Development of Risk Mitigation Guidance for Hydrogen Sensor Placement Indoors and Outdoors

Andrei V. Tchouvelev[1a], William J. Buttner[b], Benjamin Angers[c]
[a] A.V. Tchouvelev & Associates Inc., 6591 Spinnaker Cir, Mississauga, ON, Canada
[b] National Renewable Energy Laboratories, Golden, CO, USA
[c] Hydrogen Research Institute, Université du Québec à Trois-Rivières, QC, Canada

ABSTRACT

Guidance on Sensor Placement remains one of the top priorities for the safe deployment of hydrogen and fuel cell equipment in the commercial marketplace. Building on the success of Phase 1 work reported at ICHS2019 and published in IJHE, this paper discusses the consecutive steps to further develop and validate such guidance for mechanically ventilated enclosures. The key step included a more in-depth analysis of sensitivity to variation of physical parameters in a small enclosure.
and finally, expansion of the developed approach to confined spaces in an outdoor environment.

1.0 Introduction

Hydrogen safety sensors are used because of their ability to respond to unintentional hydrogen releases, which would otherwise be undetectable by human senses alone. The actual deployment of hydrogen sensors has, however, been more intuitive than scientific, and their placement and operation are not necessarily optimized for maximum safety assurance as there has been little guidance on how to optimally integrate hydrogen sensors into a facility design.

The key technical requirement and challenge here is to determine an optimal location for the placement of a hydrogen sensor (or sensors) so that the probability of detection is the highest and independent on the leak orientation / direction. This requires an ability to predict air circulation inside the enclosure depending on location of air intake and exhaust, equipment placement inside the enclosure and air flow generated by the exhaust fan. The key in this regard is to find / predict locations of low ventilation flow within the facility, which assures higher predictability of detection of low hydrogen concentrations, which are undetectable by other means (e.g., pressure sensors mounted on pneumatic lines). From this perspective, spots with hydrogen concentrations between 1,000 to 5,000 ppm are the primary targets.

Phase 1 of this research presented at ICHS2019 [1] and published online in IJHE in September 2020 [2] specifically focused on mechanically ventilated enclosures. It came up with the following recommendations subject to further analysis and confirmation:

- Suitable locations for sensor placement in a ventilated enclosure are those that meet the following criteria:

[1] Corresponding author. E-mail address: atchouvelev@tchouvelev.org

a. Not on a direct path of the airflow from the air inlet to the exhaust fan. This ensures weak to moderate sensitivity to potentially fluctuating airflow;
b. Minimum expected concentration is above the minimum practical level of 1000 ppm, while the maximum expected concentration under normal operating conditions is below 10000 ppm. For this reason, locations close to the floor, although having low sensitivity to airflow, may not be practical since their expected concentration levels are on the borderline of practicality and reliable sensor detection threshold.
c. Below the enclosure ceiling thus not obstructed by the ceiling piping and lighting fixtures or other objects. This ensures unobstructed relatively low velocity and low turbulence airflow around the sensor sampling point.

The focus of the research described in this paper is to validate the above recommendations by expanding the previously published research into two specific areas:

- **Sensitivity analysis** of the impact of variations in the test parameters relative to the conditions assumed in the initial phase. The sensitivity analysis shall then be used to determine the robustness of the validated model. A small impact on the hydrogen dispersion induced by a "large" variation in the physical parameter will be an indication of model robustness. In contrast, a large impact on dispersion induced by a relatively small parameter variation will be indicative of the need to control the variation of the parameter so as to minimize impacts and more accurately predict dispersion behaviour.
- **Confinement outdoors**: An empirically validated CFD model for a "small" indoor hydrogen facility will be expanded to a "small" non-mechanically ventilated enclosure outdoors. An outdoor high-pressure storage cabinet used at a hydrogen refueling station was selected as a relevant example of such enclosure.

2.0 Hydrogen Dispersion Sensitivity with Variation of Physical Parameters

The initial modelling and empirical verification of the indoor hydrogen dispersion primarily focused on a single set of ventilation conditions. It is known that hydrogen plume dispersions can be affected by physical parameters. The ventilation rate (flow in and flow out of the enclosure) was assumed to be a nominal uniform value, whereas in fact the flow in the air inlet could vary with outdoor weather conditions, such as wind gusts. Hence, the dispersion is sensitive to various ventilation regimes. Also, the initial CFD modeling focused on only two release directions, whereas in reality releases can have components in 6 main directions (±X, ±Y, ±Z). Finally, anecdotal observations indicated that released gas density (controlled by the gas temperature) will have an impact on the dispersion behavior and sensor behavior, including response time and final indication at a specific sample point. By varying the input conditions, the sensitivity of these parameters on hydrogen dispersion can be quantified using the Phase 1 validated CFD model. The objective is to perform a sensitivity analysis of the impact of variations in the test parameters relative to the conditions assumed in the initial phase. The

sensitivity analysis shall then be used to determine the robustness of the validated model. A small impact on the hydrogen dispersion induced by a "large" variation in the physical parameter will be an indication of model robustness. In contrast, a large impact on dispersion induced by a relatively small parameter variation will be indicative of the need to control the variation of the parameter so as to minimize impacts and more accurately predict dispersion behavior.

2.1 Approach and Methodology

The objectives described above have been achieved by the following approach and methodology:

1. Conduct a detailed sensitivity analysis to test the robustness of the previously developed CFD model with regards to variation of the following physical parameters:
   a. Direction of release: East, Up, West, South and Downward;
   b. Ceiling obstacles and grid refinement, and
   c. Ambient temperature variations.
2. Re-evaluate the previous recommendations based on North direction releases experimental results using detailed sensitivity analysis for the "small" enclosure mentioned above.
3. Adjust "Suitable", "Uncertain" and "Not Suitable" locations for the "small" enclosure accordingly.
4. Adjust the previous recommendations accordingly and draft the generic guideline for sensor placement for mechanically ventilated enclosures.
5. Check the robustness of recommendations for the "small" indoor enclosure on a "small" non-mechanically ventilated enclosure outdoors.

2.2 Sensitivity Analysis

2.1.1 Sensitivity Analysis to Direction of Release

For sensitivity analysis, the HyWAM (Hydrogen Wide Area Monitoring) sensor locations used in the release tests in December 2017 are shown on Figures 1 and 2 below. These results are taken as benchmark for the comparison with CFD modeling analysis.

