Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH2 Storage Vessels

Preprint

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Presented at the 7th International Conference on Hydrogen Safety (ICHS 2017)
Hamburg, Germany
September 11-13, 2017

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Conference Paper
NREL/CP-5400-68771
November 2017

Contract No. DE-AC36-08GO28308

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Empirical Profiling of Cold Hydrogen Plumes formed from Venting of LH_2 Storage Vessels

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ABSTRACT

Liquid hydrogen (LH_2) storage is a viable approach to assuring sufficient hydrogen capacity at commercial fuelling stations. Presently, LH_2 is produced at remote facilities and then transported to the end-use site by road vehicles (i.e., LH_2 tanker trucks). Venting of hydrogen to depressurize the transport storage tank is a routine part of the LH_2 delivery process. The behaviour of cold hydrogen plumes has not been well characterized because empirical field data are essentially non-existent. The National Fire Protection Association (NFPA) Standard 2 Hydrogen Storage Safety Task Group, which consists of hydrogen producers, safety experts, and computational fluid dynamics modellers, has identified the lack of understanding of hydrogen dispersion during LH_2 venting of storage vessels as a critical gap for establishing safety distances at LH_2 facilities, especially commercial hydrogen fuelling stations. To address this need, the National Renewable Energy Laboratory sensor laboratory, in collaboration with the NFPA 2 Safety Task Group, developed the Cold Hydrogen Plume Analyzer to empirically characterize the hydrogen plume formed during LH_2 storage tank venting. A prototype analyzer was developed and field deployed at an actual LH_2 venting operation. Critical findings included:

- Hydrogen (H_2) was detected as much as 2 m lower than the release point, which is not predicted by existing models.
- A small and inconsistent correlation was found between oxygen depletion and the hydrogen concentration.
- A negligible to non-existent correlation was found between in-situ temperature and the hydrogen concentration.

The analyzer is currently being upgraded for enhanced metrological capabilities, including improved real-time spatial and temporal profiling of the plume and tracking of prevailing weather conditions. Additional deployments are planned to monitor plume behaviour under different wind, humidity, and temperature

conditions. The data will be shared with the NFPA 2 Safety Task Group and ultimately will be used support theoretical models and code requirements prescribed in NFPA 2.

NOMENCLATURE

DAQ	data acquisition
FCEV	fuel cell electric vehicle
GH_2	gaseous hydrogen
H2	hydrogen
HyWAM	Hydrogen Wide Area Monitoring
IFC	International Fire Code
LFL	lower flammability limit
LH_2	liquid hydrogen
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
O_2	oxygen
RH	relative humidity
T	temperature
TC	thermal-conductivity

1.0 INTRODUCTION

1.1 Liquid Hydrogen Storage

The use of hydrogen as an alternative fuel is increasing. Hydrogen-powered fuel cell industrial trucks (e.g., forklifts) and stationary power systems for lighting and backup power are already commercially deployed. Increased use of hydrogen as an energy carrier is expected as hydrogen-powered fuel cell electric vehicles (FCEVs) are commercially released into the consumer market. Infrastructure requirements for FCEVs include increased hydrogen production capacity, transport, storage, and a system of commercial fueling stations to accommodate the commercial sale of hydrogen for FCEVs. There are different strategies for maintaining a hydrogen supply at commercial fueling stations, which include on-site production, pipeline delivery, and road delivery of hydrogen for on-site storage. Presently, on-site high-pressure storage of gaseous hydrogen (GH_2) has sufficient capacity to meet the market needs for FCEVs. However, as the FCEV fleet grows, the demand for hydrogen will increase. On-site storage in high-pressure tanks has limitations. In addition to the risks associated with high-pressure storage, GH_2 is characterized by a relatively low mass and energy density, even at high pressure. At 25°C, the density of GH_2 at 10 MPa is 7.67 kg/m^3, and at 5 MPa, the density is only 3.94 kg/m^3 [1]. Alternatively, liquid hydrogen (LH_2) has a mass density that is nearly 10 times that of GH_2 at 10 MPa (70.8 kg/m^3). Because of its higher density, LH_2 storage is viewed as a viable means to provide sufficient hydrogen for the consumer FCEV fueling market. LH_2 can be viewed as an efficient and economical alternative to GH_2 storage for operations that require a reliable supply of hydrogen at quantities in excess of what can be conveniently provided by high-pressure systems. Already fuel cell forklift operations typically use on-site LH_2 storage to assure a sufficient and cost-effective supply of fuel. LH_2 is routinely and safely used in numerous large-scale operations, which, in addition to forklifts, includes the aerospace industry [2] and various manufacturing applications. To date, LH_2 storage has been predominately within industrial facilities, which, from a safety perspective, are characterized by two main features, limited access by the general public and a large geometric area for easy compliance with setback distances. Commercial fueling facilities present unique challenges for LH_2 storage because of increased exposure to the general public within a facility that is often already space limited.

