date: 10/01/2010
- FY22 DOE funding: $925,000
- FY23 planned DOE funding: $525,000
- Total DOE funds received to date*: $5,900,000

  * Since the project started

Barriers

- Hydrogen Safety Codes and Standards
  - 3.7.5.G – Insufficient Technical Data to Revise Standards
  - 3.7.5.H – Insufficient Synchronization of National Codes and Standards
  - 3.7.5.J – Limited Participation of Business in the Code Development Process

Partners

- Project lead (PI): Dr. William Buttner, NREL
- Co-PI(s): M. Post, K. Hartmann, D. Pearman
- Partner organizations
  - AVT and Associates, Sensor Placement R&D (AOP subcontract)
  - Element One, Inc., Wireless low power sensor (AOP subcontract)
  - UMD, Center for Risk and Reliability (AOP subcontract)
  - KWJ, Inc.: TCF CRADA
  - LANL (Fuel Quality Sensor)
  - SPPs: Shell, Amphenol, CARB, Element One,
  - HFTO CRADA: GTI, EPRI, Paulsson, Element One, Renewable Innovation, Boyd Hydrogen

Relevance/Potential Impact

Role of Hydrogen Sensors/Detection

Potential Negative Impacts of Released H_2

- Potential for fire or worse; Early detection minimizes impact
- There is a need for sensos & properly implementation to assure early detection
- Detection can provide risk mitigation credits
- Hydrogen releases lead to product loss and secondary green house impacts

Hydrogen sensors are the most common way to detect and mitigate hydrogen releases.

Process Control

- Monitor for fuel impurities or constituents (e.g., FQ, H2-natural gas blends)
- Prevent system damage

Identify out-of-compliance fuels before use

From: https://electrek.co/2019/06/11/hydrogen-station-explodes-toyota-halts-sales-fuel-cell-cars/

Hydrogen Sensors are a critical element for facility safety and optimized operations but must be reliable and properly deployed to be effective.

Approach
The NREL Sensor Laboratory

Element of an Integrated Program (HSR&D)

- Sensors (detection); component reliability, and C&S to mitigate the impacts of hydrogen releases

Traditional Focus (H_2 Sensors)

- Sensor performance evaluation for specific metrics

Emerging Focus

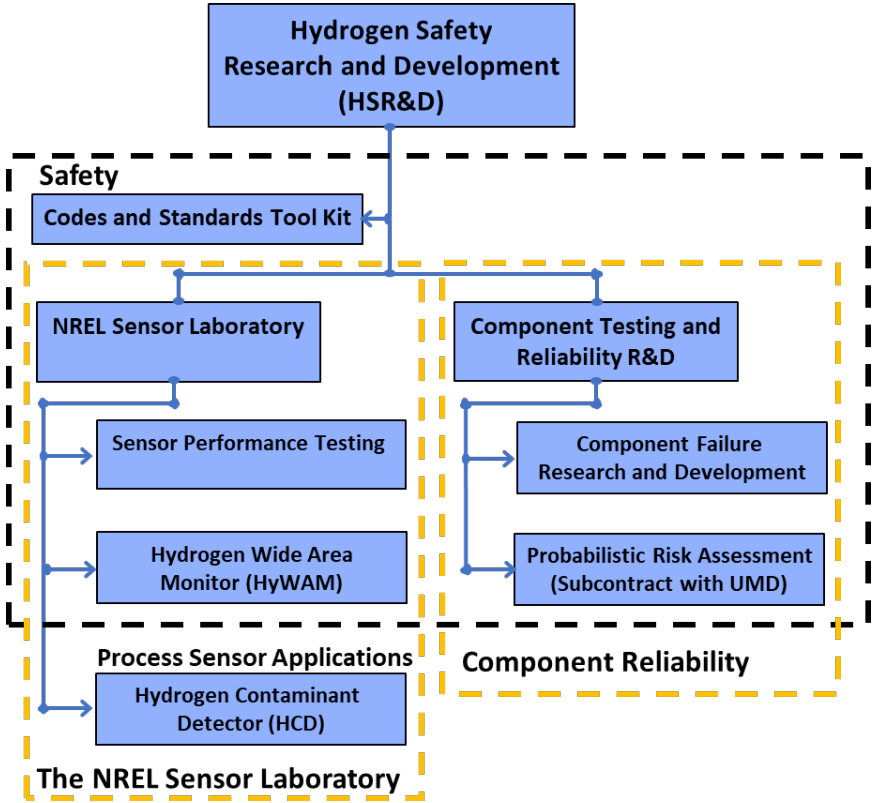
- Early warning indication for out-of-normal conditions
- Modelling & empirical sensor deployment studies
- Process optimization (FQ, Blends)
- Advanced detection methods (HyWAM/standoff methods)