The NREL HyWAM module consisted of 10 commercial thermo-conductivity (TC) hydrogen sensors (Xensor Integration, BV, Model XEN-5320-USB) and 8 K-type thermocouples (Omega) for in-situ temperature measurements [6]. The TC sensor has a response time (t_{90}) of 250 ms, allowing for the quantitative measurements of fast hydrogen transients. This hydrogen sensor has a broad measuring range up to 100 vol% H_2. Ten gas sample lines were positioned within the enclosure (see Figures 1 and 2) to draw gas from precise locations within the enclosure to the remotely deployed HyWAM modules. Gas samples were continuously delivered to each TC sensor (purge time < 1sec) through the use of a sample pump.

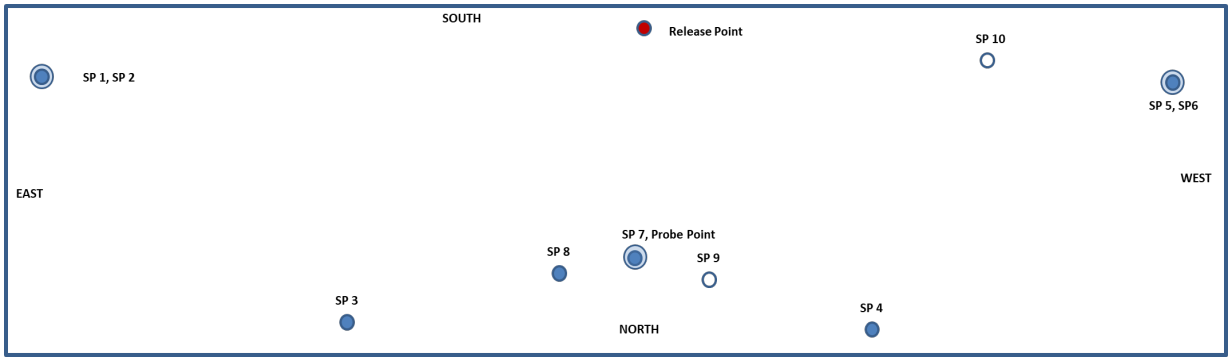


Figure 1. Location of He sensors for release tests – plan view: X (North, South) – Y (East, West) plane; coordinates origin – top right corner.

Filled circles indicate helium and temperature measurements. Shaded circles imply multiple sampling points with same X,Y coordinates but different Z (vertical) value. Open circles indicate helium measurements only. Release Point Coordinates: X = 4.0 m, Y = 0.05 m, Z = 0.6 m. The release orientations were up (toward ceiling) and horizontal (E, W, and S).

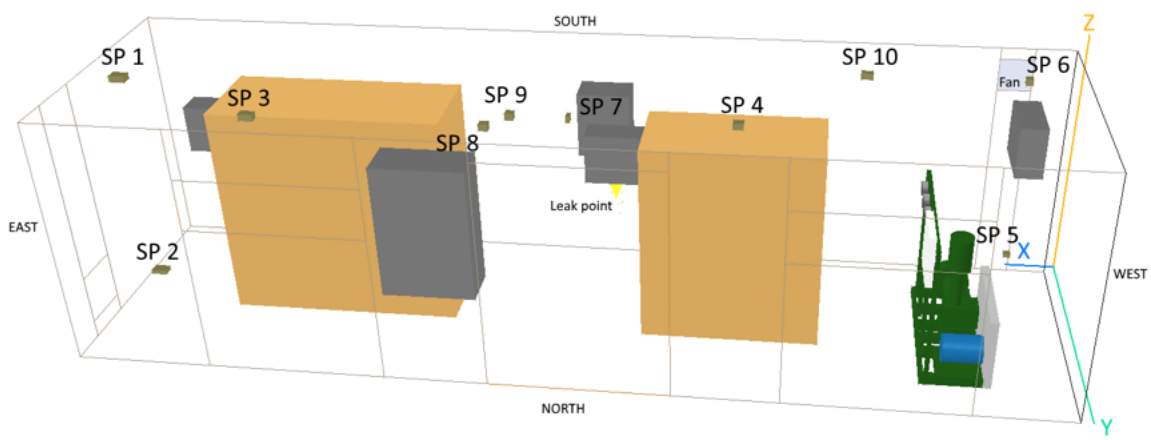


Figure 2. HyWAM actual and CFD virtual sensor locations used in He release tests on Dec 8, 2017 and consecutive CFD modeling inside the "small" enclosure.

As noted above, the sensitivity analysis to the direction of release was performed for East, Up, West, South and Downward directions. This was complementary to the North direction releases performed in Phase 1 of this project.

For EAST, UP and SOUTH directions, the conclusion are similar to those achieved in Phase 1 of this project based on NORTH releases.

For WEST releases towards the exhaust fan, in principle, the conclusions are similar to those achieved in Phase 1 of this project based on NORTH releases. The only difference is that there are more suitable locations to detect the leak in this particular direction.

DOWNWARD Direction Results and Commentary

There were no downward experimental data available. Hence, the sensitivity was tested by CFD numerical simulations only. Two of three leak locations were specifically selected as transitional scenarios to "large" facility where the leak is located 1.8 m above the floor in one of the scenarios in the FCEV maintenance facility (a subject of future publications).

Based on CFD results, "traditional" suitable locations determined for all previous cases work well. Downward leak direction makes sensors located closer to the floor more effective since the leak is directed down, however the sensor performance located underneath the exhaust fan (SP5) can only be ranked as "uncertain" due to significant draw of air by the exhaust fan above.

2.1.2 Sensitivity to Ceiling Obstacles and Grid Refinement

The results obtained by CFD modeling provide two important conclusions:

1. Piping significantly affects the readings of the ceiling sensors in the case of UPWARD leaks, but does not seem to matter much for leaks in other directions. This makes sense since during the UPWARD leaks the concentration tends to build up quickly at the ceiling level. Hence, piping fixtures tend to interfere with the ventilation preventing hydrogen dispersion, thus producing artificially high hydrogen concentrations that are not representative at the ceiling surface.
2. Grid sensitivity analysis confirms that the main selected grid is optimum and further grid refinement only marginally changes the reading, which is within acceptable numerical error.

2.1.3 Sensitivity to Temperature

In order to quantify the effect of lower temperatures on the concentration profile, the ambient temperature as well as the storage temperature was set to -40°C (233.15K) for CFD calculations on both the helium and hydrogen releases.

The experimental and CFD modeling results for the range of temperatures up to -40°C show that lower operating temperature has an effect on both helium and hydrogen concentrations by lowering them approximately by 10-15% depending on the sensor location inside the enclosure.