LH_2 is centrally produced at a remote facility and then transported, usually by road tanker vehicles, for on-site storage at or near the point of use. This often involves the transfer of LH_2 from the transport storage tank to a permanent fixed storage vessel, which is accomplished by pressurization of the transport tank. Upon completion of the transfer process, up to 50 kg hydrogen is vented to depressurize the transport tank (Figure 1). This routine and predictable release of hydrogen provide an opportunity to empirically assess the dispersion phenomena of cold hydrogen plumes under controlled temporal conditions. This approach was used to deploy in the field a hydrogen gas analyzer that was developed and used for one of the first empirical field measurements of LH_2 releases. This paper describes the development of the analyzer and the findings and significance of the initial field measurements. It is noted that alternative depressurization methods are being considered to minimize the amount of vented hydrogen.

Figure 1: LH_2 Venting

1.2 Requirements for Safe LH_2 Storage

Within the United States, National Fire Protection Association Standard 2 (NFPA 2) [3] and the International Fire Code (IFC) [4] provide the regulatory framework for the safe use of hydrogen. NFPA 2 provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH_2) form or cryogenic liquid (LH_2) form. When adopted by a local jurisdiction, the requirements prescribed within these two documents are legally enforceable. Although not universal, the majority of jurisdictions within the U.S. adopt the IFC, and since NFPA 2 is referenced by the IFC, the requirements of NFPA 2 are legally binding upon adoption of the IFC. One controlling factor safety is the setback distances for LH_2. Present setback requirements in NFPA 2 prescribed a radial line-of-site distance of 75 feet to any structure or facility border from an LH_2 system. In urban environments, the lot size for fueling stations is often restricted and thus may preclude LH_2 storage without implementing additional mitigation strategies to enhance site safety.

The NFPA 2 Hydrogen Storage Task Group, created in April 2014, was formed to explore approaches to mitigate the risks and hazards associated with LH_2 storage and utilization to facilitate its use in commercial applications. As part of its mission, the Task Group endeavored to understand the basis for the setback distances. The setback for LH_2 storage defined in NFPA 2 was based upon requirements set in earlier documents, the basis for which is presently unclear, but seems to have been more intuitive than scientific, and thus is not based on any quantified risk reductions. The Task Group is striving to understand the dispersion of LH_2 releases under various release scenarios. One scenario is the release of a significant amount of hydrogen that is vented from the fixed storage tank following LH_2 transfer from the cryogenic delivery tanker to the fixed storage tank. The amount of vented hydrogen has been estimated to be on the order of 50 kg. The hydrogen is typically vented through a vertical stack (approximately 10 m tall) on the stationary tank. As of the fall of 2015, the Task Group raised several questions regarding the hydrogen dispersion associated with this venting process (and other release scenarios), which include:

1. Will the hydrogen plume drop below the vent stack release point?

2. What will the cold hydrogen do to atmospheric gases (oxygen and nitrogen)?
3. Will the chilled air produced from contact with the cold hydrogen gas impact the hydrogen dispersion?
4. Will the hydrogen become entrained in any liquid oxygen or nitrogen produced from the cold hydrogen?
5. How significant is wind speed in impacting the hydrogen plume configuration?
6. Will there be significant ground-level hydrogen concentrations?
7. Can the dispersion model account for the actual physical phenomenon occurring during a hydrogen venting event?
8. Does the visible vapor correlate to hydrogen levels in the air?

The questions identified by the Task Group exemplify the sparsity of the available data on cold hydrogen releases. There was not a clear understanding of the fate of the released hydrogen, particularly with regards to the vertical profile of the hydrogen (e.g., if hydrogen could be observed below the point of release and if so, how close to ground level would detectable hydrogen be observed). It was unclear whether hydrogen buoyancy would be sufficient to preclude the presence of hydrogen below the release point. A sub-group of the NFPA 2 Hydrogen Storage Task Group was formed to address the questions identified above. The sub-group consists of a team of experts in the area of hydrogen measurements, hydrogen behavior and risks, LH_2 production and transport, on-site storage at a DOE and an industrial facility, safety experts in the hydrogen community, and the chair of NFPA 2. One strategy identified by the sub-group to address the questions listed above was to perform actual field measurements to spatially and temporally profile the hydrogen plume resulting from a LH_2 venting process. The following discussions present the development of the tools to perform these measurements and preliminary findings obtained from the field deployment of the National Renewable Laboratory's (NREL's) prototype Cold Hydrogen Plume Analyzer.

