

Hydrogen Wide Area Monitoring of LH2 Releases at HSE for the PRESHLY Project

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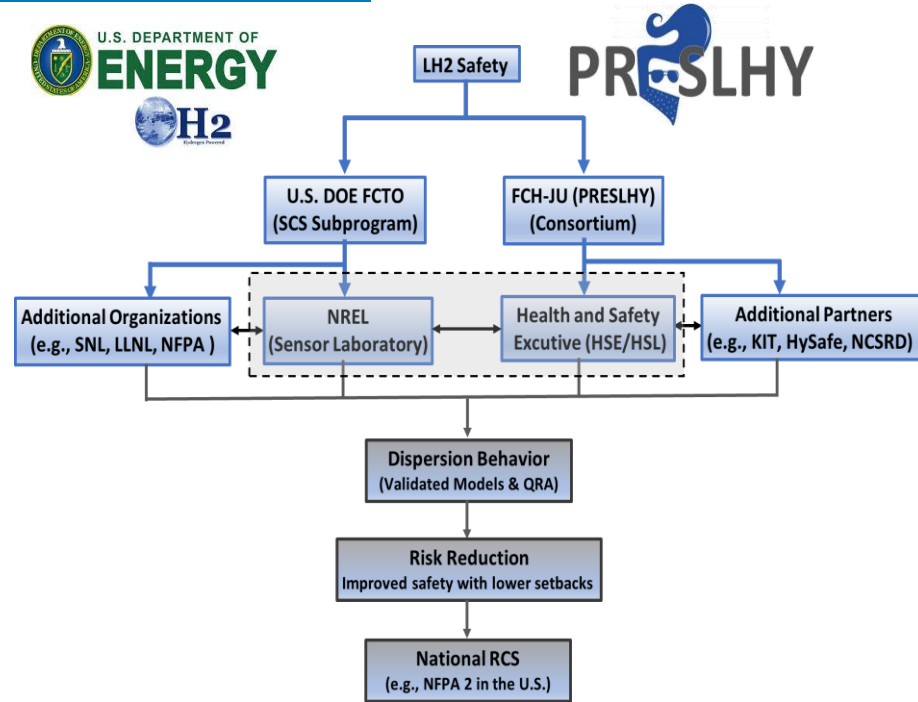
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Edinburgh, Scotland
(virtual)

Outline

- LH2 potential and safety concerns
- What is HyWAM (NREL HyWAM)
- HSE PRESLHY LH2 Releases
- Deployment of the NREL HyWAM during the HSE LH2 Releases
- Future direction for HyWAM methodologies



An outcome of the 2018 HySafe RPW
HSE and the NREL Sensor Laboratory agreed to collaborate on the PRESLHY LH2 Releases

Overview of PRESLHY

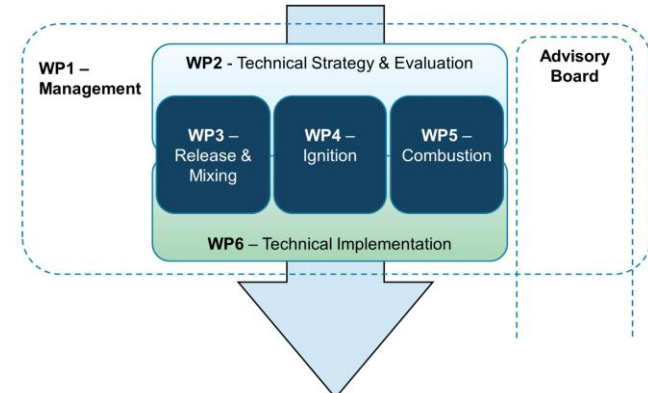
(Prenormative Research for the Safe Use of LH2)

- LH2 storage is a strategy to meet on-site capacity needs (including LD- and HD-fueling applications)
- Restrictive set back distances impedes LH2 use in urban environments
 - Risk mitigation may ease setbacks
 - Behavior modeling and active monitoring are proposed mitigation strategies to improve safety

PRESLHY (01/2018 – 12/2020)

- Identify safety knowledge gaps,
- Closed gas by developing and validating models and engineering (behavior) correlations,
- Evaluate efficient mitigation concepts for LH2 safety distance rules.

GH2 storage capacity impacts supply reliability



PRESLHY Organization

Image obtained from <https://preslhy.eu/wp/>

Overview of the NREL HyWAM (features)

The NREL HyWAM

3-dimensional distributed array of point sensors

Two Subsystems:

- Sensor modules
 - Thermo-conductivity H_2 sensors (mounted in custom housing)
 - Continuous monitoring, 0 to 100 vol% H_2 (or He); $t_{90} \approx 250$ ms;
 - Pneumatic lines to transport test gas to remote H_2 sensors
 - Enhanced with supplemental physical (P, T, RH), environmental (wind speed and direction), and chemical sensors and video
- Support Structure
 - Sample Point (SP) placement--horizontal & vertical distribution

Case Studies / deployment history

- 10-sensor HyWAM for LH₂ releases (preliminary HyWAM)
- 10-Sensor HyWAM for indoor H_2 Releases
- 32-sensor HyWAM deployed at HSE in support of PRES-LHY
- Internal NREL deployments



