NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hydrogen Leakage and Detection

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(the NREL Sensor Laboratory)
National Renewable Energy Laboratory

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Enabling **Clean Energy with Clean Hydrogen at Scale**
Hydrogen Emissions and Leakage Panel Discussion
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The NREL Sensor Laboratory

Focus Areas

Sensor Performance and Deployment (indoor/outdoor)
- Sensor performance assessment
- Sensor Deployment Strategies
- 60+ years in gas detection methodologies

Hydrogen Wide Area Monitoring
- 3-dimenstion spatial and temporal profiling (NREL HyWAM is based on a distributed net work of point sensors)
- Elucidation of Hydrogen Behavior
- Active monitoring as a risk mitigation strategy

Application Support and Emerging Markets (topical studies)
- FCEV Exhaust (ECCC, TCa)
- H2@Scale (H_2 blends, Aerospace), Battery safety

Advanced Detection Strategies and Performance
- Distributed / Stand-Off detection approaches
- Supplement/supplant point sensors

The Sensor Laboratory strives to assure the availability and optimal utilization of hydrogen detection technology

The Safety Sensor Test Apparatus

The NREL Sensor Testing Laboratory
- Commissioned 2010 for performance testing of commercial and R&D Sensors.
- Capabilities include safety and process sensor testing and indoor and outdoor deployment assessments.

Overview of Hydrogen Releases

Operational Hydrogen Releases
- Depressurization events (LH2 Tanks, fueling events)

Design Features
- Permeation through vessel walls, seals (usually small)

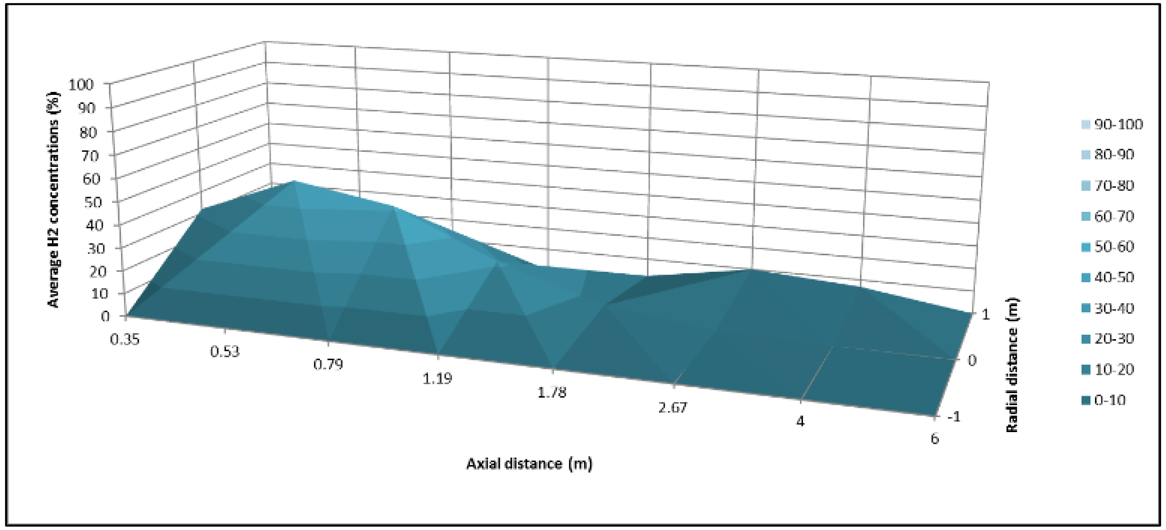
Unintended Releases (Leaks/out of normal events)
- Safety Venting (e.g., PRD activation)
- Breaches / component failure
- Size considerations
  Small leaks (“inconsequential” amounts)
  Larger Leaks (potential safety concerns)

LH2 Venting following delivery

Small leak identified by a soap solution

Reasons for Monitoring of Hydrogen Releases

- Safety
  - Avoid accumulation (below the of LFL of 4 vol% H_2)
  - Typical monitoring range of interest 0.1 to 10 vol% (1,000 to 10,000 ppm_v)
- Potential Environmental Concerns
  - Sub-ppm_v range of interest
- Maximize Product Throughput
  - Identify losses along the value chain
  - Market driven / application specific



3-dimensional concentration profile of a controlled horizontal LH2 release as measured by the NREL HyWAM (based on a distributed array of hydrogen point sensors).

