HYDROGEN VENTING UNDER VARIABLE FLOW CONDITIONS

Willoughby[1] D.B, Royle[1] M, Nilsen[2] S, Gautier[3] T .

[1]Health & Safety Laboratory UK

[2]Statoil ASA Norway

[3]Shell Global Solutions (U.K.)

Health and Safety Laboratory, Buxton, Derbyshire, SK17 9JN, United Kingdom, Tel 01298 218120, Fax 01298 218162, Deborah.willoughby@hsl.gov.uk

This publication and the work it describes were partly funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

ABSTRACT

Safety distances for hydrogen plumes are currently derived using models developed for hydrocarbon releases. It is well known that hydrogen behaves in a significantly different manner to that of hydrocarbons when released to atmosphere. There are two main aspects involved with the development of safety distances for credible hydrogen releases; the intensity of the thermal radiation from such a plume should it be ignited, and the distance downwind from the release point to the point where a flammable mixture with air no longer exists.

A number of distinct areas of venting behaviour were investigated;

Thermal radiation from ignited plumes from vertical open ended vent pipes

Far field radiation measurements for direct comparison with models

Thermal radiation from ignited plumes from vertical vent pipes terminating in a T-piece

Thermal radiation measurements from ignited hydrogen with a 45° vent termination

Hydrogen concentration measurements with a T-piece

Keywords: Thermal radiation, Ignited hydrogen plume, Hydrogen, Vent termination

1.0 INTRODUCTION

Safety distances for hydrogen plumes are currently derived using models developed for hydrocarbon releases. Hydrogen behaves in a significantly different manner to that of hydrocarbons when released to atmosphere. Therefore, work was carried out to investigate the effects of releasing hydrogen at various release rates to simulate emergency venting from hydrogen storage. The maximum release rate simulated a release of hydrogen from a 2 inch vent on an industrial facility. Smaller releases were also made to simulate other realistic scenarios, such as venting from forecourt type storage.

Thermal radiation from ignited plumes and concentration contours from unignited hydrogen releases were determined. Two different sized vent pipes were used together with a range of flow restrictors to provide varying flow conditions.

2.0 TEST FACILITY AND SET-UP

2.1 Test facility

The tests were performed on a 32 m diameter pad. The test facility comprised;

Hydrogen tube trailer containing 4000 m^3 of hydrogen at 228 bar;

Trailer connection and emergency shut off valve (ESOV);

6 m of 1” stainless steel tubing (release pipework), flow-meter and remotely operated valves to deliver hydrogen to the release point,

5.5 m high ¾” nominal bore and 2” nominal bore vent pipes;

Local instrument cabin (15 m from the vent stack) containing the signal conditioning units and data logging system and control plc;

Remote control room (150 m from the firing pad) with video displays of the trials area and the networked control system.

2.2 Release configuration

The vent stack was located in the centre of the 32 m diameter pad, and 6 m of horizontal 1” diameter pipe-work ran from the bottom of the stack to the hydrogen tube trailer. The release of gas was controlled by means of two valves: an emergency shut off valve at the tube trailer end and an experimental release valve at the stack end. Pressure and flow were measured by means of instrumentation located along the release pipe. Two 5.5 m high vent pipes were available for use, one ¾” nominal bore and one 2” nominal bore. The flow of hydrogen through either of the vent pipes could be restricted by means of orifice plates located at the bottom of the vent pipe.

3.0 EXPERIMENTAL MEASUREMENTS

The following experimental measurements were made:

Heat flux

Hydrogen concentration

Flow

Visual

Meteorological

Heat flux measurements were made using fast response (50 ms) ellipsoidal radiometers, which measure only radiative heat. The range was 110 kW/m^2 with a 160° field of view. The sensors were mounted on poles at a height of 1.8 m. The far field measurements were made using two fast response (100 ms) ellipsoidal radiometers with a range of 11kW/ m^2. These sensors were located at 25 and 40 m from the vent and nominally aimed towards the expected flame position, such that at these large distances the flame could be assumed to be a point source of radiation.

