LARGE SCALE PASSIVE VENTILATION TRIALS OF HYDROGEN

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ABSTRACT

This paper describes the investigation of a passive ventilation solution to manage hydrogen concentration within an ullage space (0.9 to 3 m deep) in a large ullage space above a liquid (liquid surface area of ~80m2) containing a hydrogen source. The aim of the ventilation is to maintain the H2 concentration within the ullage space below 25% of the Lower Explosive Limit (LEL).

The programme of tests involved examination of the ventilation performance in terms of sensitivity to:
- Chimney position
- Hydrogen release rate
- Hydrogen release point
- Ullage height
- Chimney diameter

The tests carried out lasted many hours, and the hydrogen concentration was monitored at a number of points within the ullage space. Pairs of ventilation "chimneys" with associated instrumentation systems were used to control and monitor the hydrogen concentration within the ullage space.

The paper will describe the approach to the testing, the results obtained and their analysis.

1. Introduction

Hydrogen is approximately fourteen times less dense than air, with a specific gravity of 0.0696 (air =1), and a high diffusivity[1]. As a result, hydrogen leaks rapidly disperse with the surrounding air, and even low concentrations can form buoyant pockets/flows when released into the atmosphere[2]. Based on these properties, one approach to control the build-up of hydrogen within enclosures is to employ passive ventilation, which in many ways can be regarded as an "inherently safe" or a "high reliability" approach. This paper describes experimental work that aimed to investigate the feasibility of using passive ventilation to control the hydrogen concentration in a large ullage space to below one quarter of the Lower Explosive Limit (LEL). The large ullage space sits above water, through which hydrogen bubbles were rising at a variety of rates, and from different release configurations.

Project aims and background

The aim of this investigation was to test whether a passive ventilation solution that uses chimneys in the roof of a vessel can manage hydrogen build-up to less than 1% hydrogen by volume in air for a range of hydrogen release rates. The study was performed in the large-scale test rig at HSL (see Figure 1), which is approximately 5.6 m^2 in horizontal cross section. The hydrogen was released from a grid of release points; rising through several meters of water before entering the ullage space that was varied between 0.9 and 3 m in height.

The program was designed to investigate the efficacy of chimney pairs located in different positions, according to the space and location constraints on the rig.

Figure 1. The large-scale test rig at HSL

The majority of these passive ventilation trials were performed with chimney pairs with internal diameters up to 300 mm and the following parameters were investigated:

- Chimney position:

Five combinations of chimney pair locations were investigated, varying both their physical location and separation distance.

- Hydrogen release rate:

Hydrogen flow rates covering the range 0.56 – 2.25 m^3hr^{-1} (equivalent to 9.4 – 37.5 litres/min) were examined.

- Hydrogen release point:

The effect of concentrating the hydrogen release into individual quadrants as opposed to distributing it across the whole area of the base of the tank was investigated.

- Ullage height:

The bulk of the trials were carried out with an ullage height of 0.9 m but a set of tests was also done with a 3 m ullage height for comparison.

- Chimney diameter:

A comparison was made between chimneys having internal diameters of 150 and 300mm.

Models and Curve fitting

Prior to the start of the work, the results from a computational fluid dynamics (CFD) model of the system showed that the time dependence of the hydrogen concentrations in the ullage would be consistent with a simple mass balance equation of the form:

$$\text{conc.} = c.(1 - e\text{-}t/\tau) \qquad [1]$$

where c is the asymptotic final value of the hydrogen concentration, t is time and τ is the time constant of the system.

This mass balance equation was used in the experimental control system software to determine when to end a test. As the data were collected, the software fitted an exponentially rising curve of the form given in equation [1]. From this fit, the software calculated τ, the time constant for the test. After a period preset by the operator, the software applied a preset multiplier to τ to create a duration for the test. After each test, the data were fitted to a slightly different form of equation [1] to produce c or the final hydrogen concentration (Section 2.4).

The Hydrogen Release System

The hydrogen was released within the water in the vessel via a bubbler system which consisted of 100 release positions, designed in a grid pattern over the floor of the tank. Each release position was a syringe barrel connected to the hydrogen supply and a frame which raised the open end of the syringes above the floor of the tank. The syringes were set at an approximate angle of 10 degrees to the vertical. This produced hydrogen bubbles of approximately 20 mm diameter, that rose unimpeded from the open end of the syringe through the water column to the ullage. These bubbles were oblate spheroids (Figure 2).