Gas sensors/detectors are the most common strategy for the direct detection and empirical characterization of hydrogen releases

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.)

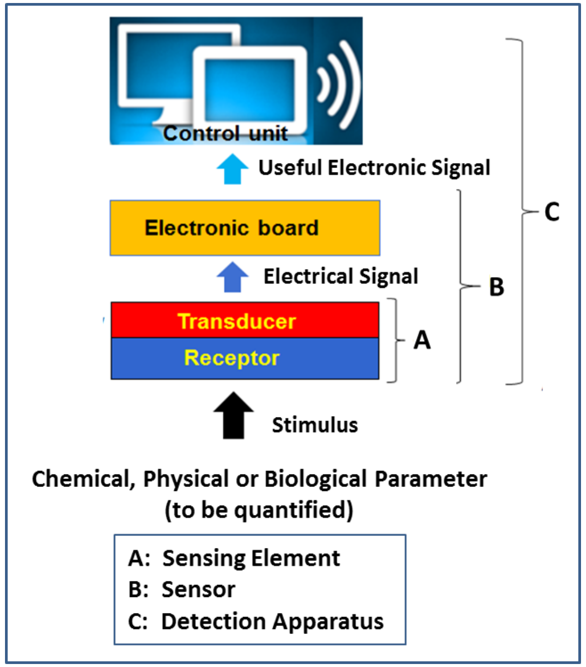
Sensor: Provides quantitative information

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

Detection Apparatus (Analyzer, etc.):

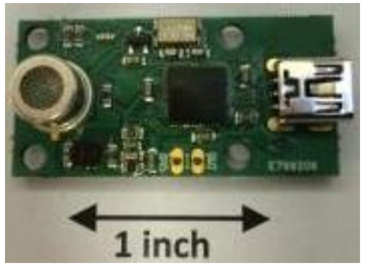
- Quantification, Alarms, and Control Functions

Sensor vs. Sensing Element vs. Analyzer



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

vs.



Sensor ($50 to $500)
(vol% H_2)

vs.

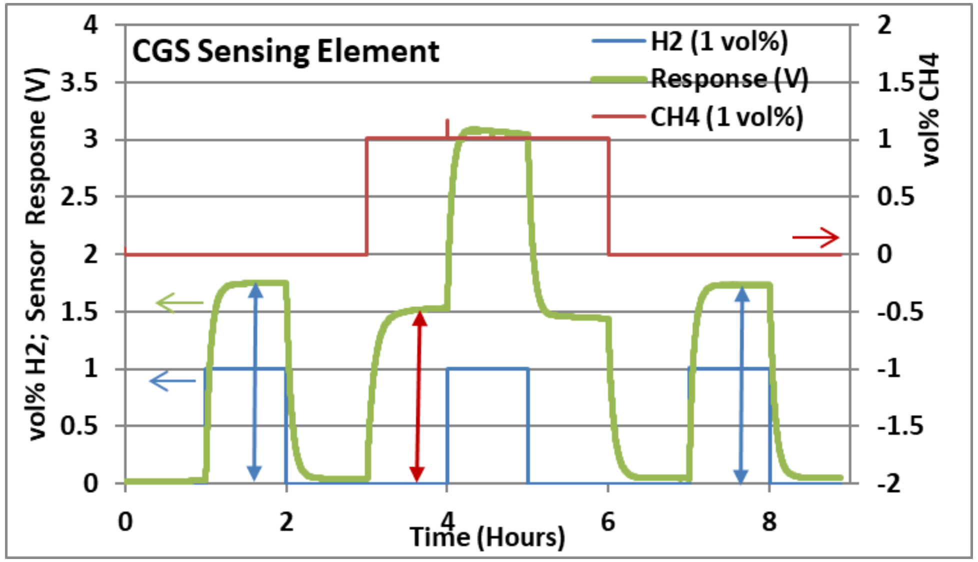
Analyzer (>$500)
(Control Functions)

The term "*sensor*" can have different meanings among stakeholders within the hydrogen community.
Practical definition: A hydrogen sensor provides quantitative information on the presence and amount of hydrogen.