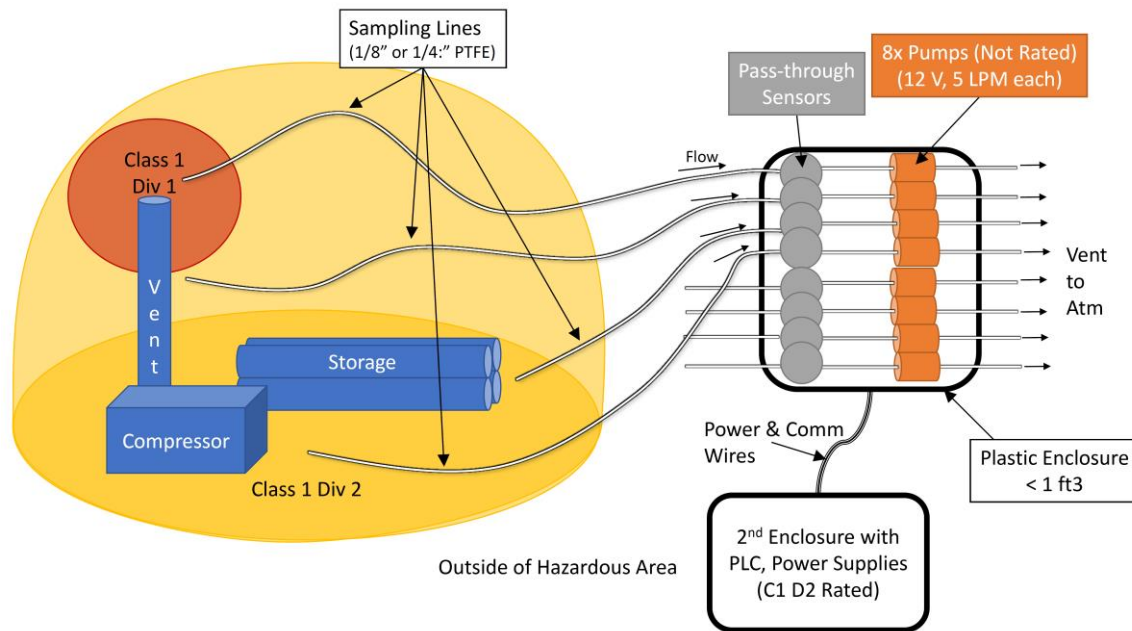
The NREL HyWAM Sensor Module
(2019)

Hydrogen Wide Area Monitoring (HyWAM)

The quantitative or qualitative 3-dimensional spatial and temporal profiling of planned or unintentional hydrogen releases

NREL HyWAM

Gas sampling to remote sensors

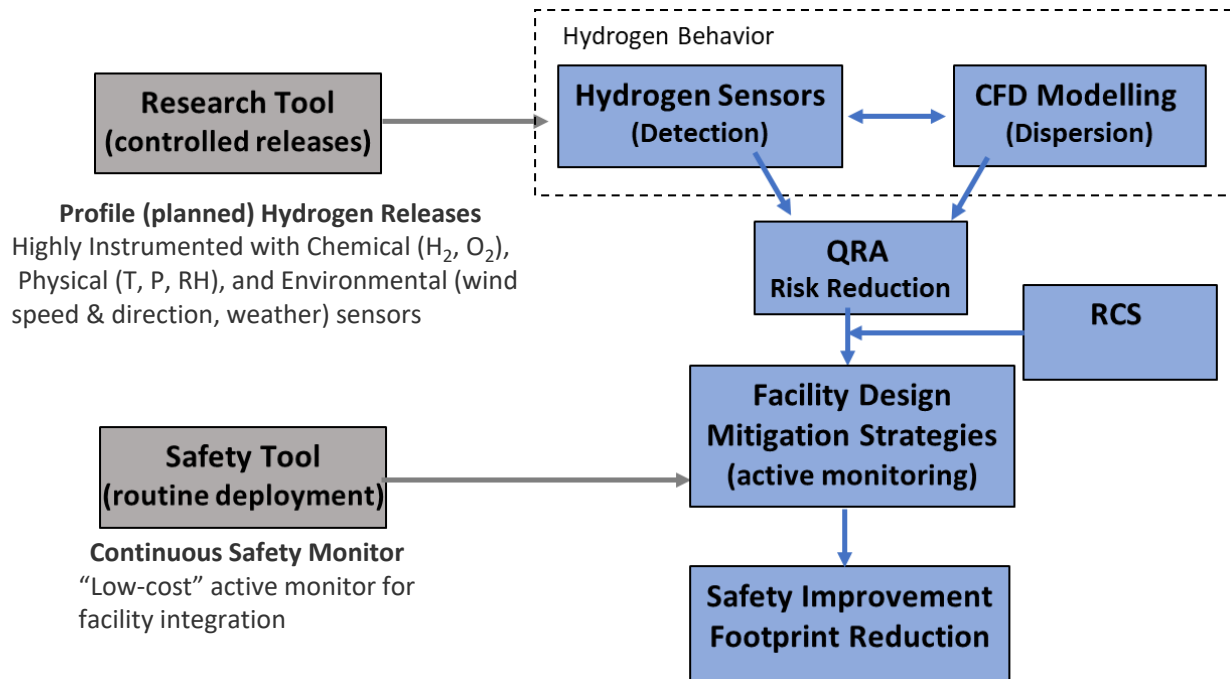


Transport of gas sample to remote H₂ sensor for analysis

- Simplifies sensor installation and maintenance
- Allows for exchange of sensors and sensor types
- Easily addresses electrical safety requirements
- Minimizes temperature impacts from cold plumes

Role of Hydrogen Monitoring and LH2 Safety

Hydrogen Wide Area Monitoring (HyWAM) (Quantitative 3-dimensional Temporal and Spatial Profiling of Hydrogen Releases)



Active Monitoring has been identified as one potential mitigation strategy to alleviate LH2 setback distances (part of performance-based risk mitigation)

HSE PRESLHY LH2 Releases Overview

Prenormative Research for the Safe Use of LH2 (**PRESLHY**)

- HSE / HSL performing multiple large scale LH2 releases (September 9 – October 31, 2019)
 - WP 3 and WP4 (Release and Mixing): *Unignited releases focusing on dispersion / source term*
ID24: Characterisation, dispersion and electrostatic hazards of liquid hydrogen for the PRESLHY project
Jonathan Hall, Philip Hooker, Kieran Lyons, et.al.
 - WP 5 (Combustion): *Ignition phenomena focusing on electrostatics / condensed phase initiation / RPT*
ID25: Experimental Parameters of Ignited Congestion Experiments of Liquid Hydrogen in the PRESLHY Project
Kieran Lyons, Graham Atkinson, Simon Coldrick, et.al.
 - WP 4 (Ignition): *Combustion characteristics including semi-confined / congested regions*
ID28, Condensed Phase Explosions involving Hydrogen, Graham Atkinson
- PRESLHY Dissemination Conference (May 5-6, Virtual)
 - WP 6 (Implementation): *To assure proper dissemination of data, results, and analyses*
ID115, Results of the Pre-Normative Research Project PRESLHY for the Safe Use of Liquid Hydrogen
Thomas Jordan, Laurence Bernard, Donatella Cirrone, et.al.