Oxygen sensors were used to measure oxygen depletion within the unignited cloud. Hydrogen concentrations were derived from these measurements.

Meteorological measurements - The air temperature, relative humidity, wind speed and direction were measured at the instrument cabin 16 m from the release location using an FT Technologies ultra-sonic anemometer and a Vector Instruments weather station. This comprised wind speed, wind direction, temperature and humidity measurement mounted 3.5 m above the ground.

4.0 IGNITED RELEASES

4.1 Open ended pipes

Releases of hydrogen were made through a 5.5 m high, ¾” diameter pipe and a 5.5m high, 2” diameter pipe (see Figure 1) both with and without a flow restrictor in place. The flow restrictors were a simple orifice, sized to provide flow rates of 40, 80 and 200 g/s at an upstream pressure of 200 bar. Without a restrictor a flow rate of 400g/s was obtained with the 2” pipe and 350g/s with the ¾” pipe. The release of hydrogen was ignited by means of pilot lights located at heights of 0.5 m and 1.5 m above the vent pipe exits.

Figure 1. Release system

4.2 T-piece vent termination

A T-piece with 200 mm lengths of pipe with ends cut at 60° was fixed onto the 2” and ¾” pipes. The release of hydrogen was ignited by means of propane pilot lights located 750 mm from each cut end.

4.3 45° Shrouded vent termination

A 45° shrouded vent termination was fitted to the ¾” pipe. The release of hydrogen was ignited by means of propane pilot light close to the vent exit.

Figure 2(a). T-piece termination

Figure 2(b). Shrouded vent

5.0 RESULTS

Ignited releases of hydrogen were performed at three flow rates, the results through both ¾” and 2” are given below. The radiometers were mounted on poles at a height of 1.8 m and angled in towards the release. The distances from the vent were 2, 3, 4, 5, 7, 9, 25 and 40 m.

5.1 2” Vent pipe

The maximum heat flux recorded at varying distances from the vent is given in Table 1. The weather conditions are summarized in Table 2**.**

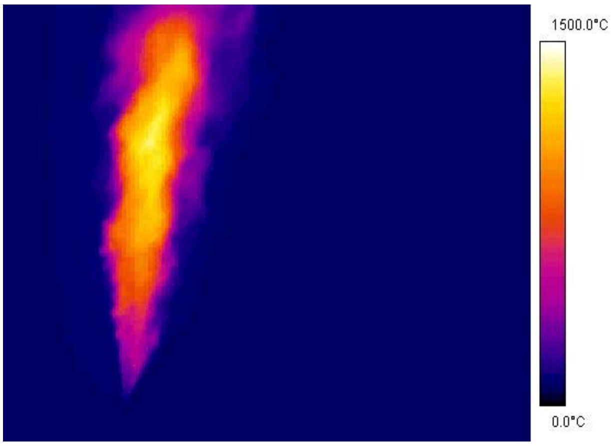
Table 1. Maximum and average heat flux (kW/m^2) recorded at different distances from the vent

Distance from vent (m)	Nominal flow rate g/s					
	80		200		400	
	Maximum	Average	Maximum	Average	Maximum	Average
2	8.0	5.65	16.6	10.17	13.7	9.43
3	6.8	5.11	10.3	7.97	6.5	5.37
4	6.0	4.59	9.9	7.37	7.1	5.74
5	4.0	2.76	5.7	4.12	6.9	3.11
7	3.6	2.06	5.7	4.37	5.84	4.0
9	2.4	1.32	4.1	3.21	5.3	4.13
25	0.2	0.10	0.3	0.33	0.7	0.61
40	0.1	0.06	0.2	0.19	0.3	0.27