Overview of Sensor Technologies for Hydrogen Detection

Overview of Hydrogen Sensor / Detector Metrologic Performance (Nominal Metrics)

Commercial Platforms	RT (seconds)	LDL (ppm_v)	MR (vol%)	Selectivity	Open Air
TC	<1	1000	to 100%	good	yes
CGS	1 to 5	1000	to ~10%	moderate	yes
MOX	5 to 30	1000	to ~10%	low	yes
Pd Thin Film	5 to 10	1000	to 100%	GREAT	yes
EC	5 to 20	10 to 100	<10%	good	yes
GC (instrument)	30 to >600	<1	broad	good	probable
MS (instrument)	30 to >600	<1	broad	good	probable
Developmental					
CGS (thin-film)	fast	<1 ppm	moderate	moderate	possible
Nano-conductor	TBD/fast	<1 ppm	variable	unknown	possible
Nanoplasmonic	1 to 2 s	<1 ppm	Broad	good	probable
µ-grove	TBD	unknown	unknown	unknown	possible
Optical	TBD	<1 ppm	good	good	probable



Cross sensitivity of a commercial "micro" sensing element to H_2 (↕) and CH4 (↕). Low ppm_v CH_4 were obtained under controlled conditions.

- Different sensor platforms for the direct detection of released hydrogen
- Most focus on safety applications (Measurement Range: 0.1 to 10 vol% H_2)
- Typically point monitoring (but can be integrated into HyWAM)
- Emerging methodology offers promise of improved detection limits

Strategies to Improve Sensor Performance Metrics and Measurement Outcomes

Sensor and Sensing Element Design Enhancement

- Innovative Transduction Mechanisms and Detection Methods
- Advanced Materials for Sensing Elements (e.g., nano-palladium catalyst)
- Advanced Fabrication (miniaturized sensing elements)
- Electronic signal optimization

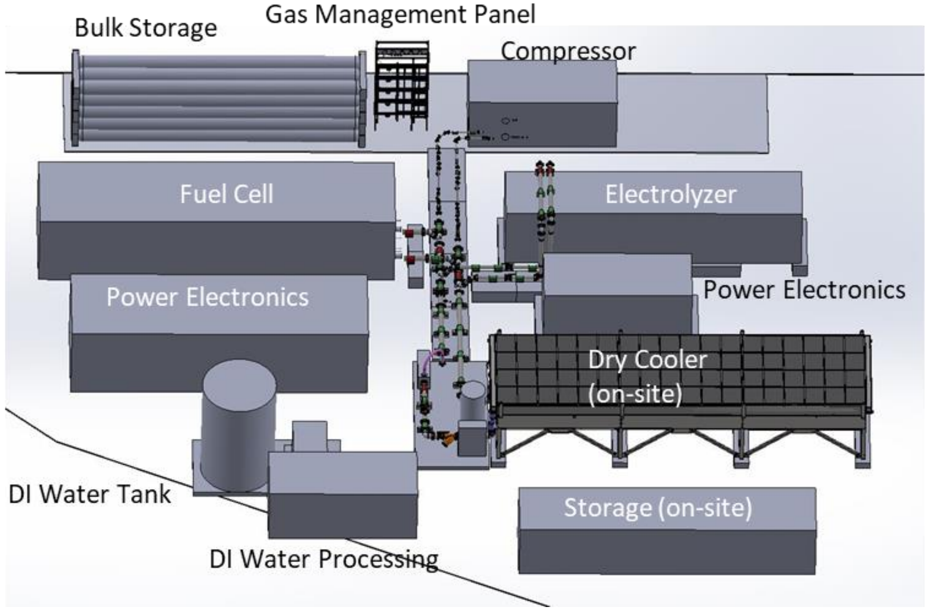
International Commitment to Innovation

- U.S. DOE and the European Clean Energy Joint Undertaking initiatives to provide tools for quantifying anthropogenic losses along the hydrogen value chain
  - Detection technology development and Behavior modelling