2.0 DESIGN FEATURES OF THE ANALYZER

At the request of the Sub-Group, the NREL Sensor Laboratory [5] was tasked with developing the analytical tools for the empirical profiling of actual cold hydrogen plume releases. It is noted that the design of a field-usable analyzer for the profiling of hydrogen plumes was guided by several constraints. As an exploratory research, development, and deployment effort with a limited budget, cost factors had to be considered. There were also metrological considerations. The physical profile of the hydrogen plume from a cold hydrogen release is poorly understood and without extensive documentation. Thus, there was little guidance with regard to the number and positions of measurement locations. Nor was there information on the likely H_2 concentration that could be encountered; obviously, pure H_2 is vented, but how it would mix with ambient air was unclear. Accordingly, there was a concern that the analyzer could be exposed to a high hydrogen concentration, if not pure hydrogen, even several horizontal feet from the release point. The potential for exposure to a high hydrogen concentration impacted both the selection of the sensor and the manner in which it was deployed. At the other extreme, a detection limit below 0.4 vol% H_2 was desired, because this concentration is 10% of the lower flammability limit (LFL) (4 vol%) and is often the required activation set point for a "warning" state in hydrogen operations. It was concluded that a flexible design for the analyzer needed to be developed that could be adapted and upgraded as more knowledge was obtained from field measurements. Remote detection methods, such as light detection and ranging (LIDAR) [6] and Schlieren [7] methods, have been reported for hydrogen, but are not noted for a good detection limit. These methods are also complicated to use and to validate. The use of lasers for probing, especially for LIDAR, also presents a major safety issue for the general use of these methods. These methods are also expensive, and thus unsuitable for routine deployment. Instead, the strategy employed for the analyzer was to use an array of robust, low-cost hydrogen sensors as the basis for the prototype Cold Hydrogen Plume Analyzer and to perform a screening measurement during an actual venting (depressurization) of a LH_2 storage tank. The term "prototype" is used to describe the Cold Hydrogen Plume Analyzer to emphasize that the design described herein and used in field studies was for demonstration and preliminary data purposes only, and that modifications would be incorporated to improve the overall performance. This approach was necessary because of the lack of data on the behavior of the hydrogen plume; hence, there was little or no guidance as to what to expect in the field on hydrogen levels or transients at or away from the point of release. The intent of the initial measurements was to gain a basic understanding of the plume behavior (locations) and not to attempt to validate any liquid dispersion model. A second goal of the initial field measurements was to assess performance of the analyzer to guide upgrades and modifications of the design to improve the quality and quantity of the data. The design of the prototype analyzer is presented below along with the results from the first deployment within a plume formed from the venting of a LH_2 storage tank. The significance of the field study is also presented along with upgrades that will significantly enhance the capability of the analyzer to profile hydrogen releases and to monitor for hydrogen over a wide area.

Figure 2: Support Structure for the Cold Hydrogen Plume Analyzer

The first version of the NREL Cold Hydrogen Plume Analyzer (e.g., the prototype) consists of two main subsystems—the Support Structure and the Analyzer Box, which were configured into an integrated, field-deployable package. Operationally, the Analyzer Box was designed to remotely analyze test gas samples automatically collected from multiple measurement points situated at discrete locations along the Support Structure.

2.1 Support Structure

The Support Structure was designed to be deployed directly within the hydrogen plume for vertical profiling. The prototype design can be deployed up to 35 feet (10.67 m) in height and accommodated ten measurement points distributed along a portion of the length of the Support Structure (typically from the top—35 feet and then down at 2-foot (0.61-m) intervals). These were numbered 1 through 10, with the lowest number referring to the highest position. The assembled Support Structure is shown in Figure 2 and was based upon a commercially available telescoping PVC pole for easy deployment in the field. Graduated markings on the pole allow for precise location of measurement points. Two strategies exist for performing the analysis at the designated measurement points:

1. Mounting of sensors directly on the pole for in-situ analysis
2. Installation of a pneumatic line to draw the gas sample from the measurement point to a remote sensor for analysis.

In-situ sensors (Option 1) have the advantage of operating the detector directly within the actual gas cloud, which can allow for faster analyses. However, remote detection through a pneumatic line has its own advantages, including minimization of fluctuation in environmental parameters (especially temperature), which can affect sensor accuracy and the operation of the electronic components (e.g., the sensors) remotely outside the restricted zone. This alleviates the need for listed (and expensive) components, simplified interfacing to a data acquisition (DAQ) system for logging of sensor response, and easier assembly of the support structure. Thus, Option 2, the use of a pneumatic line to draw gas samples to a remote sensor, was selected for the prototype Cold Hydrogen Plume Analyzer. There was one pneumatic line (made from 1/8-in. O.D., 1/16-in. I.D. polyethylene tubing) for each measurement point. During deployment, the Support Structure was stabilized by guy wires, a tripod support system, and a custom-designed base boot.

2.2 Analyzer Box

The Analyzer Box (Figure 3) contains the chemical and physical sensors for the multi-point (vertical) characterization of the plume. Using an internal, fast-responding ten-position multiport valve, a single set of gas sensors can analyze the gas collected from the ten measurement points on the Support Structure. The multi-port valve sequentially and automatically directed the gas samples drawn from each of the ten pneumatics lines to the oxygen (O_2) sensor and the thermal-conductivity (TC) H_2 sensor mounted in series for analysis in the Analyzer Box. The multiplexing of sample points to a single set of chemical sensor was implemented as a means to minimize cost and instrument complexity, while at the same time maintain a significant number of measurement points for proper characterization of the plume. Gas samples were collected with a gas pump mounted within the Analyzer Box. The gas sensor types and models, which are discussed below, were chosen because of their fast response time and robustness and having the required metrological range. Moreover, the NREL and Joint Research Centre sensor laboratories had evaluated the performance of the indicated gas sensors for other projects, and they were found to have, in general, very good performance characteristics compatible for this application. The following specific sensors were selected for use in the analyzer.