Support New and Emerging Markets

- H2@Scale / Hydrogen Earth Shot (new markets— Heavy Duty, H2-NG Blends, energy storage)

Implementation Strategies

- Strategic internal, national and international partnerships (sensor developers, end-users, regulators, modelers, CDOs and SDOs)



Approach

Unique Sensor Testing and Deployment Capability

Provide unique sensor performance capability

- Safety Sensor Test Apparatus and other laboratory fixtures
  - Topical Studies / Customer applications (safety/environment)
  - Emerging technologies and markets
  - Support HyWAM
- Process Sensors and Process Control Applications (Process Gas Characterization Apparatus, PGCA)
  - NEC-compliant for non-listed devices (FQ, H2-NG blends)
- Access to HITRF and ARIES (deployment studies)
  - Leak Rate Quantification Apparatus—with leak on demand

Outreach

- Direct collaboration with stakeholders (WFO)
- CDOs/SDOs, Safety Groups (Center for Hydrogen Safety)
- Conferences and Workshops

The NREL Sensor Laboratory provides a unique capability to the hydrogen community not otherwise available

The SSTA (part of the testing capability of the NREL Sensor Laboratory)

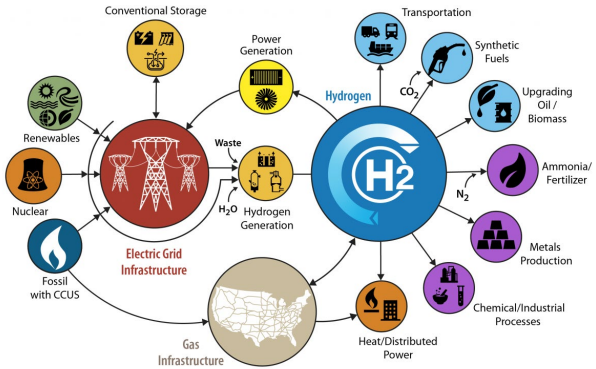
Hydrogen Infrastructure Testing and Research Facility (HITRF)

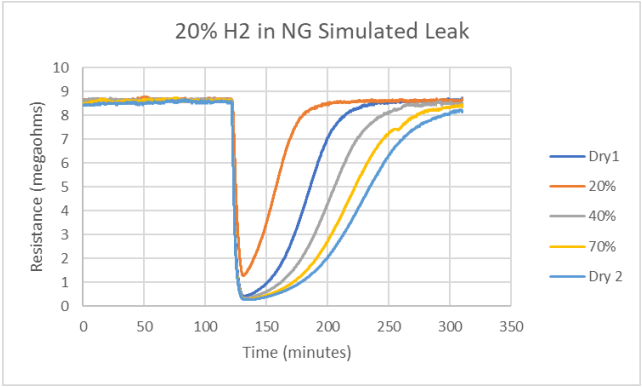
Accomplishments and Progress
(supporting emerging applications and challenges)

Hydrogen – Natural Gas Blending (H2-NG)

- H2@Scale vision include new markets and applications
  - Admixtures of renewables into NG is being mandated
  - On-going collaborations to support hydrogen admixtures
- Sensor Laboratory upgraded laboratory test equipment for safety and process sensor testing and validation
- Supporting development and validation of sensors
  - Impact on detection methods is one challenge
- Participation in safety committees (CHS) and standards (ASTM) to identify impact of blending on current practices

Hydrogen is one strategy to decarbonize the energy sector, but blending may impact detection and process control methods



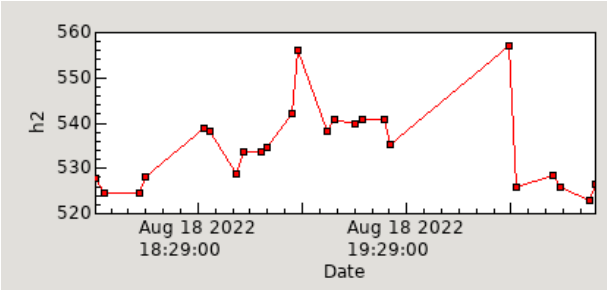


H2 sensor response to NG & H2-NG blends

Accomplishments and Progress
(adapting to emerging applications and challenges)