HSE PRESLHY LH2 Releases (Test Site and Apparatus overview)

Image obtained from HSE Report, PRESLHY deliverable D3.6

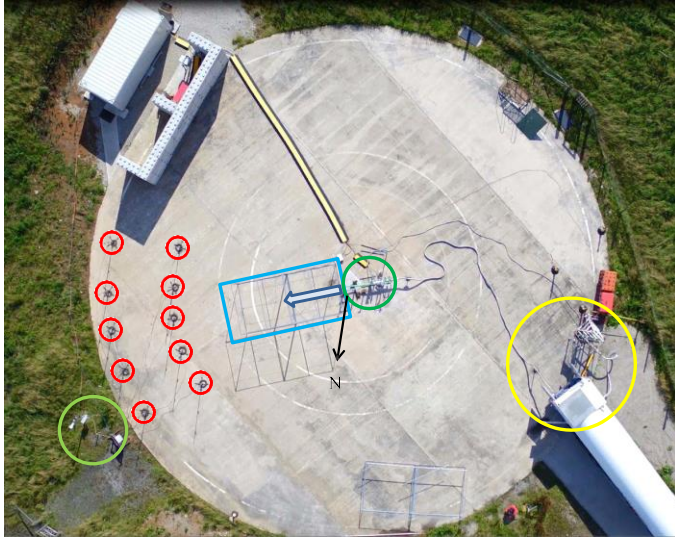
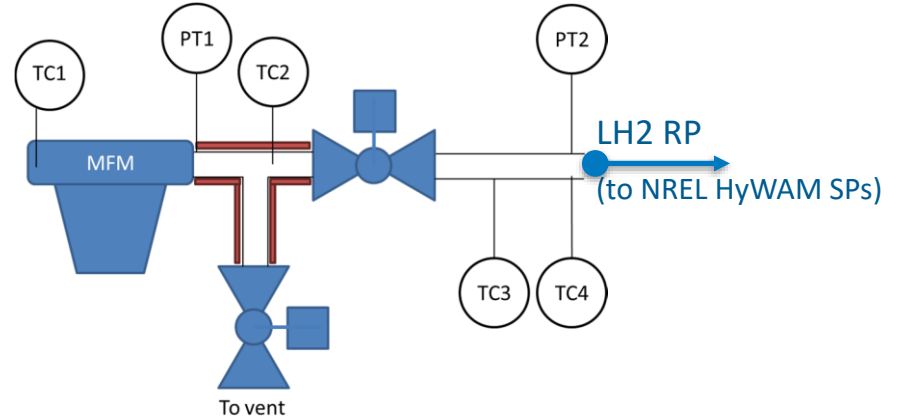


Image adapted from HSE Report, PRESLHY deliverable D3.6



The HSE LH2 Release Apparatus and RP details

- HSE LH2 release apparatus mounted in center of cement pad (32 m diameter)
 - Includes near field and far field wind direction and speed sensors (within green circles)
- Operations room behind barrier wall for experiment control and operations
 - LH2 release apparatus controls test parameters and duration
- Horizontal releases in direction of the NREL HyWAM sensor sampling points
 - NREL Sensor modules installed behind barrier wall

HSE WP3 Releases

- 18 test conditions in 25 releases for WP3
- Controlled experimental parameters
 - Release direction (horizontal and vertical)
 - Release height and direction, orifice, pressure, & duration
- Other parameters (less controllable)
 - Wind speed & direction, ambient T & RH
 - LH2 availability
- Integration of the NREL HyWAM
 - 32 SPs—four 8-sensor modules to profile LH2 releases (near-field sensors)
 - Co-located with in-situ thermocouples (most SPs)
 - Proximal weather station, video

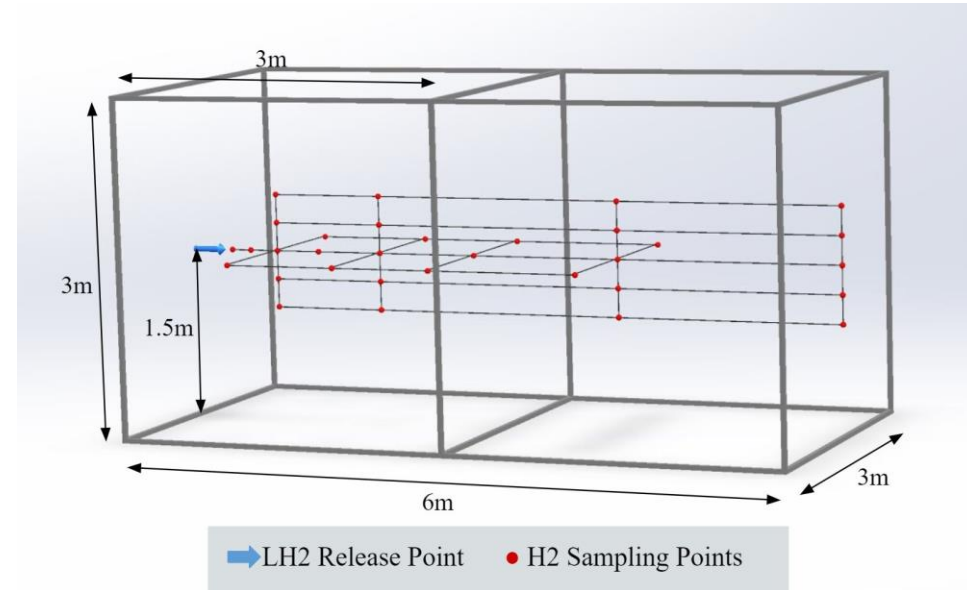
HSE LH2 Releases (PRESLHY WP3)

Adapted from Tables 2 and 3 of HSE Report, PRESLHY deliverable D3.6

Test No	Release Orientation	Release Height Above Ground (m)	Orifice Diameter (mm)	Pressure (barg)	Trial No
3.5.1	Horizontal	0.5	25.4	1	2, 3
3.5.2	Horizontal	0.5	12	1	4
3.5.3	Horizontal	0.5	6	1	1, 5
3.5.4	Horizontal	1.5	25.4	1	16, 19
3.5.5	Horizontal	1.5	12	1	17, 20
3.5.6	Horizontal	1.5	6	1	18, 21
3.5.7	Vertical Up	0.5	12	1	6
3.5.8	Vertical Down	0.5	12	1	7, 8
3.5.9	Horizontal + obstruction	0.5	12	1	9
3.5.10	Horizontal	0.5	25.4	5	10
3.5.11	Horizontal	0.5	12	5	11
3.5.12	Horizontal	0.5	6	5	12
3.5.13	Horizontal	1.5	25.4	5	22, 25
3.5.14	Horizontal	1.5	12	5	23
3.5.15	Horizontal	1.5	6	5	24
3.5.16	Vertical Up	0.5	12	5	14
3.5.17	Vertical Down	0.5	12	5	13
3.5.18	Horizontal + obstruction	0.5	12	5	15