The steel frames were aligned in pairs a set distance apart and these were laid out as a row of ten pairs with the same set distance between the rows. Figure 3 shows schematically how the rubber tubes were connected to form four grids of 25 interconnected syringes. Each grid covered a quadrant of the floor of the tank and was connected via a non-return valve to a manually operated ball valve situated outside the tank. The inlet side of these ball valves was linked via a manifold. Hydrogen was supplied to this manifold through a mass flow controller (MFC) and ancillary valves. The bubbler could be manually set to release hydrogen from any or all of the four quadrants. The MFC set the required hydrogen flow rate and the pneumatically controlled valve was used by the control system to start and stop the hydrogen flow.

Figure 2: A hydrogen bubble after it has left the open end of a 20 ml syringe.

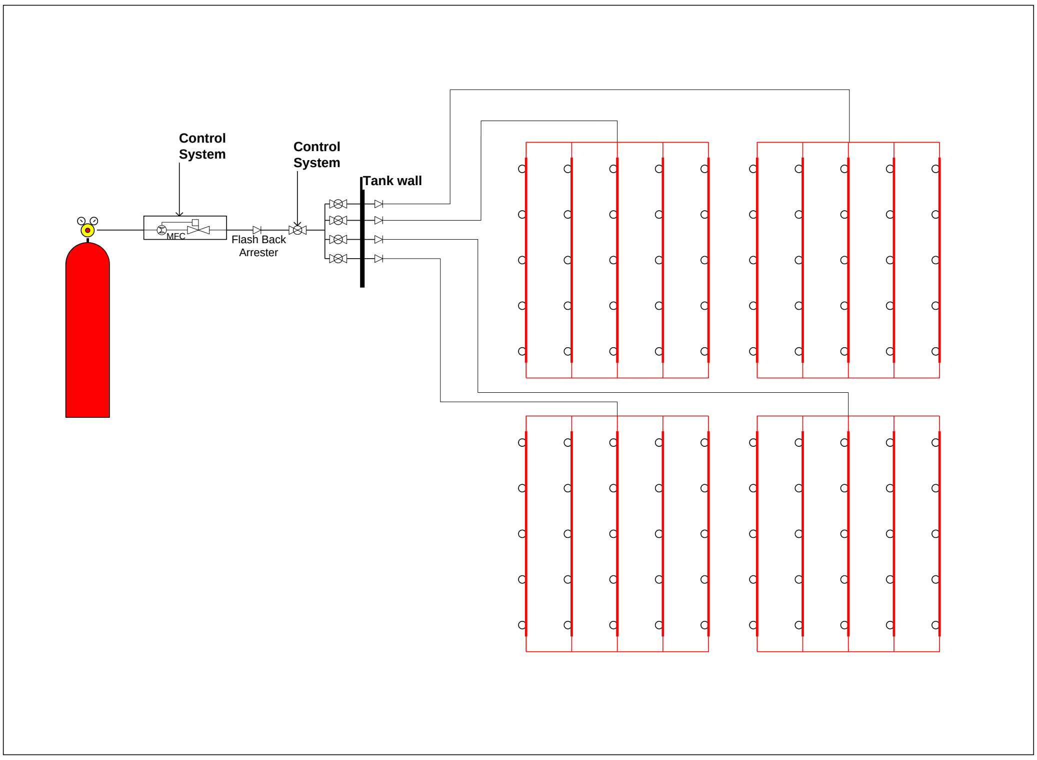

Figure 3: A schematic view of the hydrogen supply and the bubbler array.

Experimental Control System

Although the large scale test rig shown in Figure 1 is designed to withstand deflagrations, a requirement of the project was to minimise the temperature gradient between the water, the air in the ullage and the external atmosphere. The main hindrance to a successful test was the heating of the air within the ullage by solar radiation on the steel walls and roof of the tank. To avoid this, the tests were performed at night, under an automatic control system.