Hydrogen Emissions Monitoring and Quantification

- H_2 releases: Potential environmental concerns and product loss.
  - Multiple international workshops and FOAs to support hydrogen behavior models, to quantify losses, and to mitigate their impact
- Sub-ppm_v detection needed to quantify losses along value chain
  - Upgraded laboratory test equipment for ppb-level sensor validation
- Establish test site for outdoor sensor deployment and model development of released hydrogen behavior (within ARIES)
  - Completed background hydrogen measurements (with NOAA)



Background H2 Levels at ARIES (performed by NREL & NOAA)

Significance and Impact

- Supports safety and market viability of major hydrogen installations
- Develop, validate, and deploy methodologies to quantify losses along the hydrogen value chain to quantify both economic and potential environmental impacts

Accomplishments and Progress
FCEV Emissions Testing (Fuel Cell Exhaust)

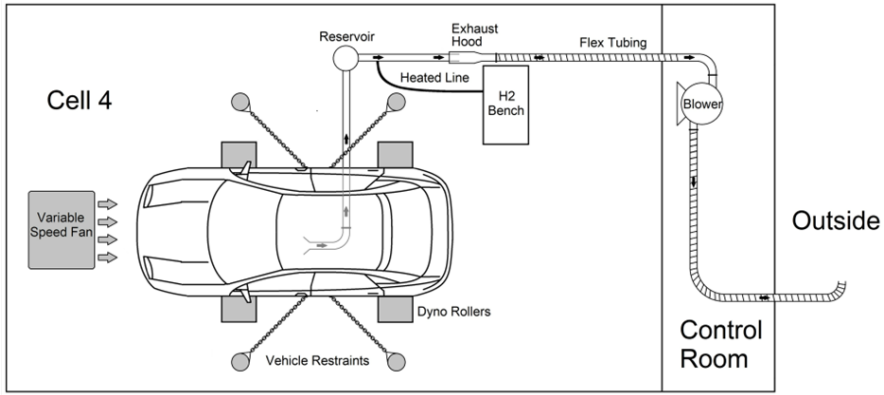
Researchers at NREL, ECCC, and TC have previously demonstrated the viability of the NREL FCEV Exhaust Gas Analyzer for quantifying H_2 levels in FC Exhaust. This work was guided by GTR-13, which defines allowable concentrations of hydrogen in the exhaust of an FCEV.

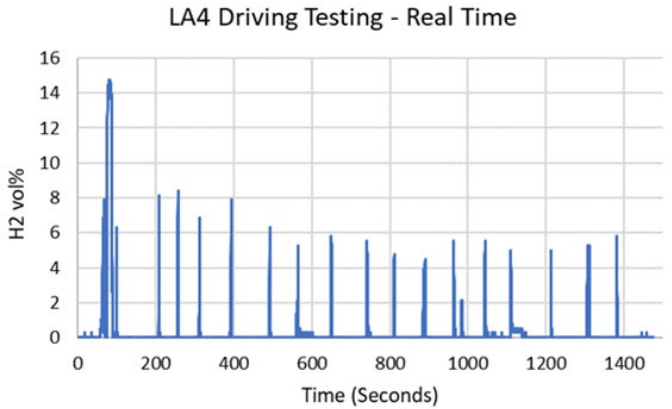
- Concentrations must be less than 4% over a 3-second moving average and always less 8% during startup and shutdown.

Emissions Monitoring

- Owing to the unique operation of a FCEV relative to ICE, the gas sample collection interface needed significant modification for use within the ECCC test facility. This has been accomplished but not demonstrated.
- Recent testing at ECCC shows that one FCEV has emitted a potentially concerning H_2 level during simulated operations.
  - Hydrogen emissions during operations are not currently monitored or regulated.
  - Future testing method will be able to monitor real time hydrogen concentrations for safety as well as track overall hydrogen emissions for environmental concerns.
- Because hydrogen is thought to indirectly contributes to global warming, hydrogen emissions from FCEVs (and other FCs) should be monitored and quantified.

Monitoring tools can assure that H_2 in FC exhaust is maintained at a safe and efficient level.