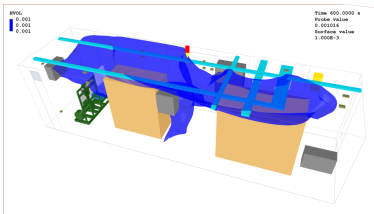
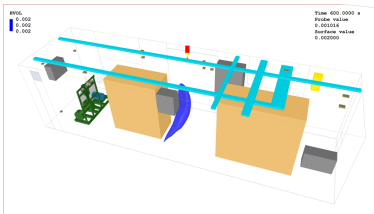
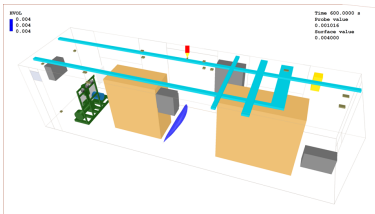
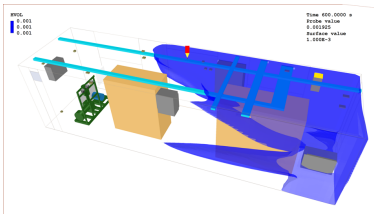
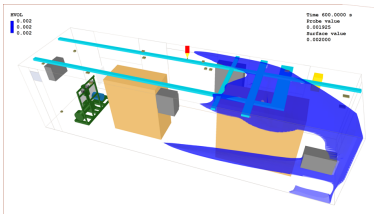
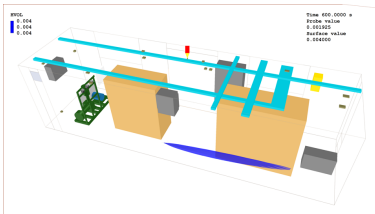
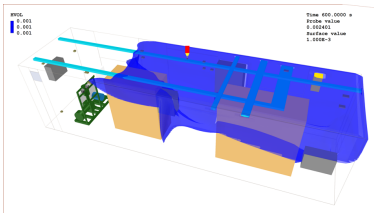
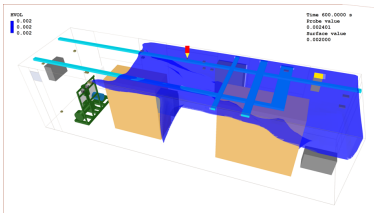
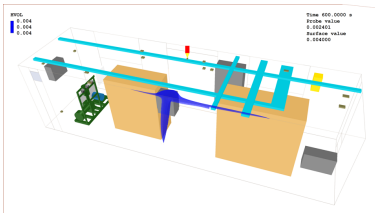
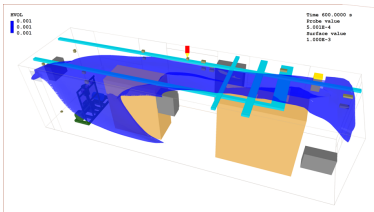
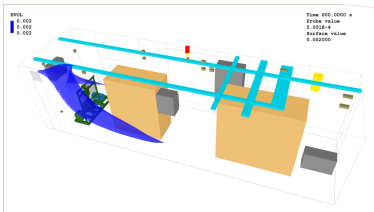
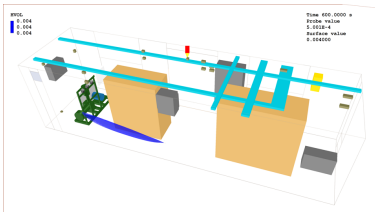
Despite the above, this effect is not significant and stays within the preferred detectability range between 1,000 and 4,000 ppm. Of course, the sensor technology should be selected appropriately to make sure it is compatible for low temperature conditions.

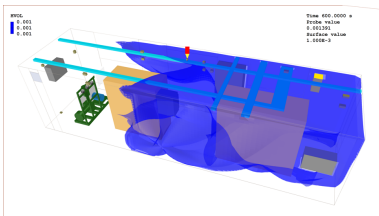
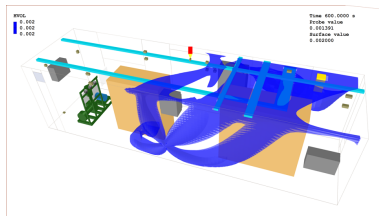
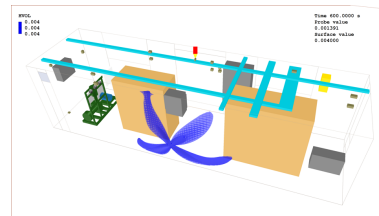
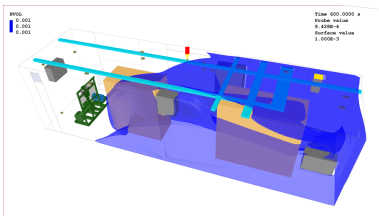
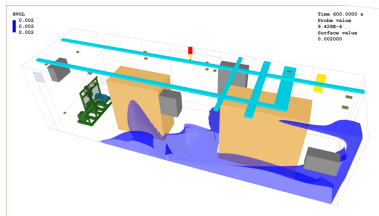
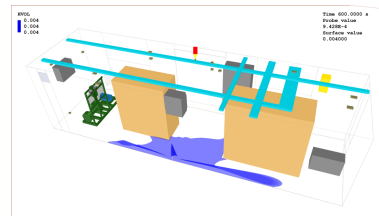
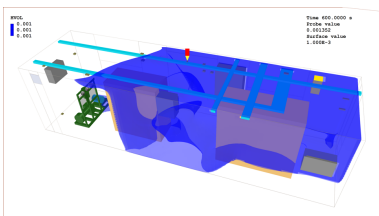
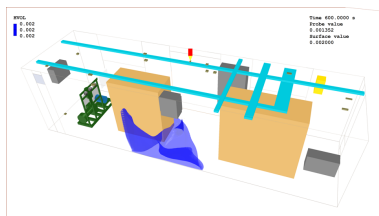
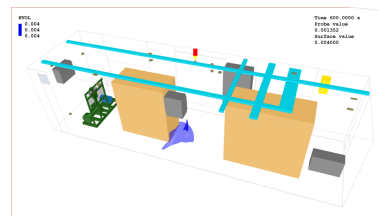
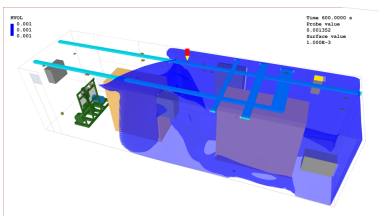
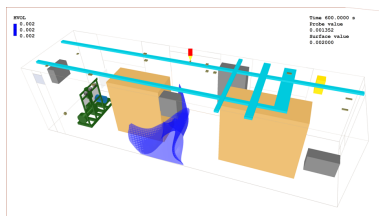
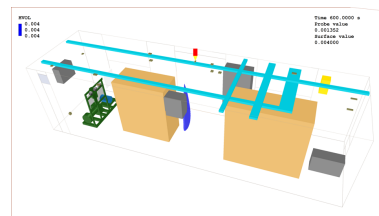
2.1.4 Sample of CFD Modeling Results and Comparison with Experiment

Representative samples of CFD modeling results and the comparison with the experimental data are illustrated by the images assembled in Table 1 and Figure 2 below. In particular, Table 1 presents the overall summary of modeling results for the helium

cloud contour 540 seconds after the onset of the leak for all leak orientations. Figure 2 presents a comparison between the experimental and simulation results for the horizontal case oriented towards the East, for various ventilation regimes.