The safety requirements for the trials required that the risk of a hydrogen deflagration in the ullage be minimised. The first step in achieving this was to create a system that would run autonomously while monitoring the hydrogen concentration, and take action if the concentration exceeded a safe threshold. Hydrogen concentration measurement sensors were connected to a logic controller programmed to close the hydrogen supply valve if any of the hydrogen sensors indicated a concentration above the threshold. This also resulted in the termination of the test.

Software logged the hydrogen concentrations from each sensor as the test progressed and fitted the data to an exponential curve of the form given in equation [1]. A time constant could be evaluated and multiples of this value used to calculate an end time for the test if all the hydrogen concentrations were below the safe threshold. At the end of a test, the software initiated a purge procedure to remove the hydrogen within the ullage. The software would then start a further test after a delay specified by the operator; it also controlled running the fan for a given period after all the hydrogen sensor measurements had fallen below a lower threshold and doing the number of tests specified by the operator.

Hydrogen Sensing

Mini-katharometer hydrogen sensors were used, each fitted in a stainless steel housing with a sintered mesh opening to allow the hydrogen to diffuse to the katharometer. Each sensor was positioned at a set distance from the water level. The hydrogen sensors were installed through ports located at various locations on the roof of the test rig.

Ambient Conditions Monitoring

The ambient conditions were logged throughout the tests. The data recorded included wind speed, ambient temperature, barometric pressure, ullage temperature and water temperature. After "flipping" behaviour between chimneys had been noticed in the commissioning trials (see Discussion), differential pressure transducers were also fitted to the chimneys to monitor the pressure difference between the shelter and the inside of the chimney.

Chimneys

Figure 4 shows a 300 mm diameter chimney fitted to a plate that is bolted to the top of the tank. The chimney height is 1.5 m from the ceiling of the tank to the top of the flange. Chimneys were used in pairs and could be fitted to a variety of locations on the tank. Alternative chimneys of 3.0 m length x 150 mm diameter were used during initial commissioning trials.

Shelters

The "shelters", used principally to provide shielding from any wind, were constructed in a similar way to an ordinary garden shed. Internally there was a wooden frame and this was covered with Tyvek to minimise the effects of wind. The outer covering was feather board, with each board having a spacer to create a louvered exterior. Initially a shallow pitched roof was fitted to the shelters. However the commissioning trials showed an unacceptable build-up of hydrogen within the shelters and subsequently the roof was removed, with little detrimental effect on the wind protection. The internal dimensions of the upper half of the shelters were 1.17 m long x 1.06 m wide x 1.04 m high. The internal dimensions of the lower half of the shelter were 1.17 m long x 1.06 m wide x 1.22 m high.

The tops of the chimneys were 1.7 m from the open top of the shelters. Figure 5 shows a 300 mm chimney inside a shelter.

Figure 4: A 300 mm diameter chimney fitted to the top of the tank, showing the hydrogen sensor connection boss and the wooden cap.

Figure 5: A 300 mm diameter chimney, fitted with hydrogen sensor, manometer tube, wooden cap and showing the bottom of the surrounding shelters

Figure 6: Two shelters side by side

Experimental Method

A weather forecast for the Buxton area was used to estimate the optimum start time for the overnight tests. The number of tests and the start time were programmed into the control system; the hydrogen supply was turned on and the system left to run the series of tests overnight. The following morning, the collected data were transferred to the laboratory network and processed to produce graphs of the hydrogen concentrations and the environmental conditions. Using MathCAD, the hydrogen concentration values were fitted to a curve of the form given by equation [2] and extrapolated to estimate the final hydrogen concentration for each sensor.

$$conc = a.\ e^{b.t} + c \qquad [2]$$

This is a more complete form of a simple material balance mathematical model given in equation [1].

Re-arranging equation [2] gives:

$$conc = a(1 - e^{bt}) + (a+c) \qquad [3]$$

where $b = \frac{-1}{\tau}$

In equation [3] the asymptotic change in hydrogen concentration is equal to a and the starting hydrogen concentration is equal to (a+c). This should be zero, i.e. c = -a, and hence the final asymptotic hydrogen concentration is equal to c.

