HYDROGEN WIDE AREA MONITORING OF LH_2 RELEASES

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ABSTRACT

The characterization of liquid hydrogen (LH_2) releases has been identified as an international research priority in order to expand the safe use of hydrogen as an energy carrier [1]. The elucidation of LH_2 release behavior will require the development of dispersion and other models, guided and validated by empirical field measurements such as those afforded by Hydrogen Wide Area Monitoring (HyWAM). HyWAM can be defined as the quantitative spatial and temporal three-dimensional monitoring of planned or unintentional hydrogen releases. HyWAM strategies are being investigated based on both stand-off methods (e.g., Raman or Schlieren) or by an array of point sensors. The Sensor Laboratory at the National Renewable Sensor Laboratory (NREL) has developed a HyWAM system based upon a distributed array of point sensors. Although various HyWAM strategies have been proposed, the NREL HyWAM has been field demonstrated in real-world indoor and outdoor scenarios, including a release at an LH2 facility [2], and is currently ready for deployment with minimal set up development. The Health and Safety Laboratory (HSL) in the United Kingdom is setting up a series of LH_2 releases to characterize the dispersion and pooling behavior of cold hydrogen releases with support provided through the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) *Prenormative Research for Safe Use of Liquid Hydrogen* (PRESLHY) project [1]. The NREL Sensor Laboratory and HSL have formally committed to collaborate on profiling the LH_2 releases. This collaboration will integrate the NREL HyWAM into the HSL LH_2 release hardware. A test plan that supports the planned LH_2 releases is being developed. The NREL Sensor Laboratory will provide HyWAM modules that will accommodate 32 measurement points for deployment during the HSL PRESLHY LH_2 releases. The HSL LH_2 releases were scheduled to initiate in the late spring of 2019, but for logistical reasons the release study was rescheduled until early September. The NREL HyWAM will be utilized throughout the current LH_2 release study being performed by HSL under PRESLHY, including Work Package 3 (WP3—Release and Mixing) and subsequent work packages (WP4—Ignition and WP5—Combustion). Under the auspices of the PRESLHY WP6 (Implementation) data and findings from the HSL LH_2 releases will be made available to stakeholders in the hydrogen community. The integration of the NREL HyWAM into the HSL LH_2 release apparatus and its performance as well as some key outcomes of the LH_2 release will be discussed in this paper and the corresponding talk at the 2019 International Conference on Hydrogen Safety (ICHS). This is a work in progress, and the actual releases associated with WP3, WP4 and WP5 are currently scheduled to initiate in September 2019, and thus much of the research activity will be after the submission date for this conference paper for ICHS. The presentation at the ICHS will however include some critical outcomes of the LH_2 cold plume behavior, as measured by HyWAM. A comprehensive summary of the HSL LH2 Release study will be presented as a series of reports that are to be prepared made available under the PRESLHY project.

1.0 BACKGROUND

The use of hydrogen as an energy carrier will continue to increase as commercial light duty fuel cell electric vehicles (FCEVs) are released into the consumer market. Infrastructure requirements for FCEVs include the need for increased hydrogen production capacity, transport systems, and storage facilities to support a network of fueling stations that can accommodate the commercial sale of hydrogen for FCEVs.

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It has already been demonstrated that on-site high-pressure gaseous hydrogen (GH_2) storage will often not have the capacity to meet current consumer needs. Liquid hydrogen (LH_2) at 20.4 K (-252.75 ˚C) has a density of 70.8 kg/m^3 [3] that is nearly 10 times that of gaseous hydrogen (GH_2) at 10 MPa, and thus is viewed as a means to assure an adequate hydrogen supply at commercial stations for the light duty FCEV fueling market. Hydrogen storage capacity requirements would be even greater for fueling stations servicing heavy duty FCEVs (e.g., long haul trucks) that are currently under development (e.g., [4], [5]). LH_2 transport and on-site storage are already routinely and safely used in numerous large-scale industrial operations, such as in the aerospace industry, for hydrogen power forklifts, and in various manufacturing processes. To date LH_2 storage has been predominately within industrial facilities, which, from a safety perspective, are characterized by two main features--limited public access and a large physical area that can conveniently comply with setback distances as prescribed by national or local regulations. Commercial fueling facilities present unique challenges for LH_2 storage because of increased public exposure within a facility that is often already space limited. One critical design parameter for the assurance of safety in LH_2 systems is the setback distances which are imposed by national or local regulatory agencies. For example, within the United States , National Fire Protection Association Standard 2 (NFPA 2) [6] and the International Fire Code (IFC) [7], which references NFPA 2, provide the regulatory framework for the safe use of hydrogen. When adopted by a local jurisdiction the requirements prescribed within these two documents are legally enforceable.