Testbed for Deployment and Validation

- Validate and deploy detection methodology
- Model Development (including “reverse CFD”)
- NREL Advanced Research in Innovative Energy Systems
  - Large Scale H2 facility with on-site production, storage, & use (Pending, but background H2 levels characterized (NOAA/NREL)

The ARIES Hydrogen Vision



- 1.2 MW Electrolysis H2 Production
- 1 MW Fuel Cell
- 600 Kg medium pressure storage
- 500+ Kg metal hydride storage

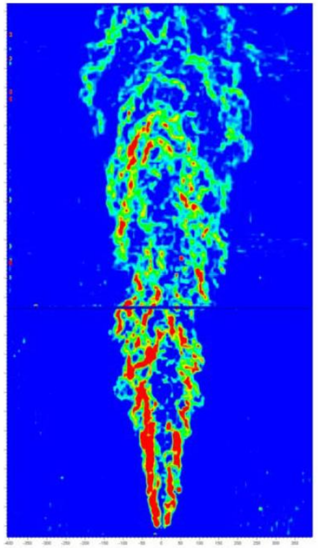
Hydrogen Background: 500 ppb (NREL/NOAA)

- Prior to any on-site hydrogen activity
- Typical for N. America

DOE, CE JU, and critical stakeholders are committed to quantifying hydrogen losses along the value chain and to elucidate the behavior and impact of released hydrogen

NREL Sensor Laboratory Emerging Hydrogen Detection Technology
"Smart Distributed Monitoring for Unintended Hydrogen Releases"

- Supported through 2021 H2@Scale CRADA Call Next Generation Sensor Technologies
- Wide area and stand-off methods
  - NREL HyWAM (distributed sensors)
  - Fiber Optic Sensors
    - Hydrogen sensitive
    - Distributed Leak signatures (acoustic)
  - Ultrasonic Leak Detection
  - Schlieren Imaging
  - Raman Methods
  - Wireless systems (RFID colorimetric wraps)



Background Oriented Schlieren Imaging of H2 release

From A. Kessler et al. "Hydrogen Detection: Visualisation of Hydrogen using Non-Invasive Optical Schlieren Technique BOS.", 2005.

Commercial ultrasonic leak detector installed at NREL

Summary (Sensors and Detection Tools)

- Sensors represent one strategy for detecting and quantifying hydrogen releases
- Current market focused on safety requirements
- Improved detection limits are feasible with technology development.
- Correlating sensor measurement profiles require modeling:
  - Elucidation of hydrogen dispersion behavior (such as CFD; validated by HyWAM to guide monitoring strategies).
  - Develop inverse models to use concentration measurements of sensors to quantify source releases
  - Precedence in the natural gas industry and environmental monitoring to quantify emissions
- Other strategies exist to support quantification of hydrogen releases from a facility
  - Leak rates through system components

Leak Rate Quantification through failed components

Goal:

To establish a scientific basis for risk and reliability analysis through integrated work with data collection, model development, and stakeholder engagement.

- Quantify leak rate quantification to ultimately allow risk reduction credits through QRA (Quantitative Risk Assessment) in RCS.
- Obtain a better understanding of leak behavior and leak size for different components and failure modes

Supplemental Outcome

- Provide quantitative mass loss of hydrogen (leak rate based on temporal P-T measurements)

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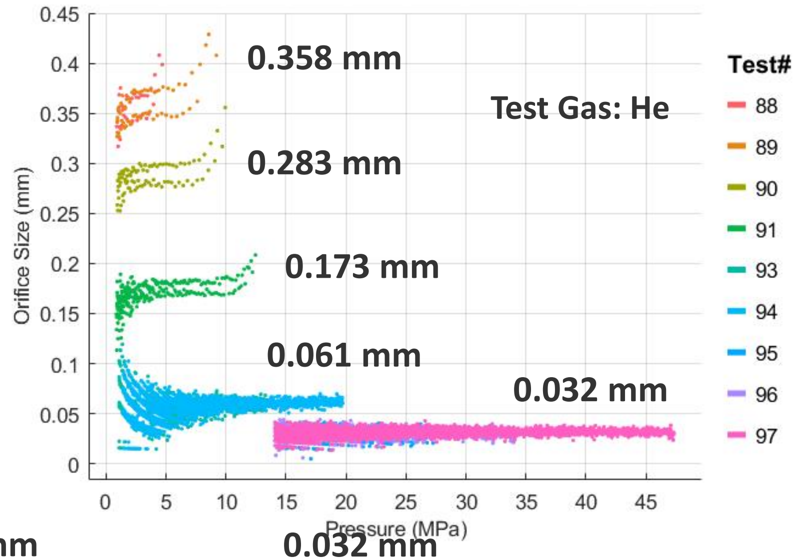
NREL Transforming ENERGY