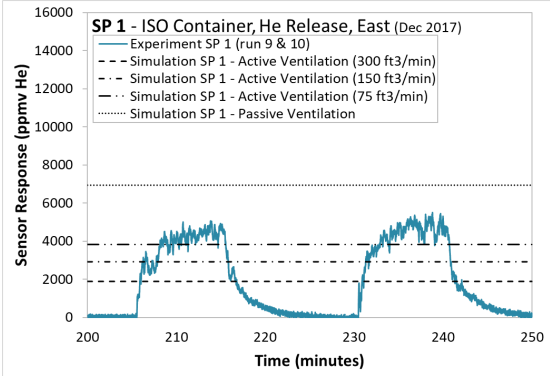
Table 1. Helium cloud contour at 0.1% (2.5% H_2 LFL), 0.2% (5% H_2 LFL) and 0.4% (10% H_2 LFL) mole fraction, 540 seconds after the onset of the leak for various leak directions. Mole fraction and corresponding LFL values at the probe location (x = 4.1, y = 1.7, z =2.2) are also provided in the first row and column respectively. Ventilation at 300 ft^3/min or 509.4 m^3/h.

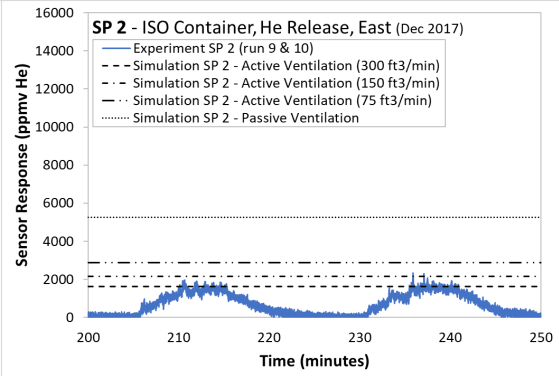
	0.1% fmole (2.5% H_2 LFL)	0.2% fmole (5% H_2 LFL)	0.4% fmole (10% H_2 LFL)
Horizontal N-wall Probe: 0.10% mole fraction			
Horizontal E-wall Probe: 0.19% mole fraction			
Vertical Upward Probe: 0.24% mole fraction			
Horizontal West-wall Probe: 0.05% mole fraction			

Horizontal South-wall Probe: 0.14% mole fraction			
Vertical Downward Probe: 0.094% mole fraction			
Vertical Downward Center Probe: 0.14% mole fraction			
Vertical Downward Center 1.8 m Probe: 0.14% mole fraction			

The above images show the variety of helium concentrations' iso-surfaces expressed in 2.5, 5 and 10% H_2 LFL, respectively. These results are unscaled. Hence, to obtain the corresponding H_2 values for the probe (numbers shown in the left column) these numbers will need to be increased by about 40%. Essentially the images confirm the main conclusion made in the previous phase of this project: the detectability range between 1,000 and 4,000 ppm will be able to detect the leak in any direction investigated in this study.

Figures below provide the insights on concentrations sensitivity to both the direction of leak as well as to the ventilation inside the enclosure, from passive to nominal 300 cfm (509.4 m^3/h (the experimental sensor responses were obtained with a nominal 300 cfm / 509.4 m^3/h ventilation).