Figure 3: The Analyzer Box with (L to R) TC sensor (in a custom-built holder), pump, O_2 sensor, and valve.

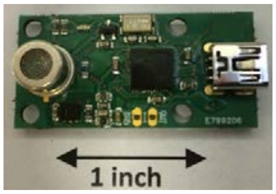


Figure 4: TC H_2 sensor

TC hydrogen sensor with integrated temperature (T) and relative humidity (RH) sensing element: There are numerous platforms for hydrogen sensors [8, 9]. The TC platform was selected for the Cold Hydrogen Plume Analyzer. Because this sensor type responds to changes in the physical environment (heat transfer) as opposed to a chemical interaction with hydrogen, it is noted for a fast response, including a quick recovery time from an exposure to pure hydrogen. Specifically, the Xensor Model XEN-5320 (Figure 4) was selected for the analyzer. It is a solid-state device that is commercially available in a miniaturized package for fast, robust operation. The selected sensor has a range of 0 to over 10 vol% H_2 with a response time (t_{90}) of approximately 250 ms [10], which thus allows the sensor to quantify fast hydrogen transients. The sensor is also available with a range of 0 to 100 vol% H_2, but this is achieved with a loss of resolution and accuracy at lower hydrogen concentrations. Presently, the 0 to 100 vol% H_2 range version of this sensor is not used in the NREL Cold Hydrogen Plume Analyzer, but may be considered for updated future designs if deemed necessary. The sensor we selected also has integrated T and RH sensing elements, which were used to measure the T and RH of the test gas as it is being analyzed.

Oxygen sensor: An electrochemical oxygen sensor was selected to monitor the concentration of oxygen in the test gas (Teledyne Model UFO-130-2G, see Figure 5). The model we selected has a response time (t_{90}) of less than 1 sec. The oxygen sensor provides an indication of oxygen displacement, and thus could also be related to the concentration of hydrogen. This method is not accurate at low hydrogen concentrations [11], but was considered to be used for hydrogen levels beyond the range of the TC H_2 sensor. Condensing of oxygen by the cold hydrogen release will affect the accuracy of this displacement approach to quantify high hydrogen levels. With a range of 0 to 100 vol%, the sensor could also identify oxygen enrichment due to the possible condensing of air by cryogenic hydrogen. Exposure of cryogenic hydrogen (LH_2: -253°C) to air has been reported to condense or even solidify nitrogen and oxygen components [12]. Oxygen enrichment of the condensed air may occur due to oxygen's higher boiling temperature (-182.6°C) than nitrogen (-196°C), a phenomenon that may increase flammability hazards.

Figure 5: O_2 sensor

Thermocouples with remote eight-channel logger: K-type thermocouples with a nominal temperature range of -200°C to 1,370°C were mounted directly on the Support Structure to measure *in-situ* the ambient temperature at the gas measurement points. An eight-channel logger (Omega Engineering, Inc., model TC-08) was used to acquire the temperature readings from the thermocouples and store the resulting measurements in an electronic data file for subsequent workup. The temperature measurements were collected at a frequency of 1 point/sec for each of the eight channels. The thermocouples were attached directly to the Support Structure at eight of the gas sampling measurement points and interfaced to the remote logger. Since the thermocouple logger accommodated eight channels, two out of the ten measurement points consisted only of a pneumatic line without temperature measurements. These two positions were identified as positions 9 and 10 and corresponded to the lowest positions on the Support Structure.

2.3 Integrated System

The prototype Cold Hydrogen Plume Analyzer was designed for easy on-site assembly and placement for field deployment. The integrated system refers to the Analyzer Box pneumatically interfaced to the Support Structure and then electronically to the computer DAQ and control system. Data collection of the sensor readings and control of the 10-position multiport valve were performed by a LabVIEW-based DAQ system operated by custom software developed specifically for the prototype NREL Cold Hydrogen Plume Analyzer. The DAQ system controlled the position of the multiport valve as well as recorded the temporal output signals of the TC H_2 Sensor, the O_2 sensor, including the T and RH sensing elements integrated into the TC sensor. The integrated T and RH sensing elements measure the test gas after it has been drawn from the plume though the pneumatic system, while the thermocouples measured the gas temperature at the measurement point. The DAQ logging rate for the TC hydrogen and oxygen sensors was 4 pts/sec (i.e., the sensor response was measured every 250 ms). The DAQ displayed in real time the hydrogen concentration from the TC sensor for each of the ten measurement points. At the same time, the thermocouples mounted on the Support Structure measured the temperature of the plume through a remotely deployed eight-channel thermocouple reader and data logger. The logged data were to be analyzed by spreadsheet software to provide temporal profiles for each of the ten gas sampling points, overlaid with temperature data from the eight thermocouples.