NREL HyWAM Sampling Point Distribution

- Open Cage Structure with distributed SPs (downstream from RP)
- In-line with RP (horizontal releases)
- Vertical Profiling of hydrogen plume (above and below RP)
- Horizontal Profiling of hydrogen plume (left and right of RP)



Sampling Point (SP) Distribution from RP:

$$(SP)_i = 6/(1.5)^{i-1} \text{ for } i = 1 \text{ to } 8$$
$$\{0.35, 0.53, 0.79, 1.19, 1.78, 2.67, 4.00, 6.00 \text{ m}\}$$

NREL HyWAM

Integration into the LH2 Release apparatus

Image obtained from HSE Report, PRESLHY deliverable D3.6



HSE PRESLHY LH2 release directed through the NREL HyWAM support structure

- 32 SP with 24 co-located in-situ thermocouples

Image obtained from HSE Report, PRESLHY deliverable D3.6

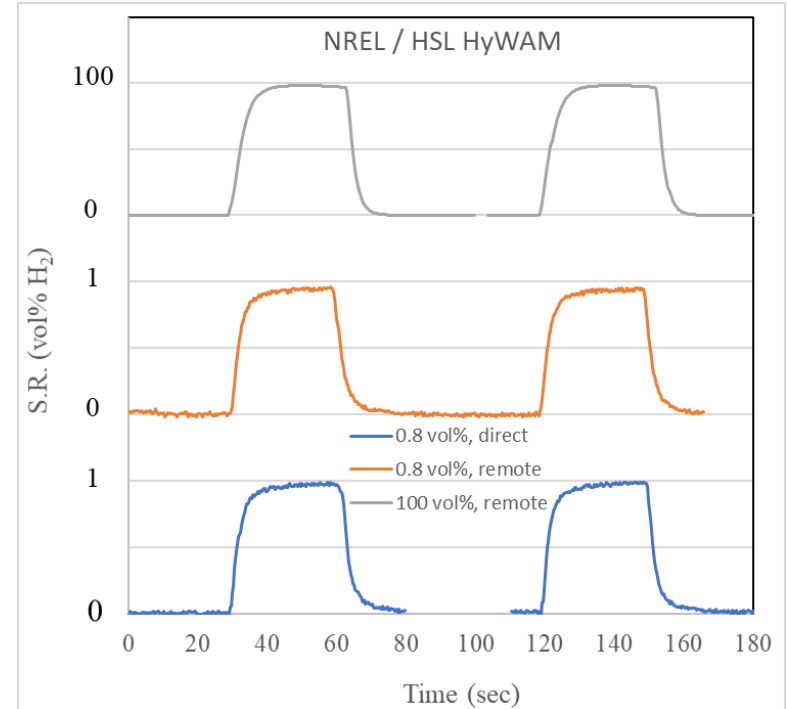


Four 8-Sensor HyWAM modules in “protective” enclosure behind barrier (sample lines are shown which will be interfaced to remote Sample Points)

NREL HyWAM

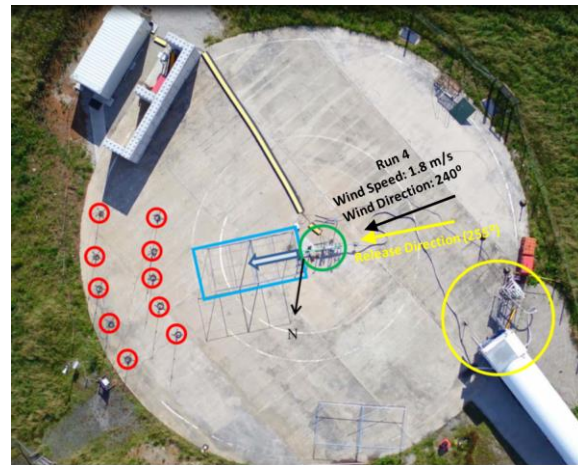
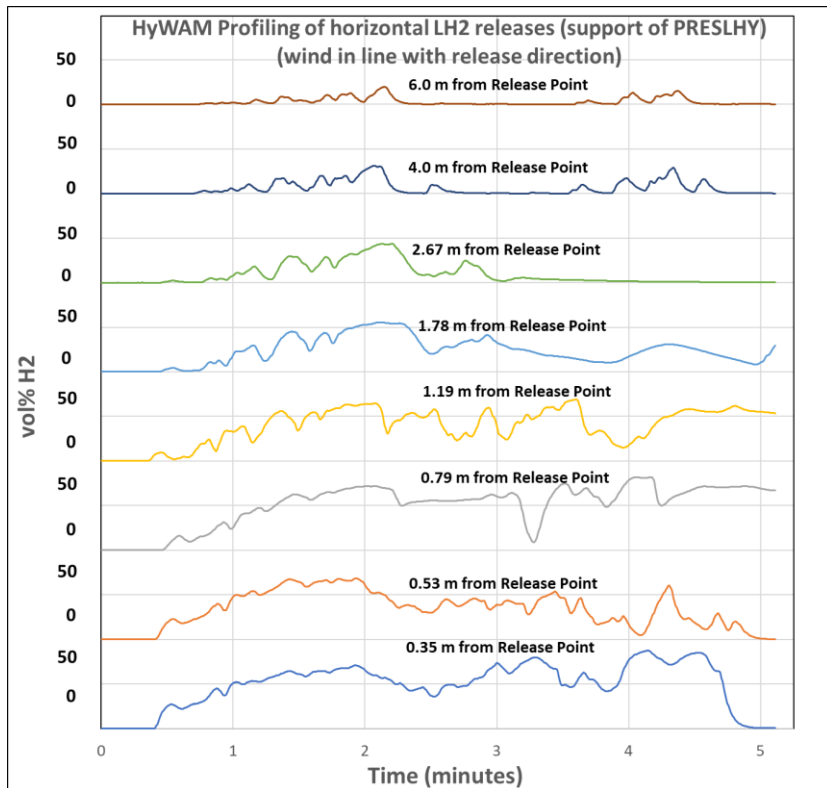
General Performance

- “Field calibration” of HyWAM sensors
 - Proximal and remote sample collection
 - 30 m pneumatic line connecting SP to hydrogen sensor
 - Near-linear response (with simple factory calibration expression)
- HyWAM operation
 - SP installed on remote support structure
 - H₂ sensor measurements logged every 300 ms
 - Other sensors (weather, thermocouples) logged every second).