The behavior of cold hydrogen plumes is still incompletely characterized which has led to misperceptions. For example, it was viewed by some hydrogen safety experts that buoyancy would sufficiently dominate the dispersion of cold hydrogen releases to preclude potentially hazardous levels of hydrogen below the release point. This will not always be the case, as demonstrated during a recent field deployment of the NREL hydrogen wide area monitor (HyWAM)[2] in which vol% levels of hydrogen were observed several meters below the release point [2]. The impact of factors such as wind speed and direction, ambient temperature, release rate and direction on cold hydrogen plumes dispersions are not yet fully elucidated. Owing to a lack of empirical data and theoretical understanding of cold hydrogen plume behavior, the regulatory setbacks established for LH_2 storage tend to be overly conservative. NFPA 2 prescribes a radial line-of-site distance of 75 feet to any structure or facility border from a LH_2 system. Comparable restrictive setbacks have been established by other national regulatory agencies. The lot size for fueling stations in urban environments will frequently not be able to accommodate the prescribed setbacks, and thus may preclude LH_2 storage in markets likely to have the largest fleet of FCEVs. NFPA 2 allows lowering the setback distance requirement through the implementation of mitigation strategies that can be shown to decrease the hazards associated with LH_2 storage and use. Such strategies are being explored, including research programs aimed at improved understanding of LH_2 behavior.

The characterization of LH_2 releases has been identified as a national and international research priority to facilitate the expanded use of hydrogen as an energy carrier. The Fuel Cell and Hydrogen Joint Undertaking (FCH JU) of the European Commission recently initiated the *Prenormative Research for Safe Use of Liquid Hydrogen* (PRESLHY) project [1], which is jointly funded by the European Commission and private industry. PRESLHY is comprised of several Work Packages (WP). The Health and Safety Laboratory (HSL) is a key consortium member of PRESLHY. HSL is part of the Health and Safety Executive (HSE), responsible for regulating and enforcing workplace health and safety in the United Kingdom [8]. HSL will be active in numerous PRESLHY work packages, including WP3 (Release and Mixing) [9], WP4 (Ignition) [10], and WP5 (Combustion) [11], as well as WP6 (Implementation) [12]. One function of WP6 is to assure proper dissemination of test results and data to the hydrogen energy community to allow modelers and other stakeholders in the hydrogen energy community access to data to validate cold hydrogen behavior and dispersion models. WP3, WP4, and

[2] Hydrogen wide area monitoring (HyWAM) can be defined as the quantitative spatial and temporal three-dimensional monitoring of planned or unintentional hydrogen releases.

WP5 involve actual LH_2 releases and their characterization. Empirical field data on hydrogen plume dispersions following releases, such as that afforded by HyWAM, will support the validation of dispersion and other behavior models associated with cold hydrogen plumes. Various hydrogen profiling approaches have been proposed [13], and may be based upon stand-off strategies, such as Raman [14] or Schlieren [15], or through a distributed network of point sensors, including the NREL HyWAM. Of these options, the NREL HyWAM has been field demonstrated in real-world scenarios, including a deployment at an industrial LH2 facility [2] and is currently ready for additional deployments with minimal set up development. The HSL PRESLHY release studies provide an opportunity to obtain empirical field measurements of real-world cold hydrogen plume dispersion. HSL has a history of investigating the behavior of cold hydrogen releases (e.g., [16] [17] [18]) and the NREL Sensor Laboratory has extensive experience in gas measurements and has developed a HyWAM to support such activity [19], including the profiling of cold hydrogen plumes [2]. One outcome of the recent HySafe Safety Research Priorities Workshop held at HSL in September 2018 [20], was a commitment between the NREL Sensor Laboratory and HSL to collaborate on the pending HSL PRESLHY LH_2 releases. This collaboration was recently formalized [21].