SP 1 - ISO Container, He Release, East (Dec 2017)
Experiment SP 1 (run 9 & 10)
Simulation SP 1 - Active Ventilation (300 ft3/min)
Simulation SP 1 - Active Ventilation (150 ft3/min)
Simulation SP 1 - Active Ventilation (75 ft3/min)
Simulation SP 1 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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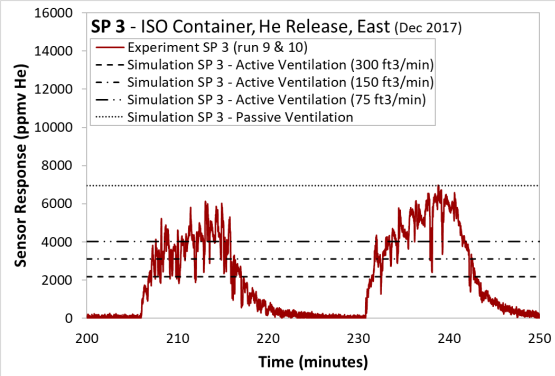
Experiment SP 2 (run 9 & 10)
Simulation SP 2 - Active Ventilation (300 ft3/min)
Simulation SP 2 - Active Ventilation (150 ft3/min)
Simulation SP 2 - Active Ventilation (75 ft3/min)
Simulation SP 2 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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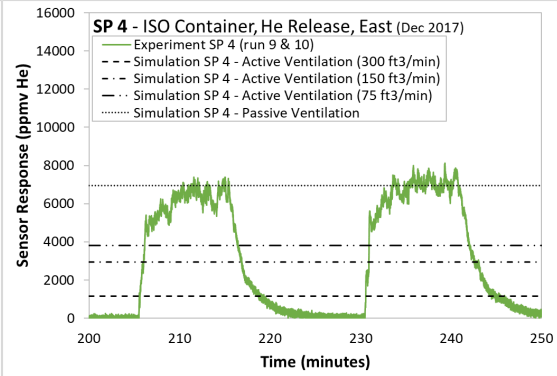
Experiment SP 3 (run 9 & 10)
Simulation SP 3 - Active Ventilation (300 ft3/min)
Simulation SP 3 - Active Ventilation (150 ft3/min)
Simulation SP 3 - Active Ventilation (75 ft3/min)
Simulation SP 3 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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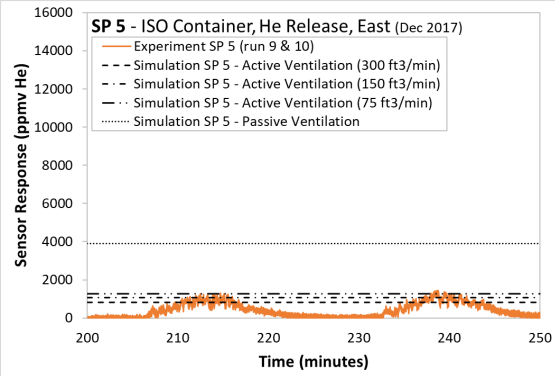
Experiment SP 4 (run 9 & 10)
Simulation SP 4 - Active Ventilation (300 ft3/min)
Simulation SP 4 - Active Ventilation (150 ft3/min)
Simulation SP 4 - Active Ventilation (75 ft3/min)
Simulation SP 4 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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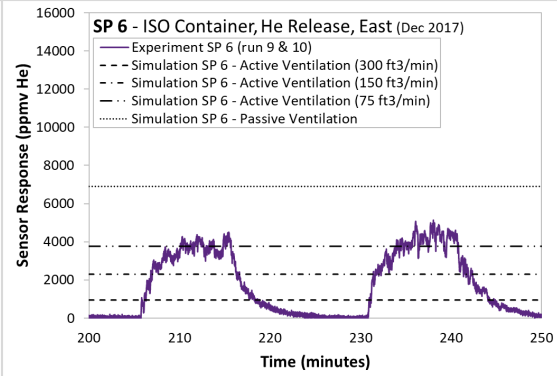
Experiment SP 5 (run 9 & 10)
Simulation SP 5 - Active Ventilation (300 ft3/min)
Simulation SP 5 - Active Ventilation (150 ft3/min)
Simulation SP 5 - Active Ventilation (75 ft3/min)
Simulation SP 5 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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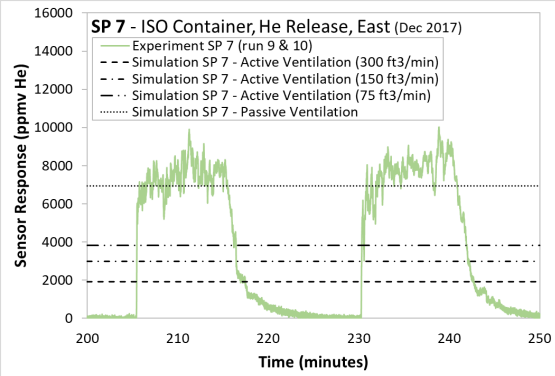
Experiment SP 6 (run 9 & 10)
Simulation SP 6 - Active Ventilation (300 ft3/min)
Simulation SP 6 - Active Ventilation (150 ft3/min)
Simulation SP 6 - Active Ventilation (75 ft3/min)
Simulation SP 6 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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Experiment SP 7 (run 9 & 10)
Simulation SP 7 - Active Ventilation (300 ft3/min)
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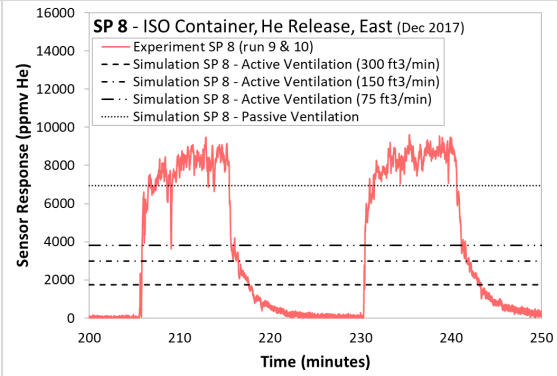
Simulation SP 7 - Active Ventilation (75 ft3/min)
Simulation SP 7 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)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Experiment SP 8 (run 9 & 10)
Simulation SP 8 - Active Ventilation (300 ft3/min)
Simulation SP 8 - Active Ventilation (150 ft3/min)
Simulation SP 8 - Active Ventilation (75 ft3/min)
Simulation SP 8 - Passive Ventilation
Sensor Response (ppmv He)
Time (minutes)

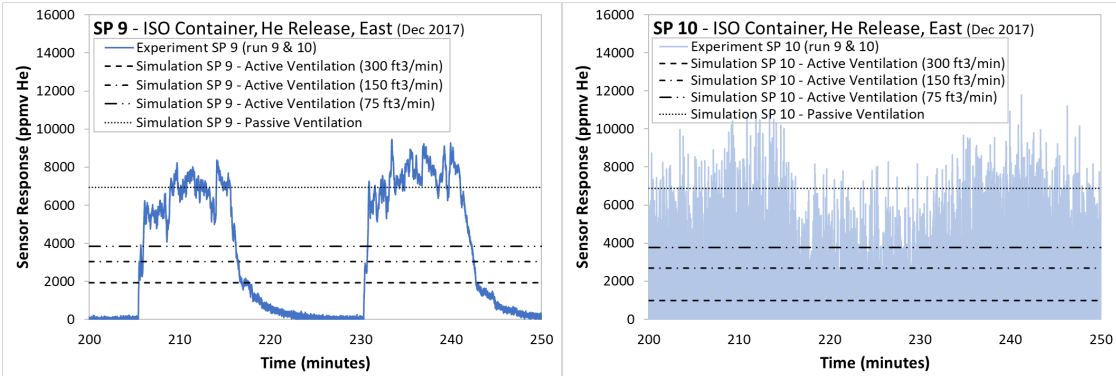

Figure 2. Experimental hydrogen sensor responses (2017-12-08) for each of the 10 sampling points for run 9 and 10 compared with CFD results for the same sampling points at 300 ft^3/min (509.4 m^3/h), 150 ft^3/min (254.7 m^3/h), 75 ft^3/min (127.4 m^3/h) and without ventilation. The orientation of the leak was horizontal towards the East wall.

2.1.5 Summary and Conclusions of Detailed Sensitivity Analysis

The sensitivity analysis summarized above essentially confirms the principal findings of Phase 1 of this project in regard to suitable sensor locations. Those identified as "best" for NORTH direction releases generally perform well and reliable for all other directions. DOWNWARD leaks make the lower sensors more effective otherwise those are not very useful.

Ceiling sensors' readings are significantly affected by piping fixtures during UPWARD leaks, but don't seem to be affected much during leaks in other directions. Nevertheless, it is recommended to place ceiling sensors below the piping fixture to make sure they are not obstructed.

Low temperature at -40 C lowers sensor readings for both helium and hydrogen, however, this effect is not significant and within preferred detection range between 1,000 and 4,000 ppm.

Table 2 below provides summary of sensor locations suitability for the studied "small" enclosure based on the detailed sensitivity analysis. North releases data obtained during the Phase 1 of this project is complemented by data from other release directions.