Characterization of Leaks with Defined Orifice Size

- Used the LRQA to characterize leaks of varying orifice size
  - Micro-metering valve used to control the leak office size
  - Determined the mass flow rate and equivalent orifice size of leaks
  - Used HyRAM to model the leak plume dispersion for the various orifice sizes at a nominal upstream pressure of 55 MPa

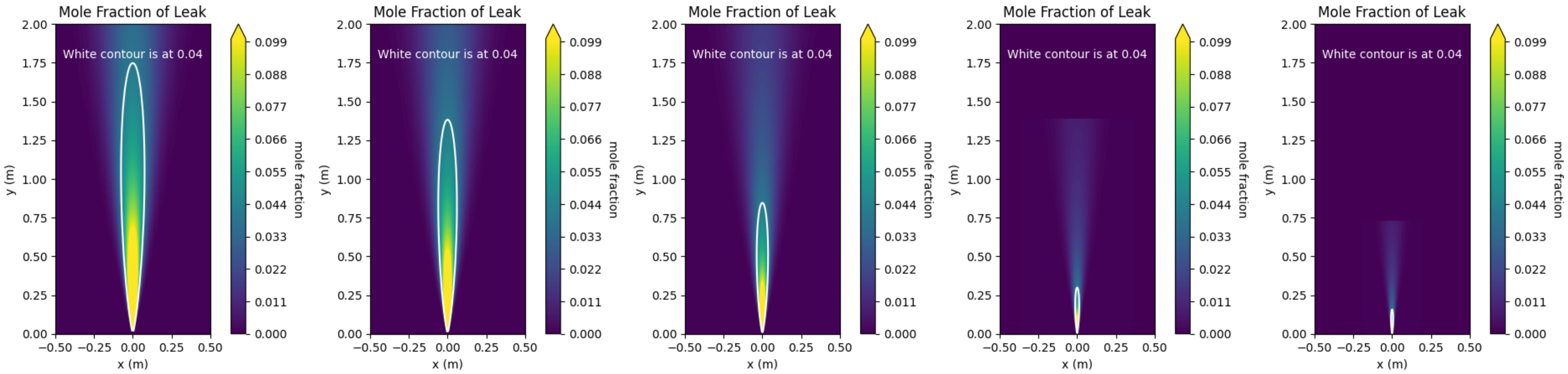
Leak Rates (mass loss) will vary with effective orifice size—impact hazardous volume and total loss of hydrogen

Micro-Metering Valve Orifice



Orifice Size: **0.358 mm** **0.283 mm** **0.173 mm** **0.061 mm** **0.032 mm**

Nominal upstream pressure of 55 MPa used



The LRQA installed on HITRF

Thank You

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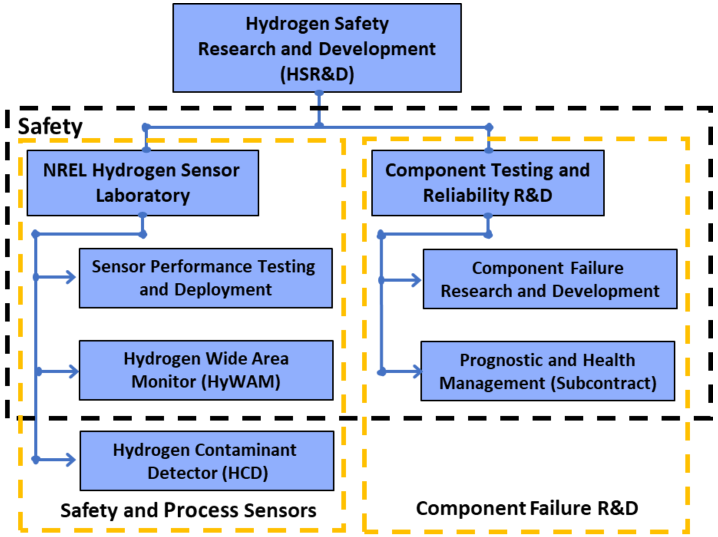
NREL Transforming ENERGY