The integration of the NREL HyWAM into the HSL LH_2 Release Apparatus and its performance as well as some key outcomes of the LH_2 release will be discussed in this paper and the corresponding talk at the 2019 International Conference on Hydrogen Safety. This is a work in progress, and the actual releases associated with WP3, WP4 and WP5 are now scheduled to initiate in September 2019, and thus much of the research activity will be after the submission date for this conference paper for the International Conference on Hydrogen Safety (ICHS). The presentation at the ICHS will however include some critical outcomes of the LH_2 cold plume behavior, as measured by HyWAM. A complete analysis of the HSL PRSHLY LH_2 releases will be made available under the PRESLHY project.

2.0 APPROACH

2.1 HSL LH_2 Release Apparatus

The HSL PRESLHY LH_2 release apparatus is being assembled analogous to a system deployed in earlier HSL projects and previously described [17]. The location of the LH_2 release apparatus is in the Frith Valley site within the HSL Buxton facility. The test site consists of a 32 m diameter concrete pad, which is shown in Figure 1. Recent facility upgrades include the construction of fenced enclosure for site safety and security, the construction of a control building approximately 2 m outside the concrete pad perimeter, and a barrier wall approximately 2 m high by 6 m long between the control building and concrete pad. The barrier wall is positioned parallel to and about 1.5 m in front of the control building. In addition, an open-frame support structure was installed just in front of the LH_2 release point to accommodate the 3-dimensional placement of thermocouples and gas monitoring points immediately downstream from the point of LH_2 release. The LH_2 release will be near the center of concrete pad.

The HSL LH_2 release hardware consists of two main subsystems—the LH_2 delivery system, which includes the LH_2 tanker truck and pneumatic interfaces to the LH_2 release system, which is the second main subsystem for the HSL LH_2 release apparatus. An illustration of the LH_2 Release apparatus is shown in Figure 2, which was adapted from a document reviewing the HSL WP3 test plan [22].

Figure 1: (Left) Aerial view of the test site for the HSL LH_2 release study. (Right) Release station with mass flow meter. For the LH_2 PRESLHY releases, the test site has been updated with an operations building positioned just off the pad and protected by a barrier wall between the pad and control building. Another upgrade has been a frame support structure designed to accommodate gas sampling points for the NREL HyWAM.

The HSL LH_2 release system has been instrumented with an array of internal sensors and control elements mounted prior to the point of release, including multiple pressure sensors (used to estimate flow), a Coriolis flow meter, a control valve to start and stop LH_2 releases, and multiple thermocouples to measure fluid temperature at and upstream from the point of release. Other operational and safety features of the LH_2 releases apparatus as described in a report [17] for earlier HSL LH_2 releases include:

- A 20-meter-long, 1-inch diameter vacuum jacket transfer line connecting the LH_2 tanker to the HSL LH_2 release system.
- A liquid by-pass to vent
- Nitrogen and hydrogen packs for system purge and tanker operation
- Local instrument cabinet for signal processing, data logging, and control functions
- Remote control room instrumented with video display of release area and network control system
- 6 m vent stack to vent excess hydrogen

In addition to internal sensors and control elements, a variety of detectors and monitors are to be installed external to the HSL LH_2 release apparatus to profile the hydrogen plume and environmental parameters during the release. These include sensors for hydrogen, temperature sensors, and weather stations for wind speed and direction measurements. The incorporation of hydrogen sensors, including the NREL HyWAM is a recently implemented feature of the HSL LH_2 release apparatus. An open-frame support structure was designed explicitly to support the NREL HyWAM hydrogen measurement points and other sensor types (e.g., thermocouples) without interfering with the cold hydrogen plume dispersion. The HSL LH_2 release system also includes monitors a control system, and data acquisition system. Details on the NREL HyWAM as deployed within the HSL LH_2 release apparatus is presented in section 2.2.