Operationally, the gas from one specific measurement point was sampled and analyzed by the sensors for a set period of time, typically 10 seconds, but longer times could be used. The actual measurement point was controlled by the position of the multi-port valve, which in turn was controlled by the DAQ. Since the sensors were logged at a rate of 4 pt/s, each 10-second window contained 40 data points. At the end of the 10-second sample time (or other user-selected measurement time), the valve was repositioned to collect gas for analysis from the next measurement point. Once all ten measurement point positions were sampled (10 seconds at each), the cycle would repeat. Thus, each measurement point was analyzed once every 100 seconds.

3.0 FIELD DEPLOYMENT—PERFORMANCE AND FINDINGS

In October 2016, the prototype Cold Hydrogen Plume Analyzer was field deployed at an industrial LH_2 storage facility during LH_2 delivery operations. This represented one of the first field measurements on an actual hydrogen plume formed during a LH_2 release. The delivery process included transfer of LH_2 from a road tanker truck to an on-site stationary storage vessel and the subsequent post-transfer depressurization venting. The depressurization process employed during the site visit differed from the protocol that was previously specified to the NFPA Task Group (e.g., approximately 50 kg of hydrogen is released through the stationary storage tank vent stack over a period of up to one hour). The depressurization process during the field test included a venting through the vent stack of the tanker truck; the height of this stack is approximately 4 m tall (13 feet), compared to 9.5 m (31.5 feet) for the vent stack on the stationary tank at the deployment site. A portion of the hydrogen was still released through the stationary tank vent stack and is shown in Figure 6. It is noted that Figure 6 captures only a moment in time and that the wind was quite variable such that the vapor stream continuously changed position laterally as well as vertically.

Figure 6: Deployment of the prototype Cold Hydrogen Plume Analyzer during LH_2 venting

During the deployment of the analyzer, gas measurements were collected at the ten measurement points along the Support Structure. Figure 7A shows the results obtained for measurement point 5, and can be used to illustrate the operation of the prototype analyzer. Information about the test conditions is also provided (e.g., “Event a” and “Event b”). Specifically, Figure 7A is a temporal plot during the LH_2

release for the volume percent H_2, volume percent O_2, and temperature at the indicated measurement point. Figure 7A illustrates the data format obtained from the prototype Cold Hydrogen Plume Analyzer. Comparable data were obtained from each of the ten measurement points. The test duration was 50 minutes and included two controlled events. “Event a” corresponded to the depressurization venting through the stationary storage tank stack, which was 9.4 (31 ft) in height, while “Event b” corresponded to the depressurization venting through the tanker vent stack, which was approximately 3.9 m (13 ft) in height. The prototype analyzer was deployed at a horizontal distance of approximately 2.4 to 3.0 m (8 to 10 ft) from the stationary storage tank vent and approximately 6.1 to 9.1 m (20 to 30 ft) from the tanker vent stack.

During the 50-minute test, the temperature (the green line in Figure 7) was measured continuously by the *in-situ* thermocouples, and is plotted as degrees Celsius. The volume percent H_2 and volume percent O_2 are indicated by the red and blue traces, respectively, but only for the time at which the multi-port valve was in Position 5, which was for 10 s out of every 100 s for the duration of the test. Each 10-second measurement window appears as an isolated “dot” in Figure 7A, but is in actuality 40 distinct data points from either the oxygen sensor or the TC hydrogen sensor. This is illustrated in Figure 7B, which shows an expanded view of the selected area in Figure 7A. Figure 7B shows the eighth measurement cycle for position 5. Each symbol in Figure 7B represents a logged data point from the indicated sensor.