- Proximal sampling vs. remote sampling
- Response to 0.8 vol% & 100 vol%

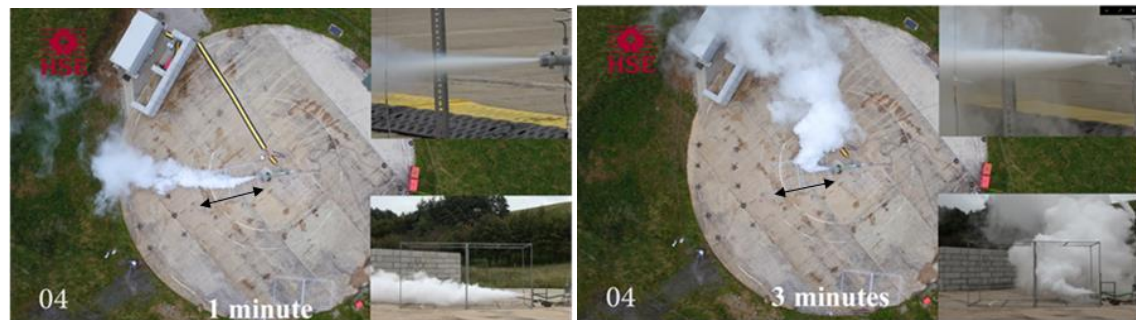
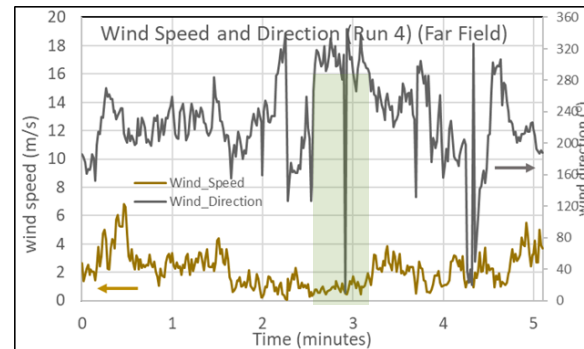
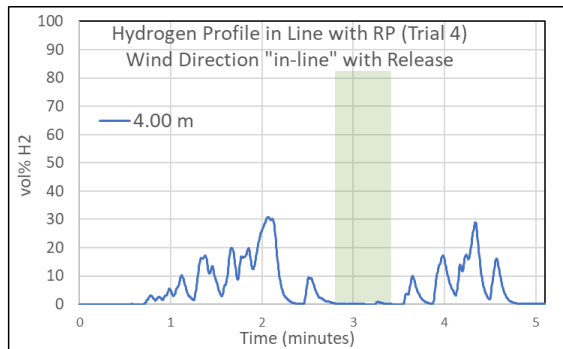
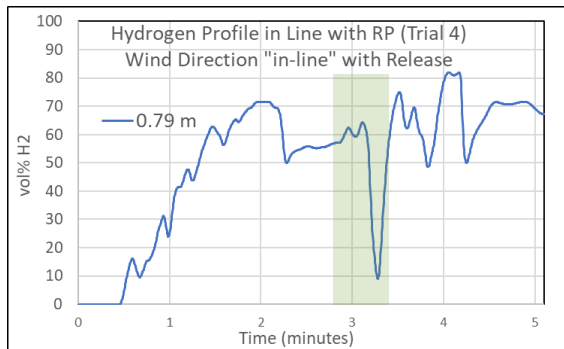
HyWAM H₂ Profiles downstream of RP (Run 4)



- 8 of 32 HyWAM SP, downstream from RP
- Near field wind direction in line with release (average: 240° and 1.8 m/s)
- Far field slightly different (average: 228° and 2.1 m/s)

HyWAM H₂ Profiles (Run 4)

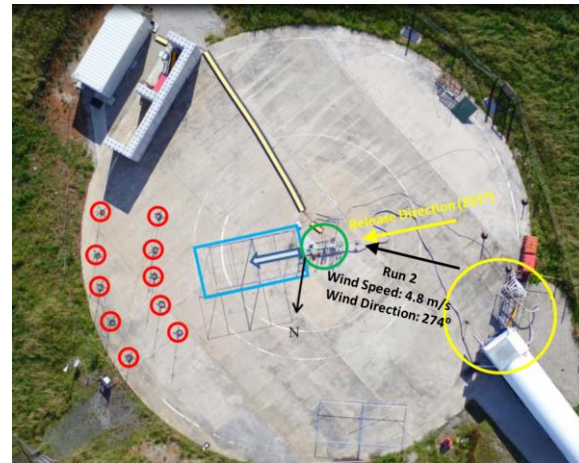
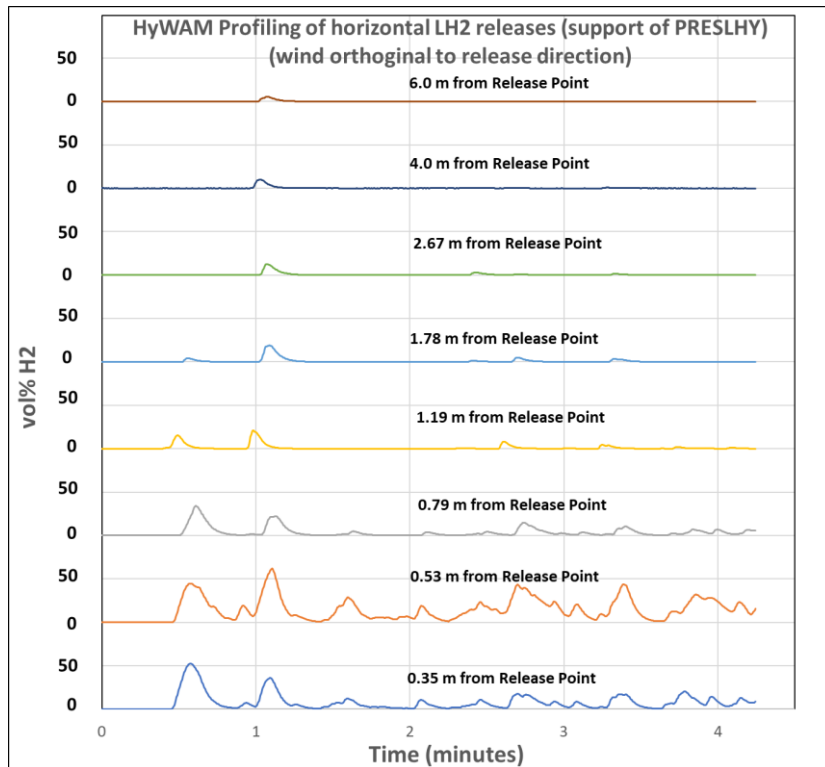
Cold Hydrogen Plume Dispersion—Correlation to Wind Parameters