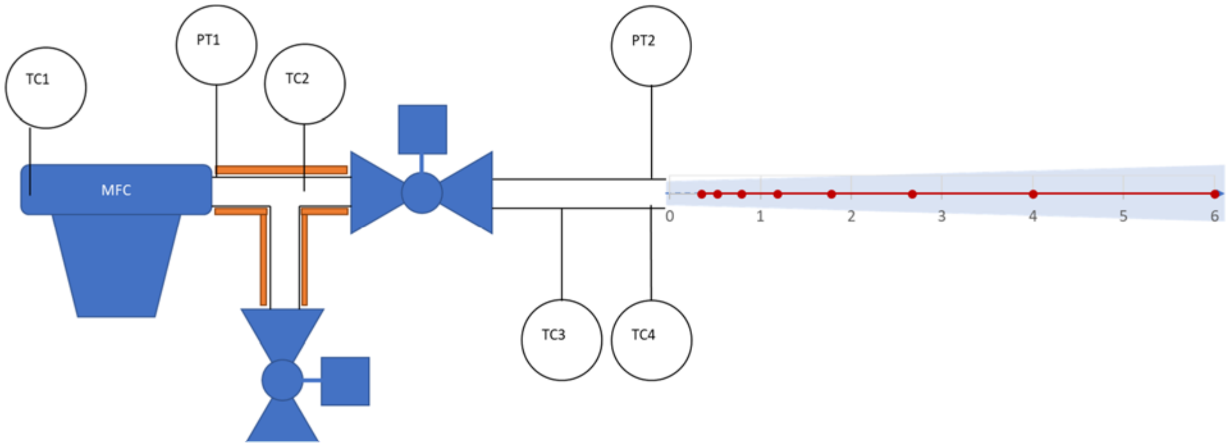

Figure 2: Illustration of the HSL LH2 Release Apparatus along with a proposed Sample Point distribution for the NREL HyWAM in line with the horizontal LH2 release (8 of 32 points).

2.2 Hydrogen Wide Area Monitoring of the Cold Hydrogen Plume

2.2.1 Overview of the NREL HyWAM

The NREL HyWAM is based upon an array of hydrogen sensors distributed around a hydrogen facility [19]. Other sensor types may be included in HyWAM, including other chemical sensor types (e.g., oxygen), physical sensors (e.g., T, P, RH, heat flux) and weather sensors (e.g., wind speed and direction). Although sensors can be mounted directly within the plume for in-situ measurements, the NREL HyWAM is presently configured to continuously collect and transport gas samples to remote hydrogen sensors using pneumatic lines and gas pumps. This approach provides real-time spatial and temporal profiling of the hydrogen plume, while accommodating site safety requirements pertaining to the use of electrical equipment within exclusion zones while at the same time allowing flexibility in positioning of the gas measurement points. In this operation mode a *sampling point* is defined by the location of the inlet of the pneumatic tube within the plume. Conversely, sensors for physical parameters, such as ambient temperature, will be mounted directly in the plume for in-situ measurements. Although this study is focusing on outdoor releases of LH_2, the NREL HyWAM has been used for characterizing indoor GH_2 releases in order to optimize sensor placement for improved safety [23]. For the HSL PRESLHY LH_2 releases the NREL HyWAM will consist of a custom-built support structure to accommodate an array of precisely positioned sampling points. Each sample point consists of a pneumatic line connected to a hydrogen sensor. Most sampling points will be co-located with thermocouples for simultaneous hydrogen and temperature profiling of the cold hydrogen plume.