Table 2. Sensor locations performance in terms ability to detect hydrogen within 1,000 – 4,000 ppm range in NREL ventilated "small" enclosure.

	Sensor locations per Dec 2017 Tests–300 ft^3/min (509.4 m^3/h) ventilation									
	SP1	**SP2**	**SP3**	**SP4**	**SP5**	**SP6**	**SP7**	**SP8**	**SP9**	**SP10**
NORTH	Y	N	Y	Y	N	N	Y	Y	Y	U
EAST	Y	N	Y	U	N	N	Y	Y	Y	U
UPWARD	Y	N	Y	U	N	N	Y	Y	Y	U
WEST	Y	N	Y	Y	N	Y	Y	Y	Y	Y
SOUTH	Y	N	Y	U	N	U	Y	Y	Y	U
DOWNWARD	Y	Y	Y	U	U	U	U	Y	Y	U
Overall Rating	Y	N	Y	U	N	N	Y	Y	Y	U

Legend: **Y** – suitable; **U** – uncertain, may work; **N** – not suitable.

The conclusions summarized in Table 2 form the basis to update the initial graphical visualization of sensor performance developed during the Phase 1. The adjusted picture is presented on Figure 3 below. The revised rankings of sensor placements were minor, which indicates that the original determinations were essentially correct.

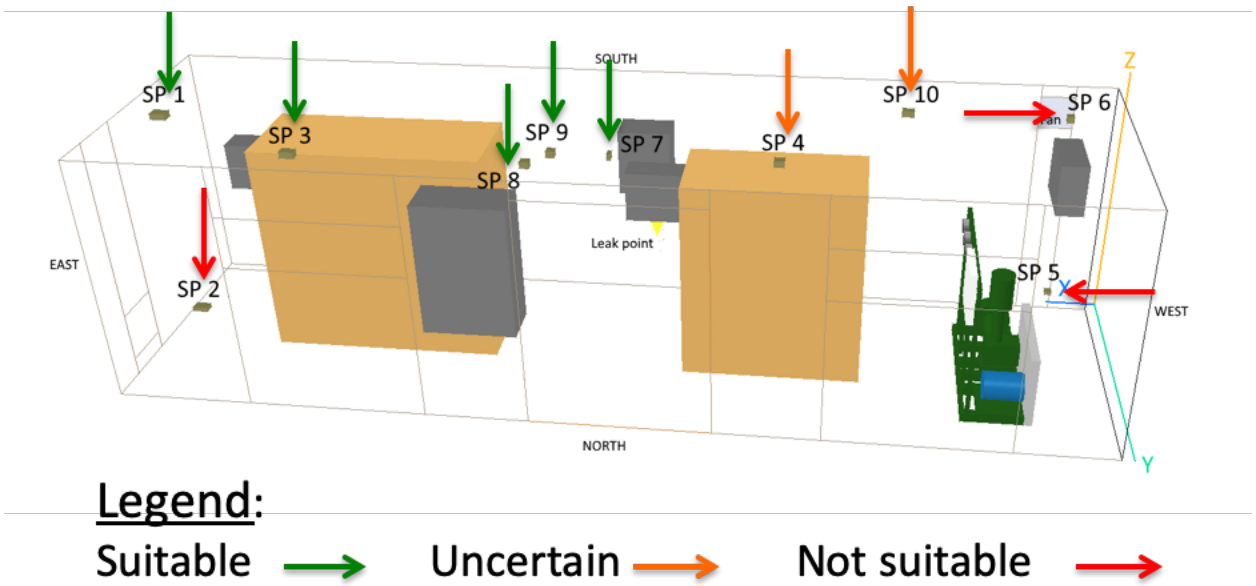

Figure 3. Updated recommendations for sensor placement strategy for "small" enclosure based on experiments and CFD results for Dec 8, 2017 HyWAM setting.

2.4 General Guidance for Sensor Placement in a Mechanically Ventilated Enclosure

Based on the above observations, the following general guiding principles for hydrogen sensor placement in a mechanically ventilated enclosure can be drafted as follows:

- **Not on a direct path of the airflow from the air inlet to the exhaust fan and not at the exhaust fan**. This ensures weak to moderate sensitivity to potentially fluctuating and turbulent airflow and thus leads to more stable and predictable hydrogen concentrations for easier detection by sensors. **This is of particular importance for outdoor placed enclosures with an exposed air intake that may be highly affected by atmospheric conditions, predominately the wind direction and velocity and precipitation, and to lesser extent by the outdoor temperature, humidity and pressure**.
- **Minimum expected concentration is above the minimum practical level of 1000 ppm, while the maximum expected concentration under normal operating conditions is significantly below 10000 ppm (on the order of 4000 ppm)**. For this reason, locations close to the floor, although having low sensitivity to airflow, may not be practical since their expected concentration levels are on the borderline of practicality and reliable sensor detection threshold.
- **For low ceiling enclosures, such as ISO containers or regular rooms up to 12 ft (3.66 m) to 16 ft (4.88 m) high max** (depending on heights of potential leak

points where maximum distance between the potential leak point and the H_2 sensor head is within 10 ft / 3 m). **Sensor placement should be below the ceiling piping and lighting fixtures or other objects to make sure the sensor heads are not in any way obstructed**. This ensures relatively low velocity and low turbulence airflow around the sensor sampling points and thus increases accuracy and consistency of readings.

- **For high ceiling enclosures with wide open areas such as warehouses, production or test facilities, ceiling sensor placement may not be effective**. In this case, if hydrogen sensors are part of the risk mitigation strategy, they should be placed directly above and not farther than 10 ft (3 m) from the equipment deemed to be mostly susceptible to leaks.

3.0 Guidance Testing in a Small Non-Mechanically Ventilated Enclosure Outdoors

This part of the described research aimed to verify whether this general guidance will work in a small non-mechanically (naturally) ventilated enclosure located outdoors. A relatively small high-pressure hydrogen storage module used at a hydrogen refueling station (HRS) was selected as a relevant example. The objective was to show that an H_2 sensor installed per the guidance can provide an early detection of a small leak inside such enclosure.

3.1 Geometry

The selected enclosure was inspired by the specification for the FS001 Hydrogen Fueling Storage from NEL [3]. The storage unit version with 11 layers used at the Sandvika (Kjorbo) HRS in Norway was considered (Figure 4).