- Far-Field weather station data (Run 4)
 - Wind direction is in line with release direction
 - Period of calm winds at 3 minutes
 - Vapor cloud becomes erratic and low vol% H₂ is observed

Screen shots of video (1 minute and 3 minute)

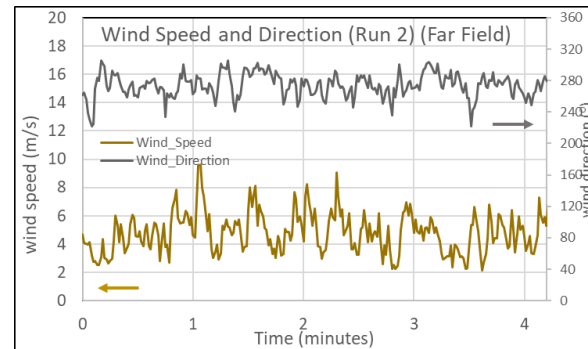
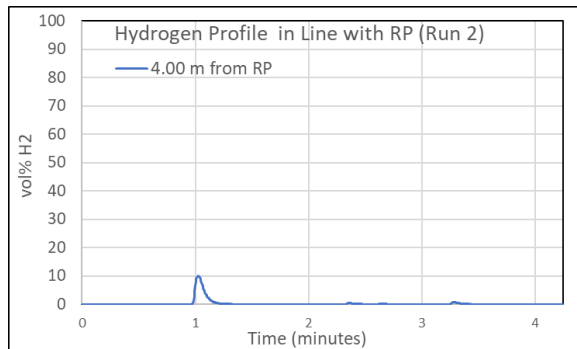
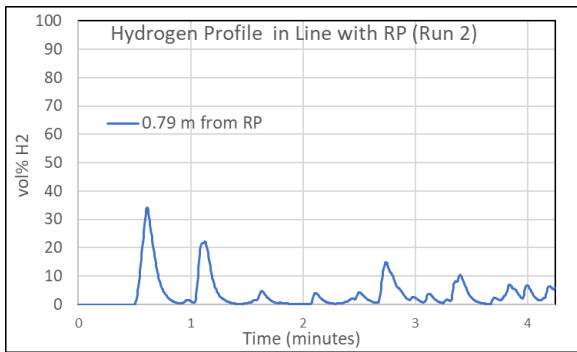
HyWAM H₂ Profiles downstream of RP (Run 2)



- 8 of 32 HyWAM SPs, downstream from RP
- Near field wind sensor was not installed for run 2
- Far field wind direction(average: 228° and 2.1 m/s)

HyWAM H₂ Profiles (Run 2)

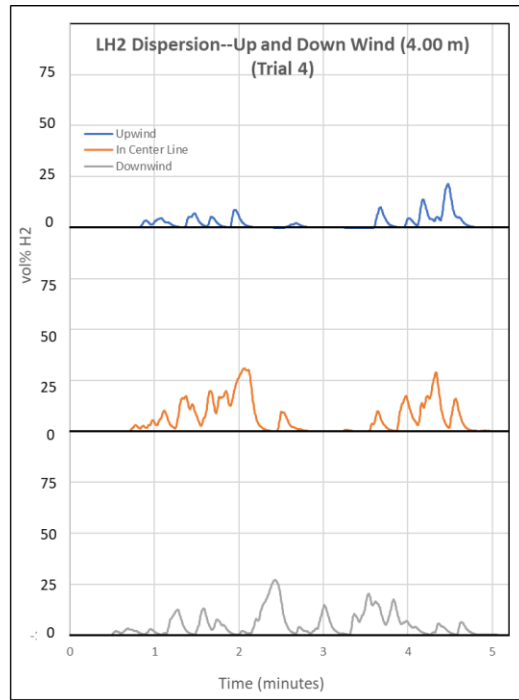
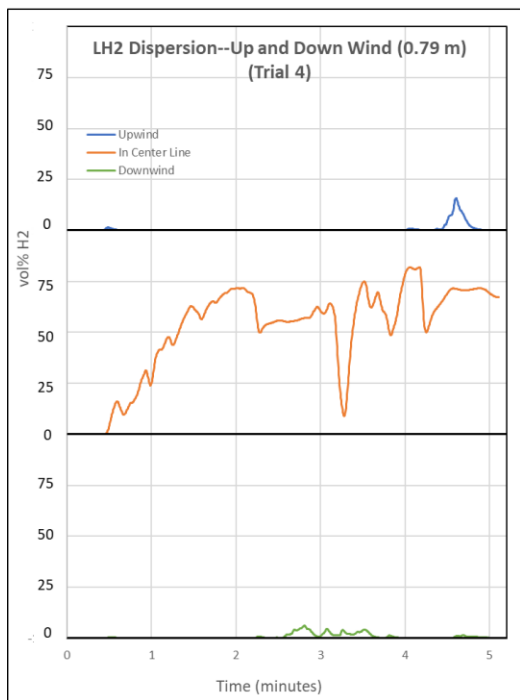
Cold Hydrogen Plume Dispersion—Correlation to Wind Parameters