2. Results and Discussion

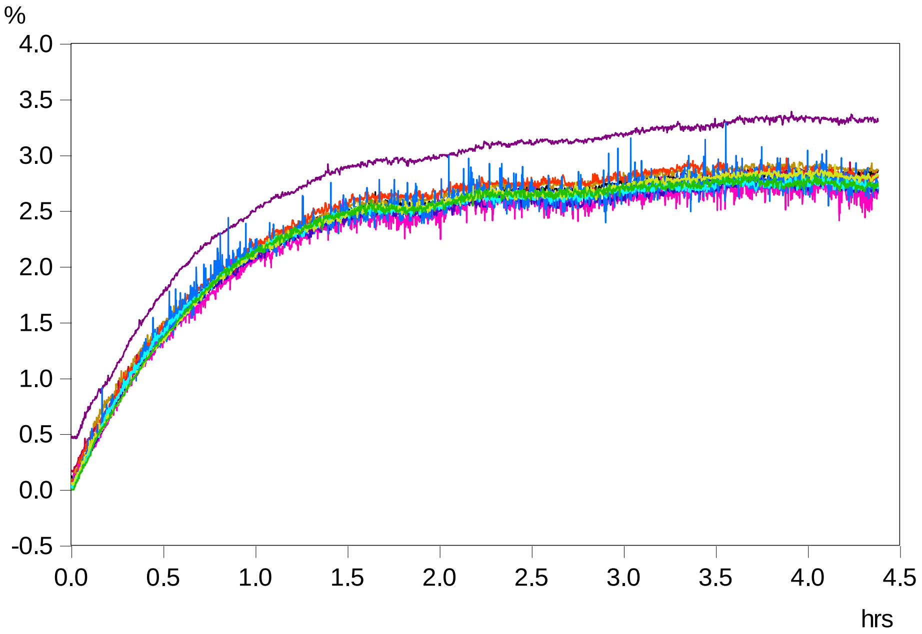

Figure 7 shows a typical set of traces recording H2 concentration as a function of time, with the hydrogen concentration settling to a steady value. One trace clearly has an offset and was omitted from the subsequent analysis.

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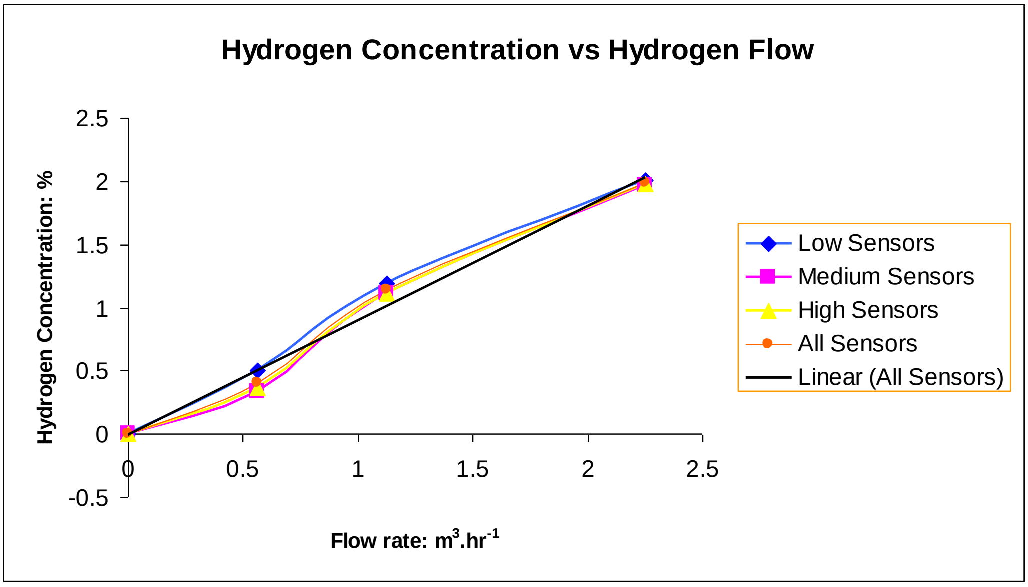

Figure 8: Mean hydrogen concentrations vs. hydrogen flow for 300 mm diameter chimneys located diagonally on the roof, separated by approximately 6.3m., with hydrogen flow bubbling over all quadrants. As would be expected, the hydrogen concentration is proportional to the flow rate.