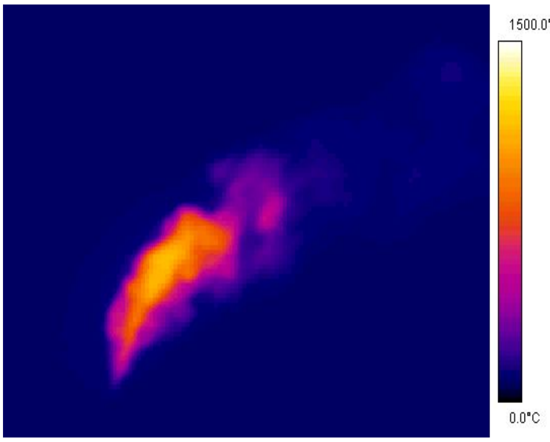
Table 2. Temperature, humidity, wind speed and wind direction

Flow rate (g/s)	Humidity (%)	Temperature (°C) at release height	Average wind speed (m/s) at release height	Deviation of wind direction relative to radiometer position (°)
80	84	1.6	2.5	15
200	83	1.6	4.2	19
400	90	0.3	3.2	3

Thermal images for hydrogen releases at 80 g/s and 400 g/s are shown below; note the temperature scale is for indication purposes only, as the camera was not adjusted precisely for thermal emissivity because of uncertainties in the values for thermal emissivity of hydrogen flames.



400 g/s release



80 g/s release

5.2 3/4”Vent pipe

The maximum heat flux recorded at varying distances from the vent is given in Table 3. The weather conditions are summarised in Table 4.

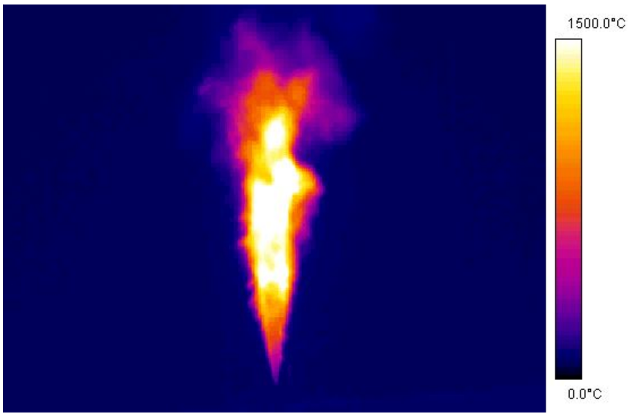
Table 3. Maximum and average heat flux (kW/m^2) recorded at different distances from the vent

Distance from vent (m)	Nominal flow rate g/s					
	80		200		350	
	Maximum	Average	Maximum	Average	Maximum	Average
2	3.4	2.32	7.8	5.77	10.8	7.62
3	2.4	1.97	4.8	4.07	6.5	5.12
4	2.2	1.95	3.4	3.10	7.3	5.51
5	1.5	1.01	2.6	1.87	4.1	2.93
7	1.7	1.11	3.7	2.94	4.9	3.88
9	1.6	1.23	2.6	2.06	5.4	3.82
25	0.1	0.06	0.3	0.28	0.6	0.45
40	0.1	0.04	0.2	0.15	0.2	0.19

Table 4. Temperature, humidity and wind direction

Flow rate (g/s)	Humidity (%)	Temperature (°C) at release height	Average wind speed (m/s) at release height	Deviation of wind direction relative to radiometer position (°)
80	92	-1.1	1.6	75
200	84	1.5	1.9	8
350	89	-0.7	4.5	75

Thermal images for hydrogen releases at 80 g/s and 350 g/s are shown below; note the temperature scale is for indication purposes only, as the camera was not adjusted precisely for thermal emissivity because of uncertainties in the values for thermal emissivity of hydrogen flames.



350 g/s release

80 g/s release

5.3 Visible flame extent for ignited releases

Four releases were carried out at night in high wind speed conditions to establish flame height and flame skew. Heat flux measurements were not made on these tests. The results of the flame heights and skew are shown below in Figures 3(a), (b), (c) and (d). The average wind speed during these releases was 10m/s.