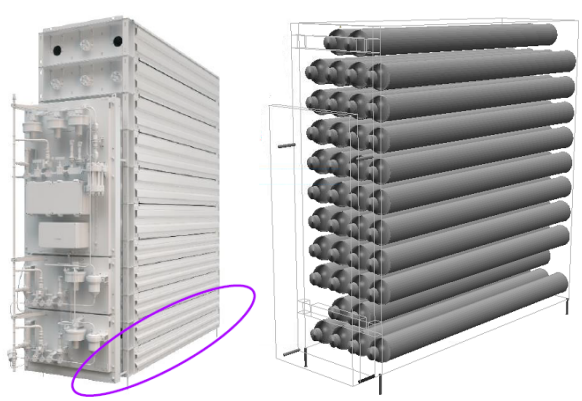

Figure 4. NEL FS001 storage unit containing 11 layers of vessels installed at Sandvika HRS in Norway (left) and visualization of the storage vessels arrangement in CFD modeling domain. Purple circle indicates the area of hydrogen leak to be discussed below in section 3.2.

As shown on Figure 4, the storage enclosure was fully filled with vessels, except in front of the openings on layers 2 and 11 to allow hydrogen and air to flow through freely. The four openings each had an area of about 0.016 m^2. The bottom was kept fully open. According to NEL specifications, the 11 layers unit had the following dimensions of length: 3410 mm, width: 1120 mm and height: 3380 mm.

One virtual hydrogen sensor was set strategically at the very top of the enclosure, in the centre above the plug portion of the cylinders. The detailed geometry for CFD modeling is shown on Figure 5.

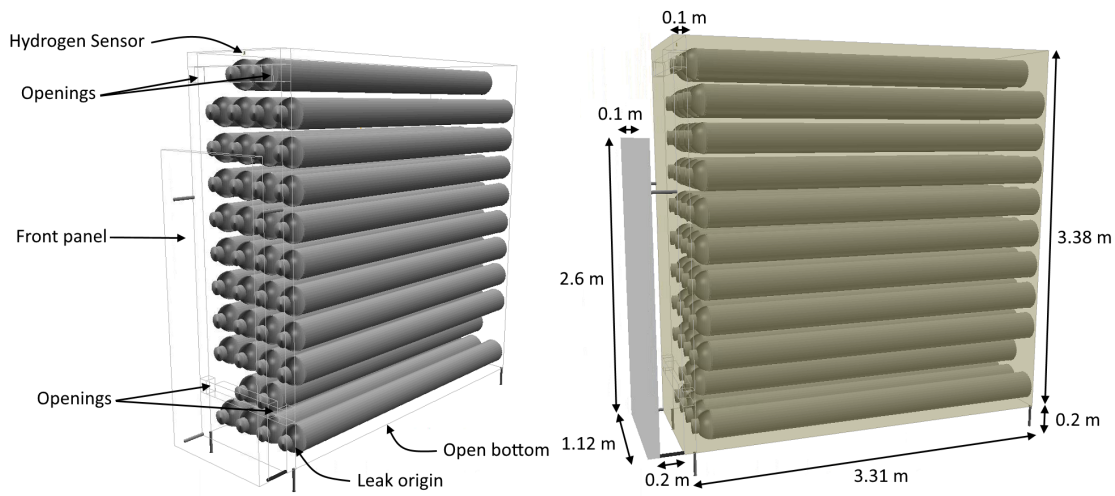

Figure 5. Modelled NEL hydrogen fueling storage enclosure.

3.2 Hydrogen Leak Location and Scenario

According to the official report on the KJORBO incident [4], a minor leakage was recorded by the control system monitoring software 2.5 hours prior the major release incident and subsequent ignition and deflagration. According to the report, 0.4 kg of hydrogen was lost over a period of 2.5 hours from one of the 950 bar hydrogen banks. This corresponds to a leak rate of 4.44 x 10^{-5} kg /s. This leak originated from one failed vessel at the bottom of the enclosure which was improperly assembled with insufficient torque on the plug.

To reproduce the circular nature of this release, the 4.44 x 10^{-5} kg /s leak was divided along the four cardinal directions as shown on Figure 6. Each leak had a mass flow rate of 1.11 x 10^{-5} kg/s. The orifice diameter (1.81 x 10^{-5} m) and equivalent diameter (3.6 x 10^{-4} m) were calculated using Birch et. al. 1984 [5] and the Abel Noble equation of state. NTP conditions were considered (293.15K, 101.325 kPa). No wind or forced ventilation were considered.

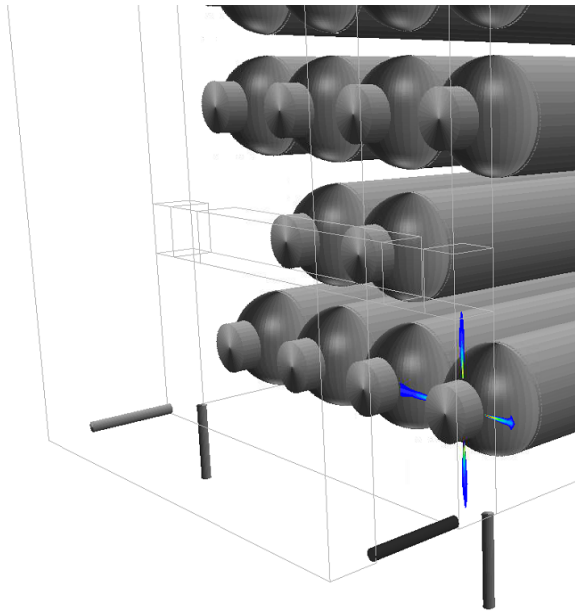

Figure 6. The 4.44 x 10^{-5} kg leak divided along four directions.

3.3 Simulation Results

As shown by the following results (Figure 7 to 9), the hydrogen released inside the storage enclosure quickly reached the sensor threshold detection concentration of 0.1 % vol. or 1,000 ppm recommended by the guidance at the top of the enclosure. It took 22.1 s after the onset of a 2.5 hours release for the detector to detect the leak.