The NREL HyWAM primarily uses hydrogen thermo-conductivity sensors (Xensor model XEN-TCG-3880), although other hydrogen sensors are under consideration and will be deployed during the HSL LH_2 releases. The selection of the hydrogen sensor is critical for proper profiling of hydrogen plumes. A thermo-conductivity sensor was selected because of its metrological properties:

- Broad, nearly linear measurement range (from 0 to 100 vol% H_2)
- Good detection limits (ca. 0.1 vol% H_2)
- Fast response and recovery times ($t_{90} < 250$ ms)
- No hysteresis (even when exposed to 100% vol% H_2)
- Good selectivity

  - The sensor responds to helium, which is useful for modelling studies. However, it is unlikely that helium will be encountered in hydrogen operations. Generally, the thermo-conductivity hydrogen sensor exhibits low sensitivity to other gases
- Compensated to minimize thermal and humidity interference with on-board T and RH sensing elements
- Commercially available at a moderate cost
- Convenient output signal format (analog, USB, and CAN). The USB configuration was chosen for use at the HSL LH_2 release. The default logging rate is one measurement every 300 ms.
- Factory calibrated
  - Signal output (data file) calibrated to vol% H_2 or ppm_v H_2.
  - The factory calibration has shown good accuracy to hydrogen levels

For HyWAM applications, the sensor is mounted in a custom-designed hermetically sealed housing (see Figure 3, right). This housing was fabricated out of Delrin® and allows for leak-free gas flow into and out of the sensor chamber for the continuous refreshing of the gas exposed to the sensor. A low-volume sensor chamber allows for fast purging, thereby minimizing any impacts of pneumatic purge time on the signal.

Figure 3: (Left) The commercial thermo-conductivity hydrogen sensor selected for use in the NREL HyWAM. (Right) A low-volume, custom built hermetically-sealed housing that includes a gas tight electrical feedthrough for the sensor USB communication line. Gas flow into and out of the sensor housing is accommodated with two gas-tight fittings for 1/4 inch (outlet) and 1/8 inch (inlet) tubing.

2.2 Deployment of the NREL HyWAM for the HSL LH_2 Releases

The NREL Sensor Laboratory assembled four 8-sensor HyWAM Modules (identified as Modules I, II, III, and IV) to provide for a 32-point HyWAM for the HSL LH_2 releases. With a range of up to 100 vol% H_2, these sensors are to be deployed immediately downstream from the LH_2 release point. A sampling point is defined by the position of the pneumatic tube inlet that collects gas from within the plume for transport to the remote sensors. Positioning the pneumatic lines is accomplished using the open-frame support structure shown in Figure 4. The open frame support structure included crosspieces at the base and top which serve to provide both stability as well as to accommodate vertical droplines running from the top to the base. The sampling point tubes and other sensors, such as the co-located thermocouples, are to be secured to the vertical droplines using adhesive strips. Precisely positioning the pneumatic tube inlets on the vertical droplines, which were themselves precisely positioned within the support structure define the sampling point positions. The support structure was designed such that the position of the cross pieces can be easily adjusted so as to allow repositioning of sample points closer or further from the LH_2 point of release. This adjustment can be conveniently performed prior to testing or even between runs. A distribution pattern for sampling points was jointly developed by NREL and HSL. For Module I, the sampling points associated with each of the 8 sensors are to be distributed up to 6 meters along a horizontal line from the point of release. This distribution pattern was based upon a geometric scaling that provides for a higher horizontal density distribution closer to the release point, as calculated from the following expression:

$$(\mathrm{S.P.})_i = 6/(1.5)^n \qquad \text{Eq. 1}$$

where n is an integer ranging from 0 to 7 and i is an integer ranging from 1 to 8, thus providing an 8-point horizontal sampling point $(\mathrm{S.P.})_i$ distribution with set points of 0.35 m, 0.53 m, 0.79 m, 1.19 m, 1.78 m, 2.67 m, 4.00 m, and 6.00 m (this is the sampling point distribution shown in Figure 2). This expanding distribution of sampling points is similar to the approach used in CFD modeling to systematically implement higher distribution densities of volume elements near a nozzle exit. In addition to a distribution in-line from the release point, the sampling point distribution includes points above, below, and to the “left” and “right” side of the release point. Table 1 and Figure 5 presents the 3-dimensional sample point distribution from the release point agreed upon by NREL and HSL Although buoyancy does not fully control hydrogen dispersion, it is a main factor for even cold plumes. Wind patterns and other environmental parameters will also likely affect the horizonal dispersion. The proposed vertical and horizonal sample point distribution pattern was developed to maximum collection of meaningful data before the hydrogen concentration disperses to insignificant levels and was based in part upon experience from earlier studies. The test apparatus was designed, however, to allow for facile adjustment of the sampling points, so that the vertical and horizontal sample point distribution can be modified based upon field observations and conditions. The basic features of this distribution pattern was presented to members of the PRESLHY consortium for comment [22], of which there were none. Thermo-couples will be co-located with most of the gas sampling points (see Section 2.2.2).