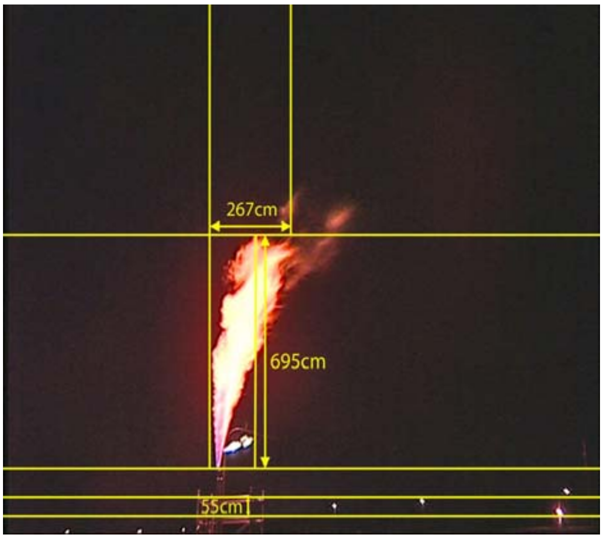


Figure 3(a). 350 g/s release ¾” pipe

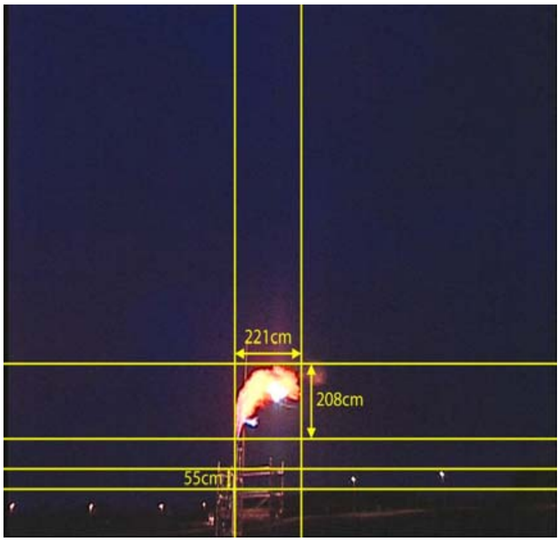


Figure 3(b). 40 g/s release ¾” pipe

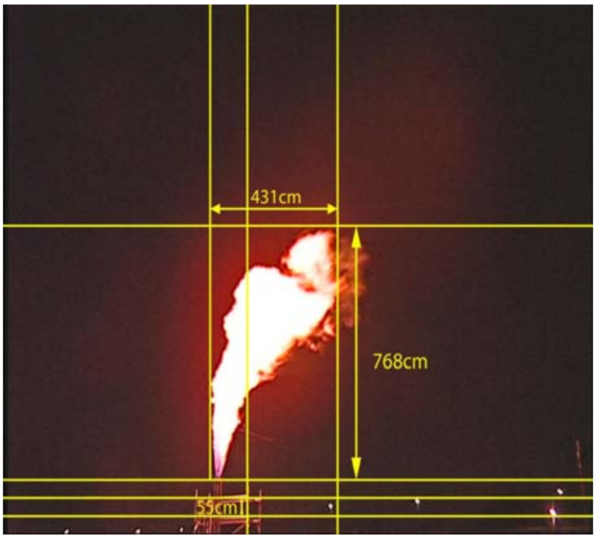


Figure 3 (c). 400 g/s release 2” pipe

Figure 3 (d). 40 g/s release 2” pipe

5.4 T-piece termination 2” and ¾” pipes

A total of four ignited releases were performed using two different flow rates. The measured maximum and average heat fluxes are summarised in Tables 5 and 6. The wind speed during the releases was between 2 – 3 m/s.

Table 5. Heat flux (kW/m^2) recorded at different distances from the vent 2” pipe

Position from vent (m)	2” pipe Nominal Flow rate			
	Test number 2T 40 g/s		Test number 3T 400 g/s	
	Max	Average	Max	Average
2	27.5	13.9	42.2	35.5
3	13.3	5.4	33.3	27.6
4	9.5	4.4	36.7	28.2
5	6.0	2.5	35.3	25.8
7	1.0	0.5	22.5	11.7
9	0.5	0.3	8.9	5.6

Table 6. Heat flux (kW/m$^{2)}$ recorded at different distances from the vent 3/4” pipe