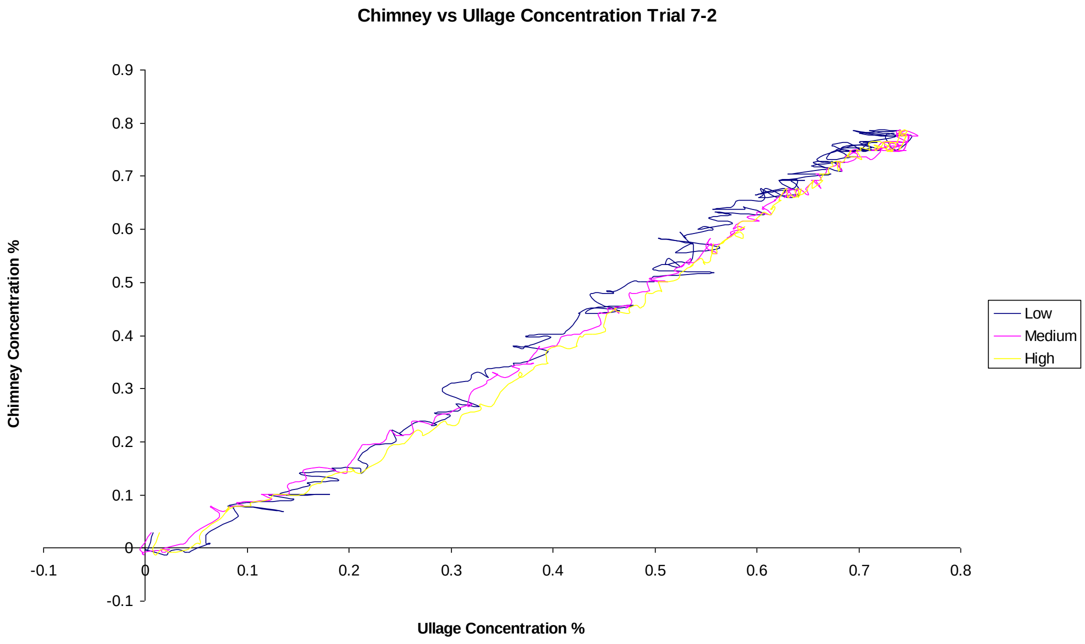

Figure 9: Chimney hydrogen concentrations vs. mean hydrogen concentrations for 300 mm diameter chimneys located diagonally on the roof, separated by approximately 6.3m., with hydrogen flow bubbling over all quadrants.

Commissioning

The first seventeen tests were used for commissioning purposes. These mostly involved optimising the setup of the "shelters" such that they protected the chimneys from the effects of the wind, whilst allowing the hydrogen to escape. The optimum conditions, which met these criteria, involved the removal of the shelters roofs (to prevent the small build-up of H_2 observed within the shelters when they were in place) and incorporation of Tyvek sheeting on the inside of the shelters.

Experimental Results

Taking the hydrogen concentration values from the collected data was not a valid method for determining the final hydrogen concentrations since in some cases, the automated system stopped the tests earlier than would have been desirable. This occurred mainly as a result of the variation in the ventilation rate during the tests due to changing weather conditions.

This can be seen by re-examining equation [1], where c and τ can be determined from the physical parameters of the system and are given by:

$$\tau = \frac{V}{Q}$$

and

$$c = \frac{G}{Q}$$

where V= ullage volume, m^3

Q = ventilation rate, m^3.hr-1
G = rate of hydrogen production, m^3.hr-1

Equation 1 can be re-written as a simple material balance mathematical model (Earnest) in the form:

$$\text{conc.} = \frac{G}{Q}(1 - e^{-tQ/V}) \quad [4]$$

The final hydrogen concentration is thus proportional to the rate of hydrogen release and inversely proportional to the ventilation rate. This explains the variability of results from nominally the same test. In the experimental system, the hydrogen concentration, ullage volume and rate of hydrogen production are known. The ventilation rate is unknown and could be calculated for each test. This would give a better comparison of tests that are nominally the same. However these calculations are beyond the scope of this paper.

3. Key Findings

The main objective of this study was to establish whether the hydrogen concentration within an ullage space, due to chronic hydrogen generation, could be kept below the target of 1% by volume using passive ventilation of the vessel. If achievable, the intention was then to investigate the sensitivity of the performance of such a system to a range of parameters, including: chimney location, ullage height, and hydrogen flow rate/distribution.