Table 1: Revised distribution of sampling points for HyWAM Modules I, II, III, and IV to be used at the start of the WP3 LH_2 releasees.

Centreline (Module I)			Below 1 (Module II)			Below 2 (Module II)			Left (Module III)			Right (Module III)			Above 1 (Module IV)			Above 2 (Module IV)		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
6.00	0	0	6.00	0	-0.25	6.00	0	-0.5							6.00	0	0.5	6.00	0	0.25
4.00	0	0	4.00	0	-0.25	4.00	0	-0.5	4.00	-1	0	4.00	1	0	4.00	0	0.5	4.00	0	0.25
2.67	0	0							2.67	-1	0	2.67	1	0		0	0.5			
1.78	0	0	1.78	0	-0.25	1.78	0	-0.5	1.78	-1	0	1.78	1	0	1.78	0	0.5	1.78	0	0.25
1.19	0	0																		
0.79	0	0	0.79	0	-0.25	0.79	0	-0.5	0.79	-1	0	0.79	1	0	0.79	0	0.5	0.79	0	0.25
0.53	0	0																		
0.35	0	0																		
8			4			4			4			4			4			4		

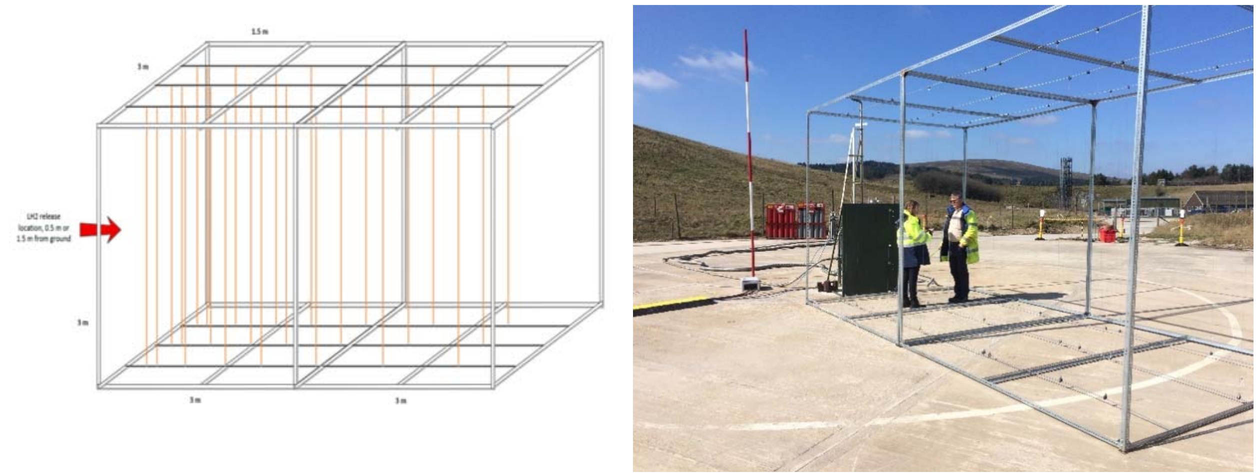

Figure 4: (Left) Open-frame support structure for the NREL HyWAM to support and position sensors and sampling points on vertical support droplines (orange lines). The frame is based upon slotted angle steel strip construction (Dexion). (Right) The fully assembled support structure (3 m by 3 m by 6 m) looking towards the release point (the release hardware is installed behind the green barrier).