Accomplishments and Progress
Hydrogen Contaminant Detector (HCD)

Objectives:

- Develop the methodologies for near on-site, real time verification of fuel quality as per SAE J2719
  - Demonstrate at NREL HITRF; deploy at commercial sites
- Provide a test bed for new HCD analyzers
- Integrate in-line hydrogen contaminant detectors into commercial fueling dispensers for both LD and HD fueling infrastructure

The HCD enclosure is positioned outside the electrically classified area and installed with a shade canopy

Recent Accomplishments:

- Implemented Developed an interface to integrate HCDs into operational dispensers for in-line FQ verification using hydrogen vented from the hose depressurization
  - Demonstrated sample collection of a hose volume
  - Demonstrated sample delivery to the HCDs at the necessary flow rates and duration for analysis
- Developed an HCD environmental control enclosure
- Initiated market analysis for water analyzer and other HCDs

On-site fuel quality verification minimizes the likelihood of dispensing out-of-specification fuel which can severely damage FCEVs.

Accomplishments and Progress
Hydrogen Wide Area Monitor (HyWAM)

The NREL HyWAM:

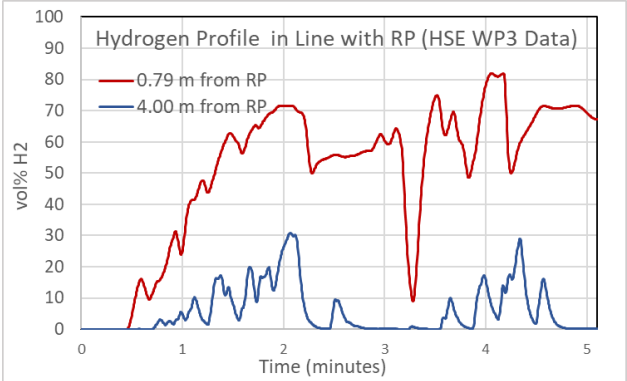
- Distributed network of *remote* point sensors connected to a 3-dimensional network of Sampling Points (SP)
  - Each sensor reads 0 – 100 vol% & t_{90} = 200 ms
- Developed as a R&D tool to profiling LH2 (and GH2) releases

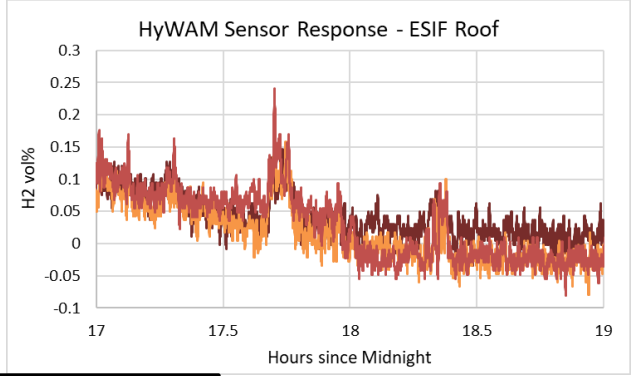
Recent Deployment

- HyWAM was used to track hydrogen entrainment into ESIF labs from a rooftop electrolyzer vent (operational releases).
- Hydrogen was detected near the air intake but at the metrological limits of the sensor (~75 feet from the vent)
- Construction of new low detection limit sensor units has initiated with acquisition of sensors with ppm LDL.

Pending Deployment:

- LH2 pooling experiment within a ventilated “tunnel” with SNL.
- Support of the HFTO CRADA on Next Generation Detection Technologies





Hydrogen Wide Area Monitoring: The quantitative or qualitative 3-dimensional spatial and temporal profiling of planned or unintentional hydrogen releases

Accomplishments and Progress
The NREL HyWAM (ignition of cold hydrogen releases)

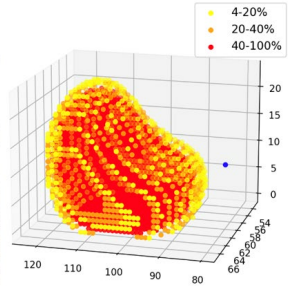
HSE PRESLHY Data on LH2 Releases (WP5-Combustion)
Prenormative Research for the Safe Use of LH2 (01/2018-12/2020)