- Far-Field weather station data (Run 2)
 - Wind direction is more orthogonal with release direction
 - Near Field weather station not installed
 - Variable hydrogen levels

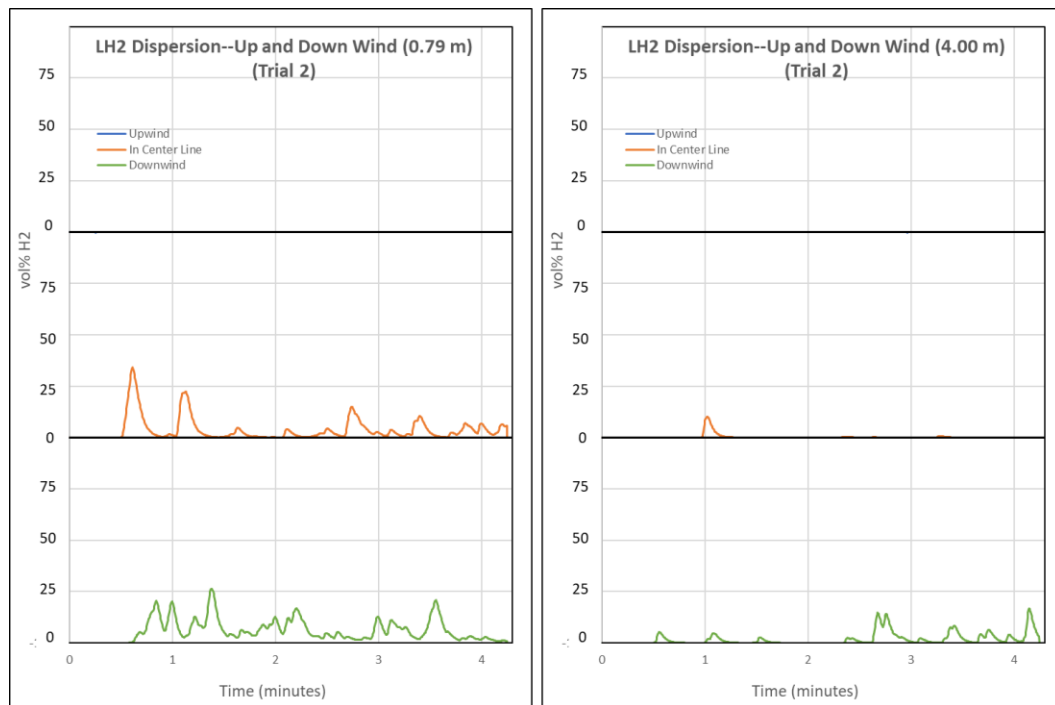
Screen shots of video (1 minute and 3 minute)

HyWAM Horizontal Profiling of H₂ (in-line wind direction)



- SPs distributed L and R of the RP
 - 4 SPs positioned 1 m left of RP
 - 4 SPs positioned 1 m right of RP (0.79 m, 1.78 m, 4.00 m & 6.00 m)
 - Release is momentum driven (low hydrogen levels L or R of RP for close SP positions)
 - “Symmetric” hydrogen levels for far SP positions)

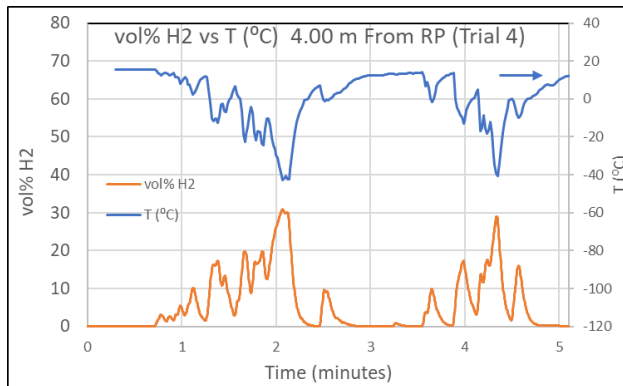
HyWAM Horizontal Profiling of H₂ ("orthogonal" wind direction)



- SPs distributed L and R of the RP
 - 4 SPs positioned 1 m left of RP
 - 4 SPs positioned 1 m right of RP (0.79 m, 1.78 m, 4.00 m & 6.00 m)
 - Release is affected by wind even for close downwind SP positions
 - Downwind SP has dominant H₂ level for far SP positions

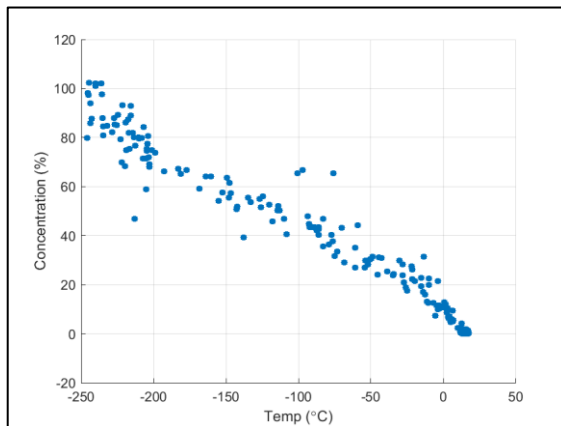
Plume Temperature Correlation to Hydrogen Concentration

Temporal correlation
for vol% H₂ and T



- Strong correlation between local plume T and vol% H₂ (for “near field” sensors—the NREL HyWAM)
- Supports adiabatic mixing assumption for H₂ concentration; quantitative correlation pending

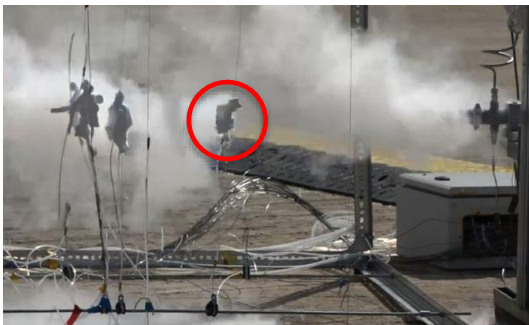
Empirical relationship
for maximum vol% H₂
and minimum T for
each SP in each run.