A total of 69 individual tests were carried out using a range of experimental conditions and the key findings from this study, which are summarised in Table 1, were:

Chimney Position Sensitivity

Some variation in the final hydrogen concentration was seen with chimney location. The pair of 300 mm chimneys, located along the midline of the roof of the test rig appeared to be the most effective.

The “worst case” for the 300 mm chimneys, giving the highest final ullage hydrogen concentration under these conditions was a pairing located close together on the roof.

The observed differences with chimney location are however considered to be relatively small and may be approaching the experimental variability resulting from other factors, such as e.g. ambient weather conditions.

Hydrogen Release Rate Sensitivity

A series of trials was carried out using the 300 mm chimneys in locations on diagonally opposite corners of the rig, in which the hydrogen was released at three rates (0.56 m^3hr^{-1}, 1.125 m^3hr^{-1} & 2.25 m^3hr^{-1}), evenly distributed across the base of the tank. Under these conditions the final hydrogen concentration was observed to show a roughly linear dependence on release rate (Figure 8). This would be expected from equation [4] where final hydrogen concentration is proportional to the hydrogen release rate. The final hydrogen concentration was inversely proportional to the ullage ventilation rate. The deviation from the best fit line most likely reflects changes in the weather conditions during the tests which in turn resulted in somewhat variable ventilation rates (Figure 8).

Hydrogen Release Point Sensitivity

As noted above, the bubble release system was constructed such that the hydrogen could either be distributed over the whole area of the base of the test vessel or released into selected individual quadrants. There was some evidence of a small difference in the final hydrogen concentration in the ullage space between releases made from individual quadrants compared to releases evenly distributed across the base of the tank (for 300 mm chimneys, with the same total flow rate in each case of

1.125m^{3}hr^{-1}). Under these conditions, the final hydrogen concentration in the ullage was somewhat lower when the gas was released into a single quadrant.

Ullage Height Sensitivity

A comparison was made between ullage heights of 0.9 and 3.0 m, using the 300 mm at a hydrogen release rate of 1.125m^{3}hr^{-1}. The increased ullage height resulted in a reduction in the final hydrogen concentration in the ullage space from 1.13 to 0.73%.

Chimney Diameter Comparison

For a hydrogen release rate within the ullage of 1.125m^{3}hr^{-1}, chimneys of a nominal 300 mm diameter were found to be needed reach a final, plateau concentration of 0.7 – 1.3%, depending on the other experimental conditions.

From a comparison of the results from 150 mm and 300 mm diameter chimneys (both 1.5m. in length in this case), there was some indication that hydrogen concentration is inversely proportional to diameter. The 150 mm chimneys gave a mean hydrogen concentration of 2.55% while the 300 mm chimneys gave a mean concentration of 1.27%.

Ambient Conditions

Every effort was made to try and minimise the influence of ambient weather conditions on the results from this study, through the design of the "shelters" used to shield the chimneys. In addition, the trials were performed overnight and, whenever possible, in calm weather to minimise issues relating to temperature variations and wind effects, respectively.

General Observations

In all of the trials, the data from the hydrogen sensors were found to follow the expected material balance model, with the hydrogen concentration in the ullage reaching a final, plateau value. This enabled curve fitting to be used effectively to establish the final hydrogen concentration in the ullage space. In a few tests some of the hydrogen sensors produced data that could not be fitted to the material balance model curve and in these cases the values were omitted from the table of results. In most cases the failure to fit a curve was due to the data recording period being too short coupled with a noisy trace.

Similarly, while in a few cases the data could be fitted to the curve, the final value for the hydrogen concentration was substantially higher than the values from the other sensors in the ullage. These values have been omitted from the calculations of mean values. In most of these cases the data recording period was again too short and the trace noisy.

Hydrogen sensors were fitted in a range of locations within the tank, in an attempt to establish whether there was any variation in the hydrogen concentration or stratification of the gas in the ullage space. While some variability is apparent, the differences appear relatively small (to within approximately 0.2% of the overall mean hydrogen concentration) and an initial analysis does not reveal any consistent pattern. A further, more detailed statistical analysis of the data was felt to be outside the scope of the current investigation.