The NREL Hydrogen Safety Research and Development (HSR&D) Program
(within the Hydrogen Power, Production, and Storage Group)



HSR&D– an integrated approach to H_2 safety

Testing apparatus and expertise for hydrogen safety and process sensors

- The NREL Sensor Laboratory-experts in hydrogen detection and monitoring
  - Unique capability and resource
  - Safety and process control sensor testing and deployment studies
  - Advanced wide area / stand off detection technology (for H2@Scale)
  - Hydrogen release behavior modelling
  - Detection as a risk reduction strategy
  - Support sensor developers, and end-users.
- Hydrogen Component Reliability R&D for probabilistic risk reduction QRA.
- Active membership on CDOs and SDOs (NFPA, ISO, UL, SAE, ASTM)
- National & International strategic partnerships to directly support stakeholders

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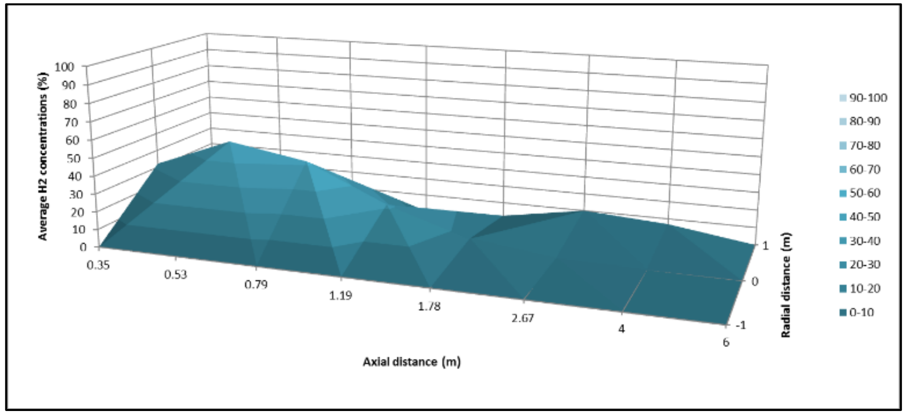
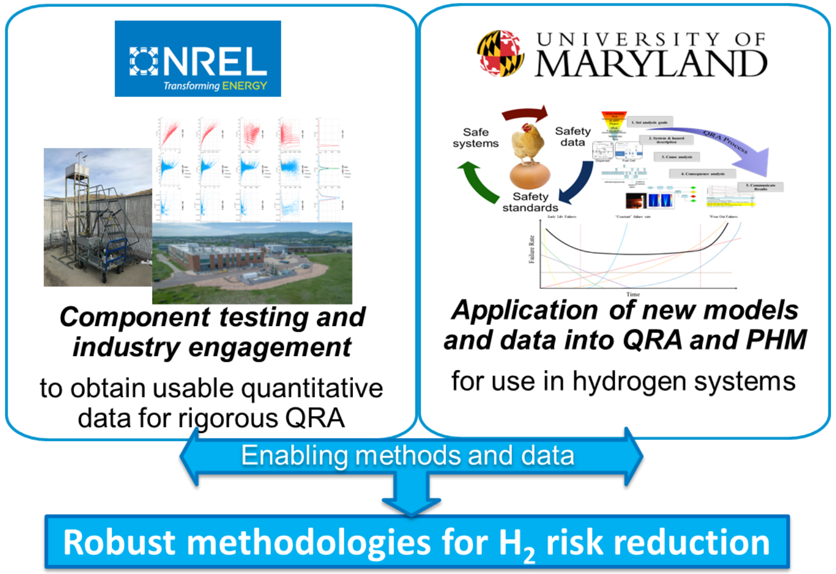


Hydrogen Wide Area Monitoring: H_2 release profiling using the NREL HyWAM



Hydrogen component R&D merges failures with probabilistic risk reduction (with UMD)