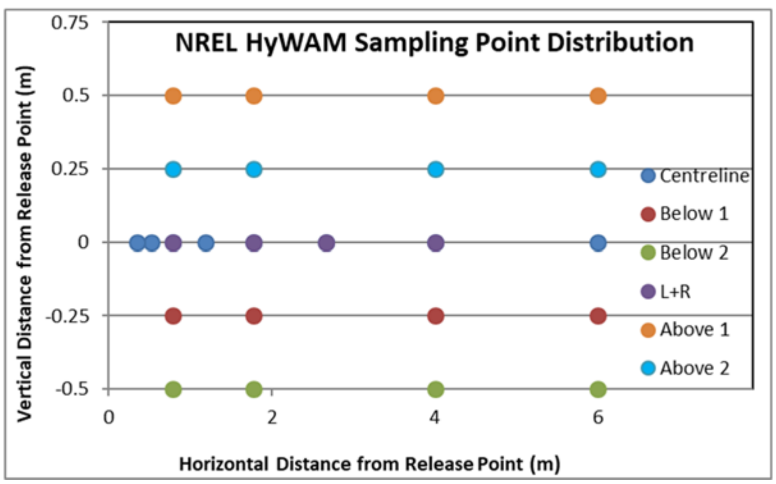

Figure 5: Consensus sample point distribution that is to be implemented for the NREL HyWAM Modules I through IV for the initial horizontal WP3 releases. The sample point distribution may be adjusted based upon field observations and conditions. Up to 32 thermocouples will be co-located with selected Gas Sampling Points.

2.2.2 Supplemental Sensors for the HSL HyWAM Deployment

In addition to the NREL HyWAM, HSL received multi-gas monitors (32 units) from Dräger (model X-am 5000), instrumented with three unique hydrogen sensing elements and an oxygen sensing element for ambient oxygen level measurements. The hydrogen sensing elements within each unit had a range of either up to 2000 ppm_v or up to 4 vol% (the lower flammable limit for hydrogen), depending upon sensing element type. These gas monitors are to be distributed around the perimeter of the concrete pad where hydrogen levels are expected to be low and will supplement the near-field measurements by the NREL HyWAM with "far-field" monitoring. The NREL HyWAM hydrogen sensors have a broader measurement range (0 to 100 vol% H_2) than the Dräger sensors (0 to ≤ 4 vol% H_2), and thus more amenable for use near the point of release.

Temperature measurements have been used to estimate hydrogen levels in cold hydrogen plumes based upon the adiabatic mixing assumption. This assumption will be tested. Thus, as a supplement to direct hydrogen measurements with the NREL HyWAM, up to 24 thermocouples (TC) will be installed on the support structure (there are 32 thermocouple readers, but several have been allocated to other functions within the HSL LH_2 release apparatus). It is proposed that these TC are to be co-located with gas collection lines associated with the HyWAM sampling points, or at least as many of the 32 sampling points as possible. Co-location will assure that the TC measure the temperature of the test gas that is collected at the sample point. To assure that the "co-location" is as close as possible to the gas collection line, a "Y" fitting will be used to mount the TC wire within the gas collection line of the Sample Point, such that the TC tip would stick out slightly from the "Y" fitting to minimize any potential distortion of the temperature measurement by the fitting itself. Referring to Figure 5, the proposed thermocouple distribution will be as follows:

8 TCs along the horizontal Centerline from the point of release	(● in Figure 5)
4 TCs along the horizontal Above 1 line above the point of release	(● in Figure 5)
2 TCs along the horizontal Above 2 line above the point of release	(● in Figure 5)
4 TCs along the horizontal Below 1 line below the point of release	(● in Figure 5)
2 TCs along the horizontal Below 2 line below the point of release	(● in Figure 5)
2 TCs along the horizontal Left line level to the point of release	(● in Figure 5)
2 TCs along the horizontal Right line to the point of release	(● in Figure 5)