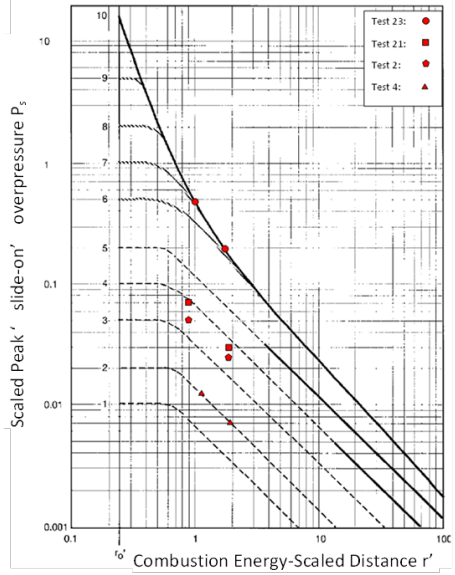
- HSE carried out a series of controlled LH2 releases
  - Multiple work packages: WP 3 (pooling); WP 4 Electrostatic Discharge; WP 5 (Combustion)
  - Cold plums profiled by the NREL HyWAM (16 or 32 points)
  - Data in repository maintained by KIT

Recent Data Analysis of WP5 (HSE and NREL)

- Gaussian Process Regression was implemented on liquid hydrogen releases within a congestion cage (with ignition)
  - Showed reasonable representations of gas plumes.
  - Higher density clouds corresponded to larger explosive events.
- TNO method showed that values corresponded to explosive characteristics, and produced values in the appropriate range

To be presented and published: *Visualisation and quantification of wind-induced variability in H_2 following releases of LH2, liquid hydrogen*, ICHS (9/19/2023) I. Palin, K. Lyons, W. Buttner et al.



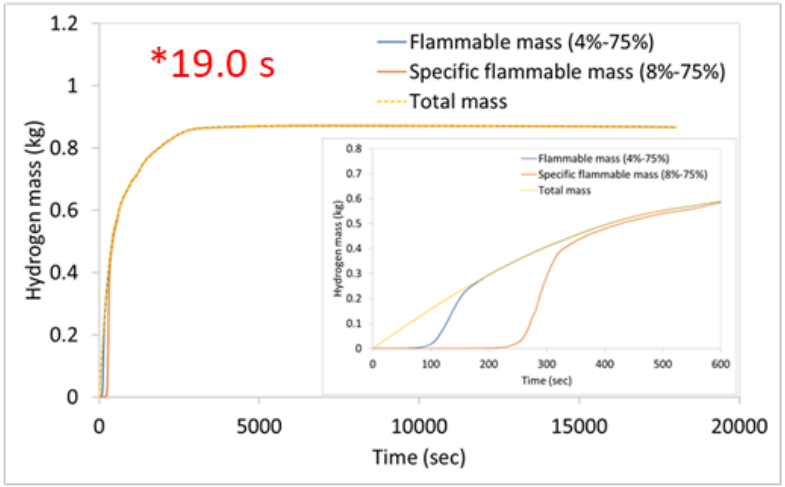


Accomplishments and Progress
Applying Credible Leak Scenarios to Indoor Enclosures

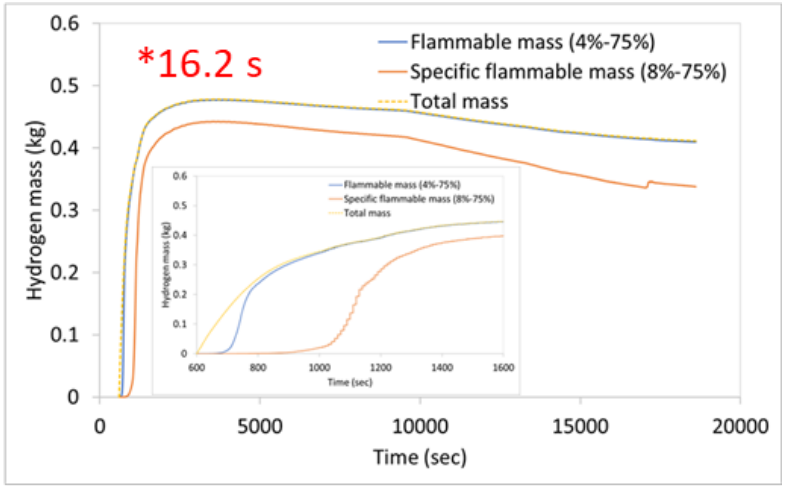
*detection time of 0.1% vol. target

Leak Position 1
Horizontal X+

No Ventilation



595 CFM

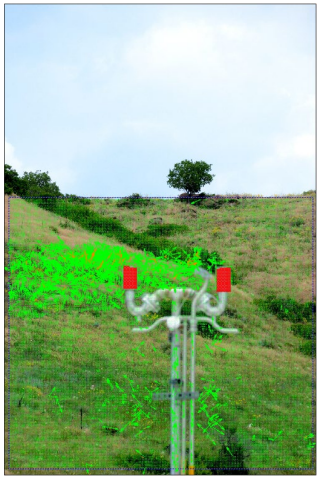


Faster detection time and reduced (by x 2) hazardous flammable mass.
Integration of hydrogen behavior (CFD) within enclosures and credible leak, to optimize detection strategies within ventilated enclosures-- See SCS001 Hartmann et al. “Component Reliability”