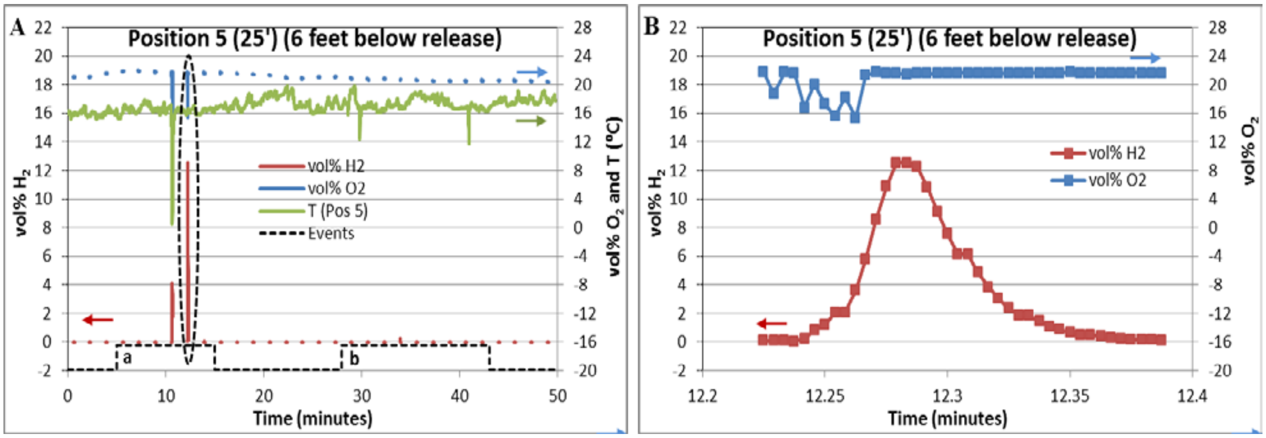


Figure 7: (A) T, vol% H_2, and vol% O_2 measurements from the prototype Cold Hydrogen Plume Analyzer for position 5 during actual field deployment. (B) Expanded view of the indicated area in A that shows the transient hydrogen behaviour and high concentration. Measurement details are given in the text.

3.1 Field Measurements

Figure 7A presents T, vol% H_2, and vol% O_2 for position 5. Plots for the other measurement points are given in Figure 8, and the main findings are summarized in Table 1. There are several significant findings. First, for “event A,” which was the hydrogen venting through the 9.5 m (31.5 feet) tall vent stack on the stationary tank, the presence of hydrogen was observed for numerous measurements points, including several that were below the point of release. This unequivocally clarified a question posed by the NFPA Hydrogen Storage Task Group, namely whether hydrogen buoyancy would be sufficient to preclude the presence of hydrogen below the release point. Not only will hydrogen migrate below the release point, it can be observed at significant concentrations. A hydrogen concentration of 12 vol%, which is three times the LFL, was detected at 2 m (6 ft) below the point of release. Even at 8.5 feet (2.6 m) below the point of release, hydrogen was detected above the LFL (5.6 vol%). The hydrogen concentration at various heights was variable during the release event. This is likely due to the variable wind. It was also found that the average temperature measured by the thermocouples (the temperature measurement devices deployed mounted on the support structure) was essentially ambient (ca. 17°C to

18°C), but there were sporadic cold temperature transients. The cold temperature transients were quite fast, but could be quite cold; for example down below -20°C at measurement position 3, which was below the release point. There was, however, not a strong correlation of hydrogen level to the cold transients, and thus the transients were not likely due to droplets of hydrogen. It is postulated that these transients are due to condensed droplets of air that contact the thermocouple, but this is at present not confirmed.

"Event b" had comparable observations, but it is noted that the horizontal distance from the vent source was significantly greater than that for "Event a," and thus we did tend to observe a lower hydrogen concentration. Although the hydrogen concentration was generally lower, it was observed at nearly every measurement point and more frequently, and on several occasions was above the LFL. Temperature transients were also still observed, one of which was down to below -60°C.