In some instances, "flipping" behaviour was observed whereby the two chimneys switched between inlet and outlet mode, sometimes rapidly and repeatedly. It is thought that this might be related to the wind conditions at the time of these particular tests, but this is unproven and would need further investigation. It should be noted however, that there is no indication that the "flipping" results in a deterioration of performance in terms of managing the hydrogen concentration within the tank.
The readings from the hydrogen sensor located in the output chimney can, in some circumstances, provide an accurate representation of the mean concentration within the ullage space. The graph in

Figure 9 shows a reasonably linear relationship between the concentration measured in the chimney and the concentrations measured in the ullage. However it should be noted for the graph shown, there was no “flipping” between chimneys. It must also be borne in mind that there will be some transport delay between the hydrogen concentration measured in the chimney and that found in the ullage.

4. Conclusions

Based on the programme of tests performed, it has been demonstrated that the use of a pair of chimneys (of appropriate size) provides an effective means to passively ventilate a large ullage space and remove hydrogen.

For a hydrogen flow rate of $1.125 m^3 hr^{-1}$ released over the full area of the ullage, the results obtained from the trials show that two 300 mm diameter chimneys maintained the hydrogen concentration in the ullage in a range between 0.9% and 1.5% vol/vol. When the same hydrogen flow rate was released over a single quadrant of the vessel, the chimneys maintained the hydrogen concentration in the chimney between 0.75% and 1.2% vol/vol.

Although this work clearly demonstrates the power of the passive ventilation technique, a combination of factors need to be considered when designing a system for plant to reach the overall ALARP (5) solution with respect to management of hydrogen. These include chimney diameter, hydrogen generation rate, acceptable performance criteria (50% or 25% of LEL), hydrogen release distribution and temperature effects.

TABLE 1. Results Summary

Chimney Position

Chimneys	Location	H2 Flow (m^3/hr)	Average [H_2] (%)	Release Point	Ullage Height (m)
2 x 300mm	Midline, 3.6m separation Diagonal, 6.3m separation Parallel to Roof Edge, 1.3m separation	1.125 " "	0.7 1.13 1.27	Overall " "	0.9 " "

Hydrogen Release Rate

Chimneys	Location	H2 Flow (m^3/hr)	Average [H_2] (%)	Release Point	Ullage Height (m)
2 x 300mm	Diagonal, 6.3m separation " "	2.25 1.125 0.56	1.98 1.13 0.38	Overall " "	0.9 " "

Hydrogen Release Point

Chimneys	Location	H2 Flow (m^3/hr)	Average [H_2] (%)	Release Point	Ullage Height (m)
2 x 300mm	Diagonal, 6.3m separation "	1.125 "	1.13 0.73	Overall Single Quadrant	0.9 "

Ullage Height

Chimneys	Location	H2 Flow (m^3/hr)	Average [H_2] (%)	Release Point	Ullage Height (m)
2 x 300mm	Diagonal, 6.3m separation "	1.125 "	1.13 0.73	Overall "	0.9 3

Chimney Diameter

Chimneys	Location	H2 Flow (m^3/hr)	Average [H_2] (%)	Release Point	Ullage Height (m)
2 x 300mm 2 x 150mm	Parallel to Roof Edge, 1.3m separation "	1.125 "	1.27 2.56	Overall "	0.9 "

5. REFERENCES

1. ISO/TR 15916, “Basic Considerations for the Safety of Hydrogen Systems”, section 6.2.2

2. Barley C.D,, Gawlik K, Ohi J and Hewett R, 2007 “Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings”, Conference Paper NREL/CP-560-41081, August 2007.

3. Earnest, G S; Mickelsen, R L; McCammon, J B; O'Brien, D M, Carbon monoxide poisonings from small, gasoline-powered, internal combustion engines: Just what is a "well-ventilated area"?, American Industrial Hygiene Association Journal, Volume 58, Issue 11, November 1997, Pages 787-791

4. XEN-TCG 3880 Data Sheet http://www.xensor.nl/pdffiles/sheets/xen-tcg3880.pdf Hydrogen Concentration vs. time graphs

5. Control and Mitigation Measures, Dangerous Substances and Explosive Atmospheres Regulations 2002, Approved Code of Practice and Guidance, HSE Publication L136, 2003, ISBN 978 0 7176 2201 6