HyWAM Sample Inlets near RP (high LH2 release rates)

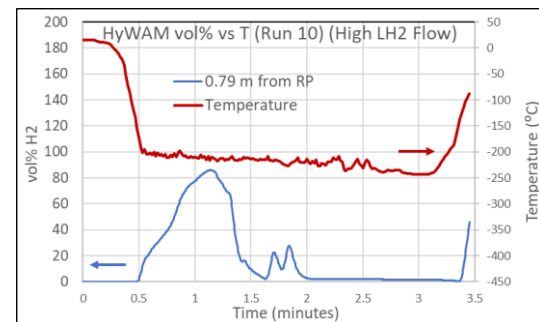
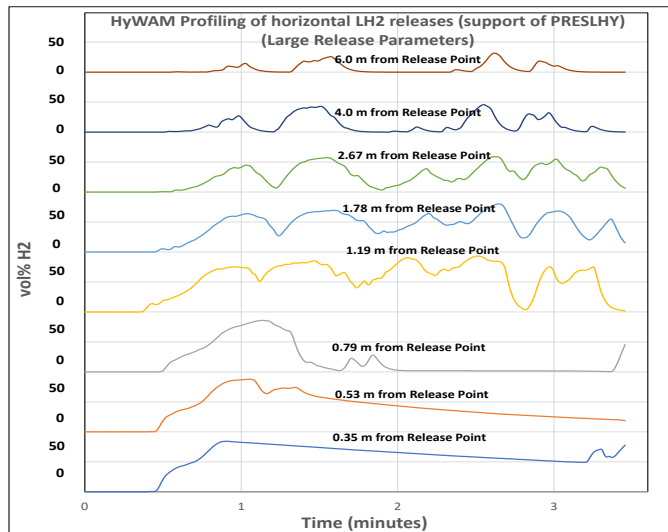


Prior to release

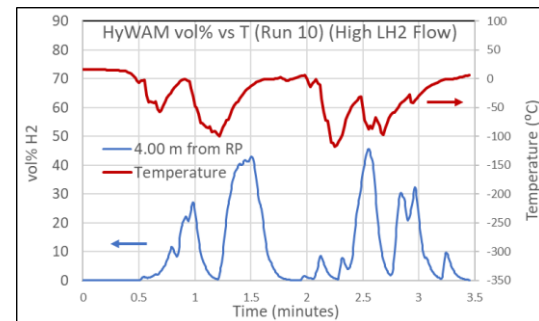


During release

- Icing at near SPs observed at high LH2 release rates.
 - Impacted HyWAM H₂ and T readings
 - Loss of correlation (hydrogen and T)
- May lead to blockage of gas intake
 - Impacted HyWAM H₂ and T readings
- Not observed for down-field SP.



SP near RP



SP away from RP

Summary

- The safe use of LH2 is critical for FCEV hydrogen infrastructure, but present setbacks are an impediment
- Validated dispersion models can support risk reduction strategies (integration into QRA) leading to lower setbacks and increased LH2 use in the consumer market
- The PRESLHY LH2 release activity (WP3, WP4, WP5) was aimed at the elucidation of LH2 release behavior
- NREL and HSE collaborated to profile the spatial & temporal dispersion of cold hydrogen releases
 - Ambient conditions (wind speed, direction) impacted dispersion
- The LH2 releases were performed for a specific set of controlled test parameters but uncontrolled weather conditions
 - NREL is to deploy HyWAM at commercial facility with regular LH2 deliveries (and release)
- NREL – HSE collaboration expanded to support other HSE hydrogen RD&D efforts (e.g., WP4 and WP5, HyDeploy and HyTUNNEL)
- HyWAM data is to be available at the PRESLHY repository

Conclusions

The deployment verified the viability of the NREL HyWAM and its potential as an active monitoring system. Operationally, several key findings can be made for the NREL HyWAM:

- The NREL HyWAM performed well throughout the release program and showed no signs of drift or temperature effects caused by the LH2. The use of pneumatic lines to collect samples from within the plume minimized the impact of the harsh conditions within the plume and simplified the deployment requirements associated with use of equipment in classified areas.
- The NREL HyWAM is simple to deploy and use (and was operated at HSE without on-site NREL Support)
- The open frame support structure performed well and supported both the HyWAM sampling points and co-located thermocouples, at least for horizontal releases. The open frame support structure did not appear to interfere with the hydrogen dispersion.
- The closest sample points did suffer from 'icing' for some of the tests. An attenuation of the hydrogen concentration was also observed after icing (due to a physical blockage)
- The NREL HyWAM sensors and mode of operation seem to be a very viable method of measuring distributed point concentrations of H₂ clouds from an LH2 release.
- It is envisioned that the NREL HyWAM will be the basis for a commercial instrument to support active monitoring at hydrogen facilities.

On-going Effort

- Updated Sensor modules for the NREL HyWAM
 - Thermo-conductivity H₂ sensors, manifold configuration
 - Mounted in robust environmental protective housings
 - Analog output for sensor(and calibration function)
 - Integrated to PLC computer
- Improved pump-pneumatic line compatibility
- On-going deployment within NREL ESIF (GH2)
- Planned deployment as a continuous facility monitor within commercial LH2 facilities



8-Sensor HyWAM module in an environmentally robust enclosure (2021)

Future Direction

Advanced Technologies for H₂ Detection

Schlieren and Shadowgraph Imaging

Fiber Optic Sensing

Ultrasonic Leak Detection

Raman Sensing



Photo by John Adams on Unsplash

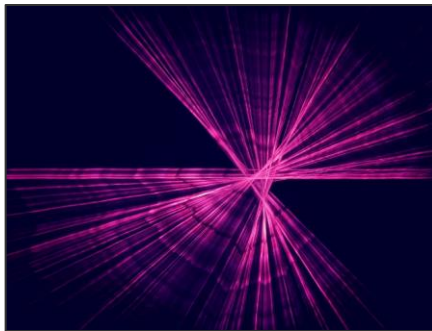


Photo by Erfan Afshari on Unsplash



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The NREL Sensor Laboratory has on-going or pending projects for the
Next Generation Hydrogen Detection Technologies

Acknowledgements

- The NREL HyWAM development and deployment was supported by DOE-EERE Hydrogen and Fuel Cell Technologies Office, SCS Sub-Program (Laura Hill, Program Manager).
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The HSE-NREL Team at HSL
(March 25-28, 2019)

HSE PRESLHY Releases:
September – December 2019
(HyWAM operated without “experts”)

QUESTIONS?