Position from vent (m)	3/4” pipe Nominal Flow rate			
	Test number 6T 40 g/s		Test number 5T 350 g/s	
	Max	Average	Max	Average
2	8.5	6.8	33.1	26.9
3	4.6	3.4	26.9	21.6
4	3.6	2.7	42.9	27.3
5	2.3	1.5	38.7	25.3
7	0.5	0.3	21.2	11.6
9	0.3	0.1	10.9	5.7

5.5 Visible flame extent for ignited releases

Two releases were carried out at night to establish flame projection. Heat flux measurements were not made on these tests. The average wind speed during these releases was 2.7m/s for ¾” release and 1.4m/s for the 2” release. The wind direction was northerly and the T-piece was orientated in a north-south direction. The results of the flame heights and distances are shown in Figures 4 and 5.

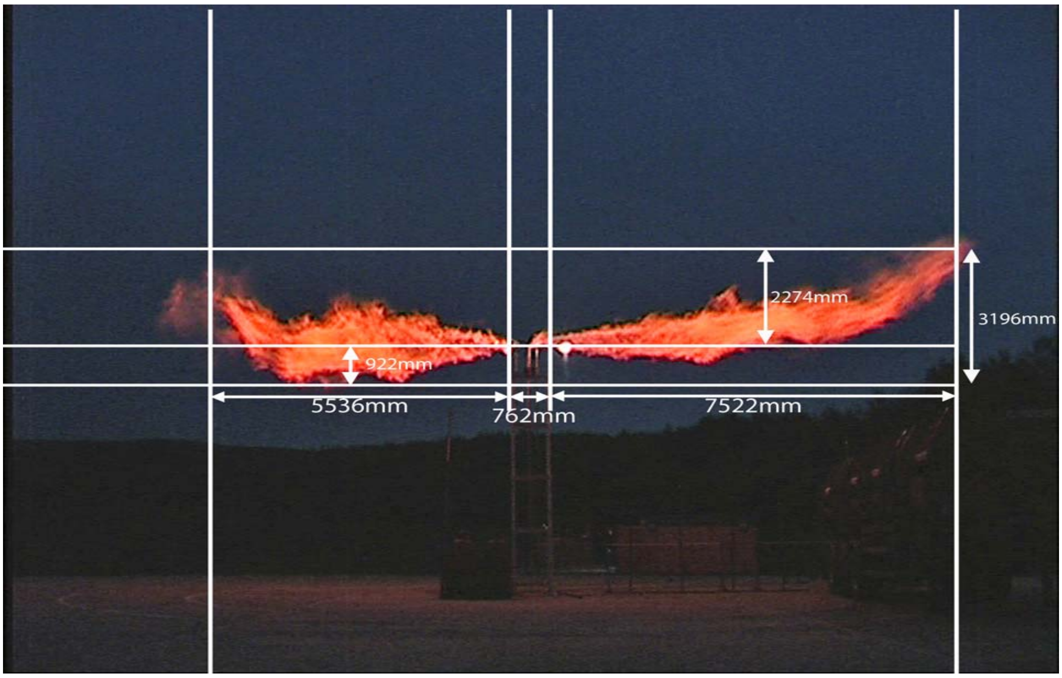


Figure 4. Visible flame releases – 2” Pipe 400g/s release T-piece fitted

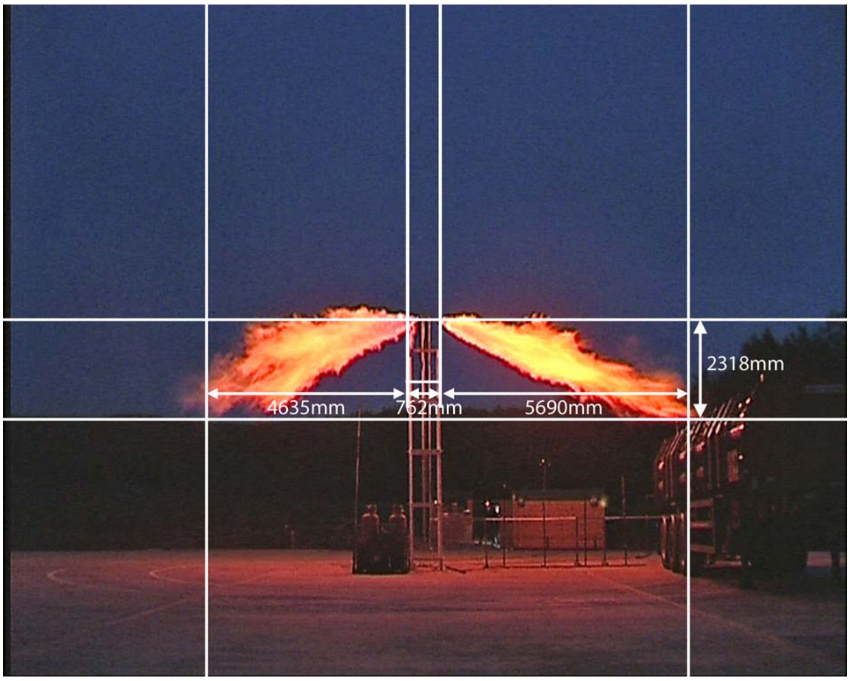


Figure 5. Visible flame releases – ¾” Pipe 350g/s release T-piece fitted

5.6 45° shrouded vent termination - ¾” pipe ignited release

Two ignited releases were carried out at hydrogen flow rates of 350g/s and 40g/s. The maximum heat flux recorded with increasing distance from the vent is given in Table 7.

Table 7. Heat flux (kW/m^2) recorded at different distances from the vent 3/4” pipe

Position from vent (m)	Flow rate - 350 g/s		Flow rate - 40 g/s	