Accomplishments and Progress
Emerging Hydrogen Detection Technology

- NREL is investigating emerging and advanced hydrogen detection methods
- Wide area and stand-off methods
  - NREL HyWAM (distributed sensors)
  - Fiber Optic Sensors
    - Hydrogen sensitive
    - Pathway of Leak signatures (acoustic)
  - Ultrasonic Leak Detection
  - Schlieren Imaging
  - Flame Detection
  - Raman Methods
  - Wireless systems (RFID colorimetric wraps)

HFTO CRADA "Next Generation Hydrogen Leak Detection--Smart Distributed Monitoring for Unintended Hydrogen Releases" is implementing advanced detection methodologies



Background Oriented Schlieren Imaging of a hydrogen vent stack at NREL

Commercial ultrasonic leak detector installed at NREL

Accomplishments and Progress
(Internships within the NREL Sensor Laboratory)

Continued mentoring of undergraduate scientists and engineers within the NREL Sensor Laboratory

- Mutually beneficial; Real-world research experience in H_2 and alternative energy R&D
- Assigned as “technical lead”
  - Interactions with clients
  - Good publication record
- Current interns:
  - Ian Palin (Sensor Testing Support and Analysis)
  - Kayla Lee (Sensor Testing and Sensor Market Survey)
- Successful careers
  - Several have hired on at NREL (FTE & Consultants)
  - Two members of the HSR&D Team are former interns from the NREL Sensor Laboratory

(Former) Intern David Pearman working on the NREL HCD-Interface hardware

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

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

Project Strengths:
This is a highly productive project, with excellent growth potential into being proactive in applying sensor technologies to develop low-risk systems. This is particularly important as we move to H2@Scale. The collaborations developed are large in number and broad in scope, and each one is relevant to improving the deployment of low-risk systems..

Reply:
The NREL Sensor Laboratory continues to explore collaborations to efficiently support the safe implementation of hydrogen infrastructure and new markets as envisioned by H2@Scale and the Hydrogen Earth Shot. In FY22-FY23, we continue to expand our collaborations through formalized partnerships with a range of stakeholders (CRADAs, TSAs, FIA).

Project Weaknesses:
The project seems to be supporting other projects more than developing and proving technologies that could more immediately affect the rollout of hydrogen infrastructure. For example, the HyWAM technology is useful for research, but it is not in a useful state for deployment to active systems...

Reply:
The NREL Sensor Laboratory has been looking at methods of detecting and quantifying hydrogen leaks other than through point sensors. Our team provided support to optimize the use of P-T monitoring of hydrogen storage tanks within NREL to detect unintended releases. We are also looking at the integration of hydrogen detection for QRA and risk minimization. As for commercialization of HyWAM, we are working with a private company through the DOE TCF program to support the design of a commercial HyWAM.

The NREL Sensor Laboratory AMR Presentation was not reviewed in 2022.
This slide is based upon reviewer's comments from the last review.

Collaboration and Coordination

HyWAM Deployment/H_2 Releases
- Health and Safety Executive,
- Sandia National Laboratory,

Sensor Testing and Deployment
- Environment and Climate Change Canada
- Transport Canada
- Shell Hydrogen (TSA)
- Amphenol (TSA)
- Element One (FIA)

Fuel Quality Analysis and Applications
- Las Alamos National Laboratory
- California Air Resource Board (FIA)
- ASTM D03 Committee on Gaseous Fuels

Advanced Detection Methodologies
- HFTO CRADA: GTI, EPRI, Paulsson, Inc. Renewable Innovations, Element One, Boyd Hydrogen
- Emerson, Draeger

New Market Support: Hydrogen Natural Gas Blends
- SoCalGas; CHS, Blends working group