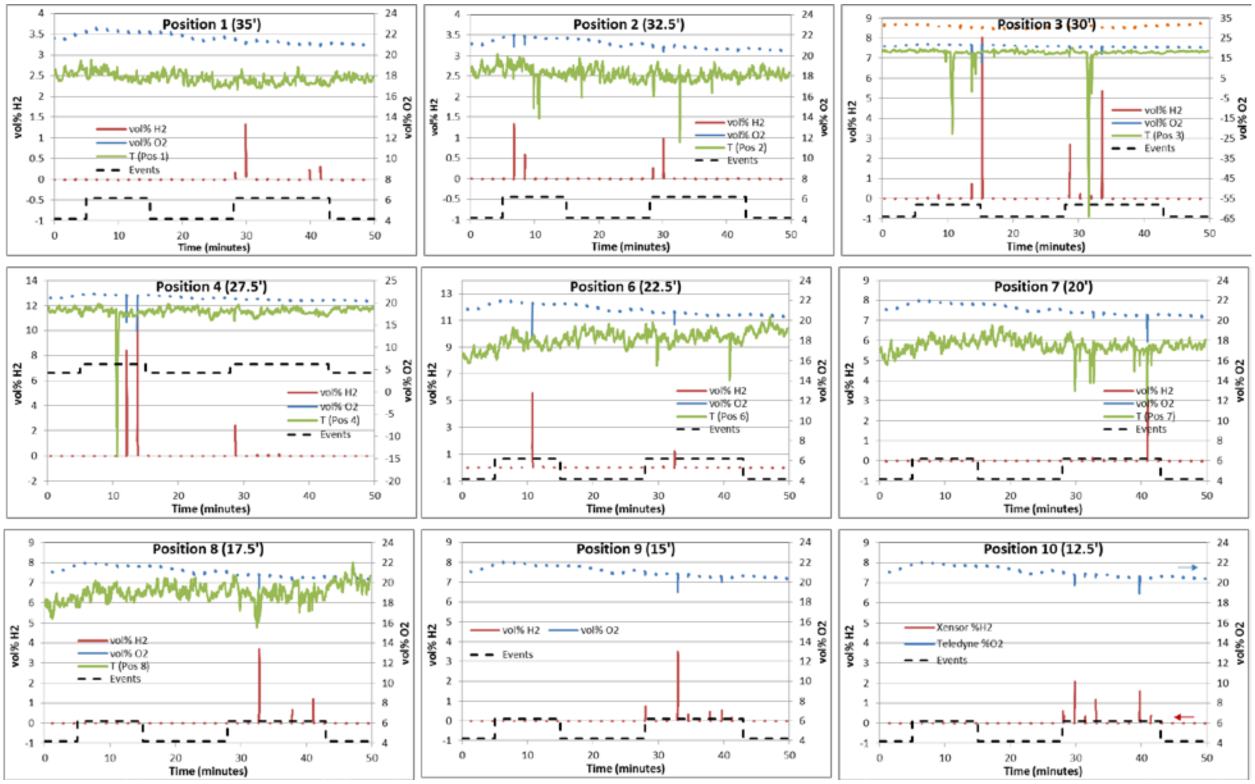
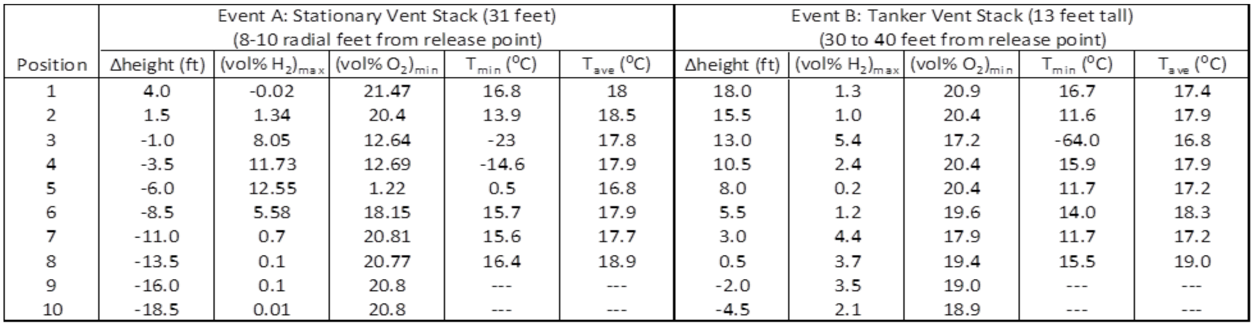


Figure 8: Volume percent H_2, vol% O_2, and T measurements for nine measurement positions from the Cold Hydrogen Plume Analyzer during actual field deployment.

Table 1: Summary of measurements by the prototype Cold Hydrogen Plume Analyzer for LH_2 venting



	Event A: Stationary Vent Stack (31 feet) (8-10 radial feet from release point)					Event B: Tanker Vent Stack (13 feet tall) (30 to 40 feet from release point)				
Position	Δheight (ft)	(vol% H_2)$_{max}$	(vol% O_2)$_{min}$	T_{min} (°C)	T_{ave} (°C)	Δheight (ft)	(vol% H_2)$_{max}$	(vol% O_2)$_{min}$	T_{min} (°C)	T_{ave} (°C)
1	4.0	-0.02	21.47	16.8	18	18.0	1.3	20.9	16.7	17.4
2	1.5	1.34	20.4	13.9	18.5	15.5	1.0	20.4	11.6	17.9
3	-1.0	8.05	12.64	-23	17.8	13.0	5.4	17.2	-64.0	16.8
4	-3.5	11.73	12.69	-14.6	17.9	10.5	2.4	20.4	15.9	17.9
5	-6.0	12.55	1.22	0.5	16.8	8.0	0.2	20.4	11.7	17.2
6	-8.5	5.58	18.15	15.7	17.9	5.5	1.2	19.6	14.0	18.3
7	-11.0	0.7	20.81	15.6	17.7	3.0	4.4	17.9	11.7	17.2
8	-13.5	0.1	20.77	16.4	18.9	0.5	3.7	19.4	15.5	19.0
9	-16.0	0.1	20.8	---	---	-2.0	3.5	19.0	---	---
10	-18.5	0.01	20.8	---	---	-4.5	2.1	18.9	---	---

4.0 SUMMARY

4.1 Highlights of the Field Deployment

The deployment of the prototype Cold Hydrogen Plume Analyzer was one of the first field measurements of the hydrogen plume formed during LH_2 releases. In this deployment, personnel from the NREL Sensor Laboratory worked directly with site personnel. Although anecdotal, the consensus of the site personal was that hydrogen would be observed below the vent stack, even at ground level, an impression that was based on in-the-field experience. We are now gaining comparable experience. Hydrogen was in fact observed at almost every measurement position on the analyzer. Moreover, as part of site protocol, personal gas monitors for hydrogen were used (at near-ground level) during the LH_2 transfer and depressurization process. During venting, the personal gas monitors did detect hydrogen, but it is noted that this was at low volume percent levels and below the LFL. However, the prototype Cold Hydrogen Plume Analyzer detected hydrogen above the LFL several times during the release process, both for "Event a" and "Event b," and at levels below the vertical release point. This observation confirmed that hydrogen buoyancy will not be the sole factor controlling the dispersion of a cold hydrogen plume,