	Max	Average	Max	Average
2	20.5	9.76	1.7	1.08
3	11.6	5.97	1.1	0.89
4	9.6	5.28	0.23	0.13
5	16.8	9.01	0.84	0.41
7	7.8	3.71	0.13	0.04
9	6.0	3.15	0.14	0.05

The weather conditions are summarised in Table 8

Table 8. Temperature, humidity and wind direction

Flow rate (g/s)	Humidity (%)	Temperature (°C) at release height	Average wind speed (m/s) at release height	Deviation of wind direction relative to radiometer position (°)
350	100	3.2	1.0	200
40	100	2.6	1.2	190

5.7 Shrouded vent visible flame release

A 350g/s release was carried out at night to establish flame projection. Heat flux measurements were not made on this test. The average wind speed during this release was 1.0 m/s. The visible flame can be seen in Figure 6 below. The dimensions of the flame are 5.6m long and 1.9m wide.

Figure 6. Visible flame releases – 45° shrouded vent termination

5.8 Un-ignited releases 3/4" vent pipe – T piece

An un-ignited release at 350g/s was performed. Fifteen concentration measurements were deployed in the same direction as one arm of the T-piece. The heights and distances were based on the flame trajectory observed in the ignited tests. The sensor positions relative to the vent exit (T-piece) are shown in Figure 7.

Maximum hydrogen concentrations at each position are shown in Table 9.