3.0 Installation and Functional Demonstration of the HyWAM

The installation of the NREL HyWAM included both the physical mounting and operation of the system within the expected plume volume and the electronic integration of the sensors into the HSL computer system for electronic data file generation. Using the vendor supplied software, the HyWAM modules were successfully integrated into the HSL computer system. Sensor functionality was demonstrated by actual exposures to hydrogen-containing test gases. Figure 6 shows responses of Sensor 1 in Module I to test gas exposures ranging from 0.8 vol% H_2 to 100 vol% H_2. The data in Figure 6 demonstrates both the accuracy and precision of the sensor and gas collection system. The sensor response to two series of 0.8 vol% exposures and one exposure series to 100 vol% H_2 are shown. In one exposure series, a gas bag with the 0.8 vol% H_2 test gas was manually attached to pneumatic inlet of the sensor housing, while in the other exposure series, gas bag with the test gas was manually attached to the inlet of the 100-foot length pneumatic line connecting the sensor housing to the remote sample point on the support structure (the gas bag was attached for 30 s). With the exception of a time delay (about 10 s) for the gas transport through the sample line, the sensor signals to the two 0.8 vol% H_2 exposures were indistinguishable (a time correction was used to plot the data in Figure 6 to illustrate the nearly identical sensor responses). Also shown in Figure 6 is the scaled response of Sensor 1 to pure hydrogen (also through the pneumatic line). The results are consistent with earlier testing of the sensor with various concentrations of helium [24] that showed a near-linear response up to 100 vol% He and the manufacturer's specifications for a nearly linear hydrogen response from 0 to 100 vol% H_2.

Although originally scheduled for late May, the WP3 LH_2 releases are currently planned to start in September. Although a work in process, the HSL and NREL collaboration will nonetheless form the basis for a presentation and paper at the 2019 International Conference on Hydrogen Safety [28]. The NREL HyWAM will remain deployed within the HSL facility for the duration of the PRESLHY project, including the releases associated with WP3, WP4 and WP5. The test plan for each WP consists of multiple releases, including different release rates (controlled by orifice size) and orientation [22]. Although the plan details have been reviewed by PRESLHY partners, the actual test details that are performed may change, depending in part on the outcomes of the tests. The test plans for WP4 and WP5 and the role for the NREL HyWAM are still under development.

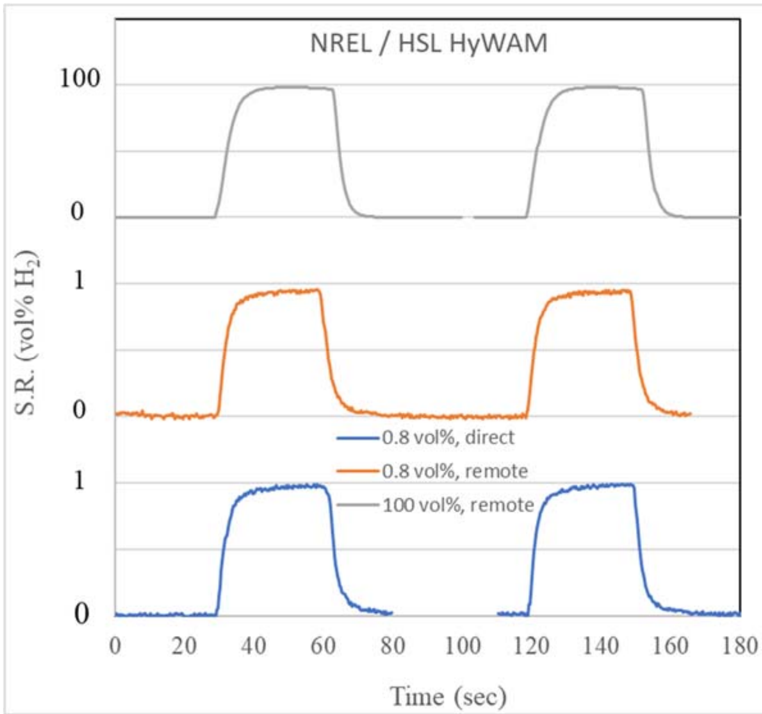

Figure 6: The sensor response (S.R.) to a series of 30-s hydrogen exposures. The sensor was exposed to 0.8 vol% H_2 directly at the sensor housing (—) and through the gas sample line (—). The sensor was also exposed to pure hydrogen (—); the results for pure hydrogen were scaled. There was a time delay of about 10 s for the transport of hydrogen through the pneumatic line, and thus a time correction was used to allow overlaying the data.

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