Although we did observe oxygen depletion during the measurements, it could not be quantitatively correlated to hydrogen by simple displacement of air/oxygen by hydrogen. Similarly, although a vapor cloud was observed, there was little relationship to high hydrogen concentrations at the measurement point, but this needs to be assessed under improved measurement protocols, such as those recommended below in the critique of the analyzer. Ambient weather conditions, most notably the wind, did have a strong influence on the measurements, and more data are necessary to quantify this effect, as well as the impact of ambient temperature and humidity.

4.2 Critique and Recommendation on the Design and Operation of the Analyzer

The prototype Cold Hydrogen Plume Analyzer performed as designed and provided critical data on the behavior of LH_2 releases. Although the main goal of the field deployment was to provide the NFPA 2 Task Group with critical data on the behavior of the vented hydrogen, it was also important to assess the performance of the tools developed to obtain this information. It is emphasized that the version of the NREL Cold Hydrogen Plume Analyzer used in this deployment was the first prototype that was built to perform preliminary characterizations of hydrogen releases.

In terms of analyzer performance, it was shown that the sample collection system to the remote sensors could capture and provide quantitative information regarding the hydrogen plumes, including hydrogen transients, such as that depicted in Figure 7B. Conversely, while economical, the multiplexing of a single set of sensors with multiple measurement points using the multi-port valve significantly limited the metrological capability of the analyzer. The hydrogen levels were fluctuating, and there was a clear loss of temporal resolution. Incorporation of a dedicated sensor (or set of sensors for multiple target analytes) for each measurement point or sample line would eliminate the need for multiplexing. This simple step alone would improve the time response for hydrogen profiling from 100 sec to 250 ms. The use of multiple sensors will lead to an increased cost, but the overall system would still be low cost (< $10,000), depending on the number of measurement points per analyzer. As an interesting embellishment, multiple analyzers could be used cost-effectively within a facility to provide low-cost wide area monitoring (WAM), which could serve as either a research tool or a facility safety monitor system. The operation of the analyzer is simple and could be configured for operation by untrained personnel or even for autonomous, unattended operation. The impact of weather parameters was significant on the hydrogen plume. It is a simple enhancement to add a wind speed and direction sensor to our system. These recommended upgrades are being implemented. In summary, potential upgrades, modifications, and deployments include:

- Dedicated sensors for each sample point for better spatial and temporal profiling
- In-situ sensors (e.g., weather sensors, special gas sensors)
- Ruggedized, more easily implemented support structures and integrated system
- Multiple analyzers for hydrogen wide area monitoring (HyWAM)
- Deployments in coordination with industrial partner under various ambients (T, wind, RH)
- Ambient weather sensors for wind speed, wind direction, and humidity
- Simplified "push button" instrument operation for ready use by untrained personnel (e.g., delivery truck drivers).

4.3 Hydrogen Wide Area Monitoring (HyWAM)

The Cold Hydrogen Plume Analyzer could be adapted with further upgrades for significantly more powerful field measurement capability for applications such as autonomous, unattended, or wide area monitoring for hydrogen. The HyWAM would include an array of ruggedized support structures, instrumented with multiple hydrogen measurement points. Additional gas sensors (e.g., oxygen, select air quality sensor) could be incorporated at appropriate measurement points. Physical (T, pressure, RH) and weather (wind speed, wind direction) will be also incorporated. The Analyzer Box for the gas sensors would be configured into a ruggedized, professional instrument case or panel with display. The support structures would be ruggedized and modified for easier deployment. Multiple structures could be situated radially and at various horizontal distances around the hydrogen storage and use facilities. Such a system would be a powerful research tool to properly characterize hydrogen plume dispersion following releases; it could also be a valuable facility safety monitor. The integrated HyWAM system would include smart, remote, two-way communication to monitor hydrogen levels in and around the facility, providing notification of hydrogen releases and migration behavior, especially for out-of-normal events associated with a hydrogen release (e.g., a leak or improper dispersion following a release). The control system for the HyWAM could initiate warnings and operations shutdown if a hazardous situation is detected.

5.0 ACKNOWLEDGEMENTS

The development and deployment of the prototype Cold Hydrogen Plume Analyzer was supported through the DOE Fuel Cells Technology Office, Hydrogen Safety Codes and Standards Program (Will James, sub-Program Manager, Laura Hill, assistant sub-Program Manager). Site access for the field deployment was provided by the Linde Group, North America, with special thanks to Mike Ciotti. Programming of the prototype Cold Hydrogen Plume Analyzer was by Bloomfield Automation (Ian Bloomfield). This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National

Renewable Energy Laboratory. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Fuel Cells Technology Office. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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