Component Failure and Reliability R&D
- UMD, Center for Risk and Reliability (subcontract)
- AVT and Associates (subcontract)

Hydrogen Safety C&S, Safety Working Groups
- BAM, CHS, IEA Task 43,Hydrogen Safety, HySafe
- SAE FCSC, NFPA, ASTM, UL, ISO, IEC

Workshop Participation and Organization
- METI Workshop on Hydrogen Detection. Mar 17, 2023
- DOE Enabling Decarbonization with Clean Hydrogen at Scale, Feb 7, 2023 (invited)
- CPUC input on Hydrogen Blends, May 17, 2023

NREL Internal
- CFD of H2 releases, Zhiwen Ma
- NFCTEC Genevieve Saur
- TEA: Mark Chung

PENDING (multiple partners)
- Hydrogen Hubs Sub
- H2 Earthshot (FOA DE-FOA-00002792); ppbv H_2 Sensors

The Sensor Laboratory is guided by direct interactions and formal collaborations with hydrogen stakeholders

Remaining Challenges and Barriers

Hydrogen Detection for Safety Applications

- **Release Hydrogen Behavior:** Outdoor H_2 sensor placement strategies are limited due to the incomplete elucidation of released hydrogen behavior (role of T, wind speed and direction). Released hydrogen modeling will be critical to quantify hydrogen emissions along the value chain to support environmental impacts and product lost.
- **Active Monitoring for Enhanced Safety/HyWAM**: An economical HyWAM with the necessary metrological and deployment characteristics to support active monitoring does not exist. Viable stand-off approaches to supplement the NREL HyWAM have not been validated but are being investigated. This was a specific topic area of a recently funded H2@SCALE CRADA (Next Generation Sensor Technologies), which include technology performance assessment in the laboratory and in field deployment at H2@Scale facilities for both outdoor and indoor applications.
- **Emerging Markets:** Current H_2 detection approaches may not be optimal for large-scale and emerging markets (e.g., H2@Scale, including H_2-NG blends, new production methods, large scale storage and hydrogen pipelines).
- **Low Level Detection:** Hydrogen detection methodologies have strived to preclude the formation of flammable levels of hydrogen. An emerging concern is improved detection capability to inventory hydrogen emissions from a facility for both economic reasons and for potential environmental concerns, which will require significantly lower limit of detection relative for conventional safety applications (possibly over 3 orders of magnitude).

Proposed Future Work

- **Continued development of HyWAM as a research tool and for general active monitoring**
  - Elucidation of released hydrogen behavior to support models through field deployments
    - Develop optimal leak detection methodology to support active monitoring for risk reduction.
    - Support sensor placement guidance
    - Hydrogen release quantification and reverse modeling needs for source location
  - Integration of active monitoring into QRA (HyRAM)
  - Basis for a commercial HyWAM (availability and deployment guidance)

- **Explore advanced detection strategies for hydrogen and gas leak detection for large scale and emerging markets**
  - Complex mixtures (e.g., H_2 in Natural Gas admixtures)
  - Advanced standoff methods such as ultrasonic, imaging methods, and fiber optic
  - System monitoring (e.g., P-T, Leak Rates through components) and maintenance strategies (e.g., PHM)
  - HD Markets (including marine, rail, and aerospace)

- **Need for lower detection limits to inventory operational and unintended releases to optimize operation efficiency and minimize potential environmental impacts.**

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

Summary

Relevance: Detection is recognized as a critical safety element for hydrogen facility risk mitigation as a tool to support H_2 behavior research and as an element in a deployed active monitoring safety system. Hydrogen point sensors play a critical role for safety and process monitoring, but other methodologies can be developed.

Approach: NREL Sensor Laboratory tests and verifies sensor performance for manufacturers, developers, end-users, regulatory agencies and SDOs/CDOs NREL deployment activity supports regulatory requirement verification, hydrogen behavior models, and method development for use by stakeholders.

Accomplishments and Progress: NREL's R&D accomplishments have supported developers, industry, and SDOs by providing sensor performance and deployment expertise not otherwise available. Development of alternative detection strategies for hydrogen applications has been initiated. HyWAM and advanced detection methodologies deployments at H2@Scale Facilities are already planned.

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

Proposed Future Work: NREL will support hydrogen deployment by the proper implementation of hydrogen sensors and advanced detection strategies. NREL will continue to support science-based codes and standards. This effort will be guided by the needs of the hydrogen community.

Thank You

www.nrel.gov

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