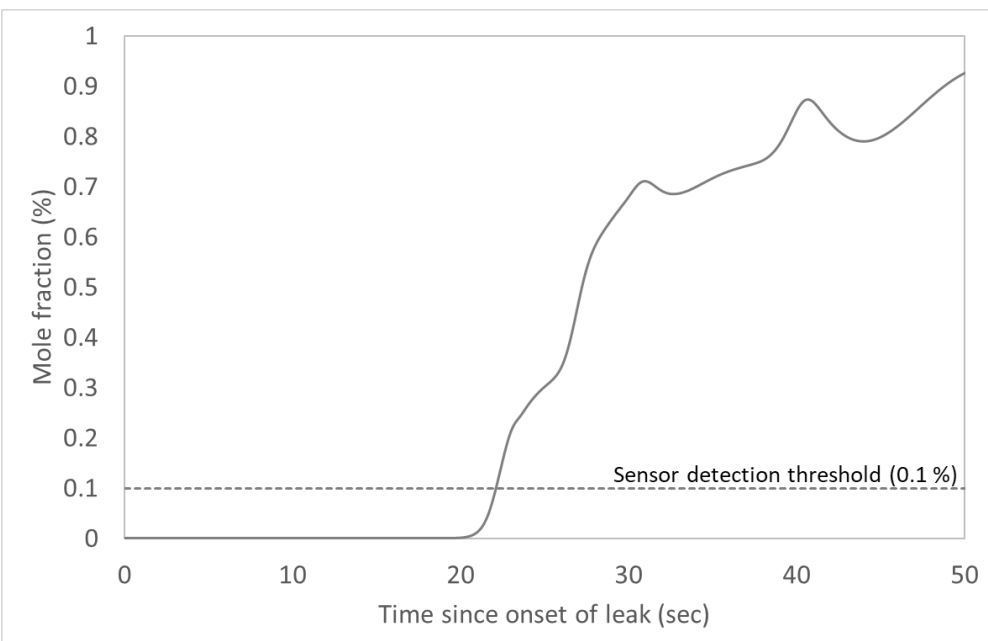

Figure 7. Mole fraction of hydrogen measured by the virtual sensor set at the top of the enclosure for the first 50 seconds after the onset of the leak.

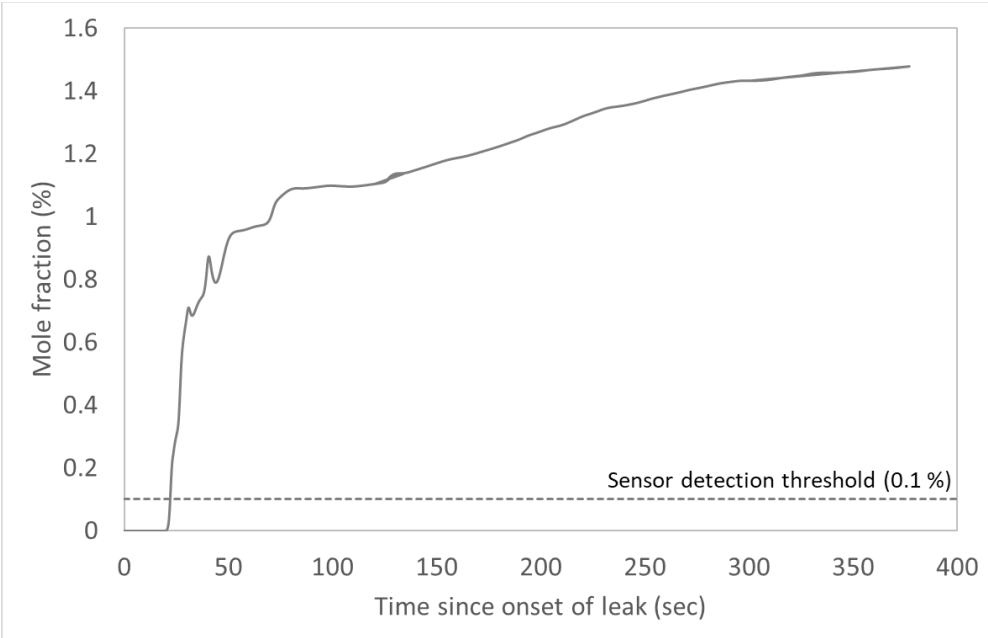

Figure 8. Mole fraction of hydrogen measured by the virtual sensor set at the top of the enclosure for the first 375 seconds after the onset of the leak.

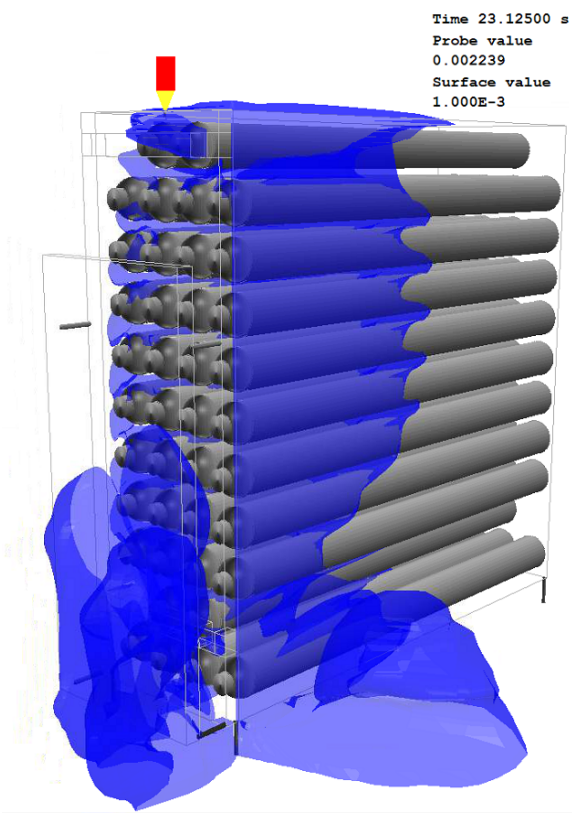

Figure 9. Iso-surface of H_2 threshold detection concentration contour (0.1 % mole fraction) 23.1 s after the onset of the leak.

4.0 Key Conclusions and Recommendations

Conclusions and recommendations resulting from the reported research:

1. A detailed analysis of hydrogen dispersion sensitivity with variation of physical parameters in a "small" enclosure has been performed. Mapping of the suitable sensor locations for earlier detection was updated.
2. Based on the above analysis and comparison, a generic guidance for sensor placement for early hydrogen detection was developed. This guidance is believed to be suitable for all mechanically ventilated enclosures containing hydrogen equipment with ceilings up to 12 to 16 ft (3.66 to 4.88 m) in height (depending on heights of potential leak points where maximum distance between the potential leak point and the H_2 sensor head is within 10 ft/ 3 m).
3. The general guidance seems to work for a "small" non-mechanically (naturally) ventilated enclosure located outdoors.

It is fair to say that specific sensor locations will depend on the internal configuration of the enclosure, specific leak / accident scenarios and arrangement of mechanical (or natural) ventilation. However, the basic recommendations stated above should still apply.

More sensitivity analysis is needed to draw more definitive conclusions. Further expansion of indoor releases to other larger facilities (such as vehicle maintenance facilities) and outdoor confined spaces is anticipated as next research steps.

5.0 Acknowledgements

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