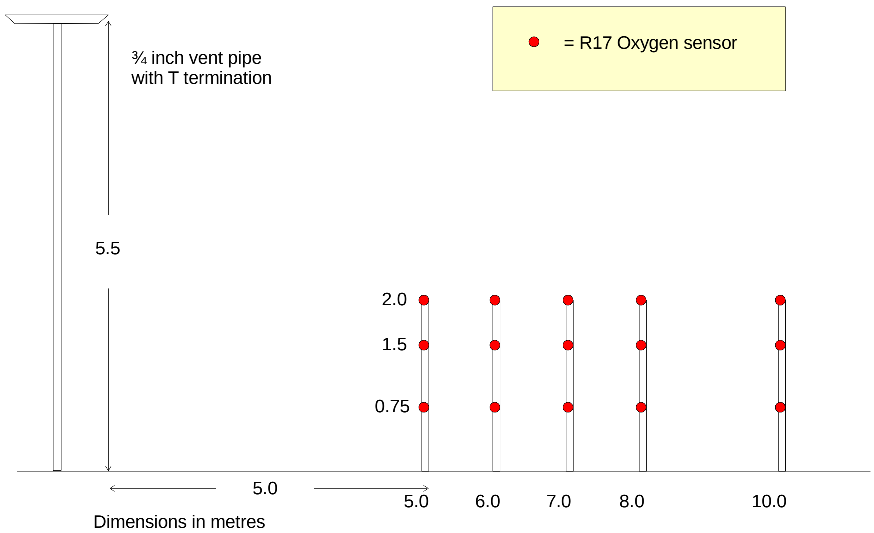


Figure 7. Location of oxygen sensors relative to release point

Table 9. Hydrogen concentrations (% vol) recorded at different distances and heights for release

Height of sensor (m)	Distance from T-piece (m)				
	5	6	7	8	10
2.0	1.7	3.0	4.9	5.6	5.9
1.5	0.9	2.1	3.4	4.0	5.4
1.0	0.4	0.8	1.7	2.7	3.7

The weather conditions are summarised in Table 10.

Table 10. Temperature, humidity and wind direction

Flow rate (g/s)	Test No.	Humidity (%)	Temperature (°C) at release height	Average wind speed (m/s) at release height	Deviation of wind direction relative to concentration sensor position (°)
350	02	94	8.1	2.0	3

6.0 DISCUSSION

6.1 Heat flux intensity against distance for vertical releases

Figure 8 and 9 show the measured heat flux versus line of sight distance between the radiometers and the release point at the top of the vent stack. For comparison, the heat flux has also been calculated using the inverse square law and the measured heat flux at the far field distance of 40m. It can be seen that at larger distances from the release point, there is reasonable agreement between the calculated and measured values. However, closer to the release point the fit is not so good with the inverse square law over-estimating the heat flux. It is thought that this is due to the fact that closer to the vent stack there is less area of flame presented to the radiometer, since the flame has a tendency to point upwards thereby presenting a greater area sideways than it does downwards. This is particularly true for the 3/4" vent.

For the purposes of setting safe distances from hydrogen vented at some height above the ground, it is more representative to use the actual measured heat flux data rather than that predicted from the inverse square law relationship for the reasons discussed above. It was found that an exponential regression gave a better fit to the experimental data in the region where the heat flux values are of interest and so this was used for the suggested safe distances referred to in this paper.

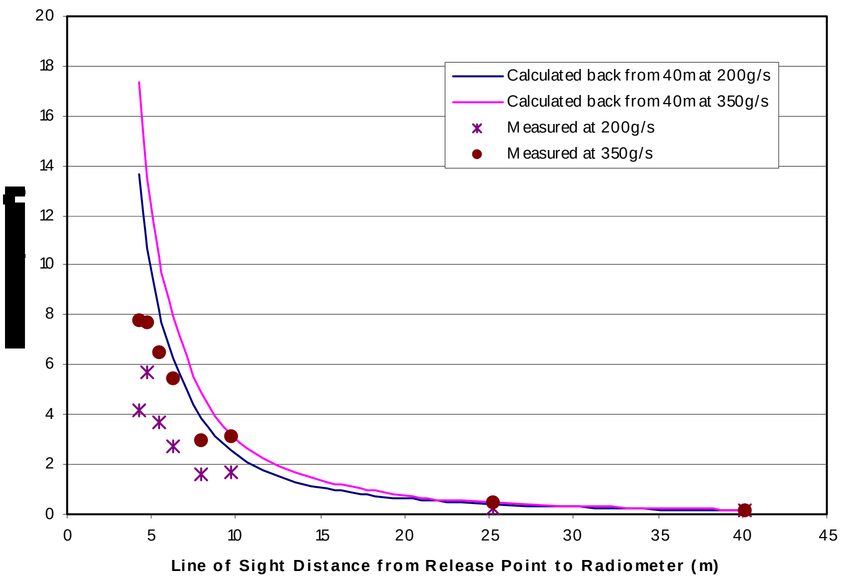


Figure 8**.** Measured heat flux intensity versus inverse square law calculation – 3/4” Pipe

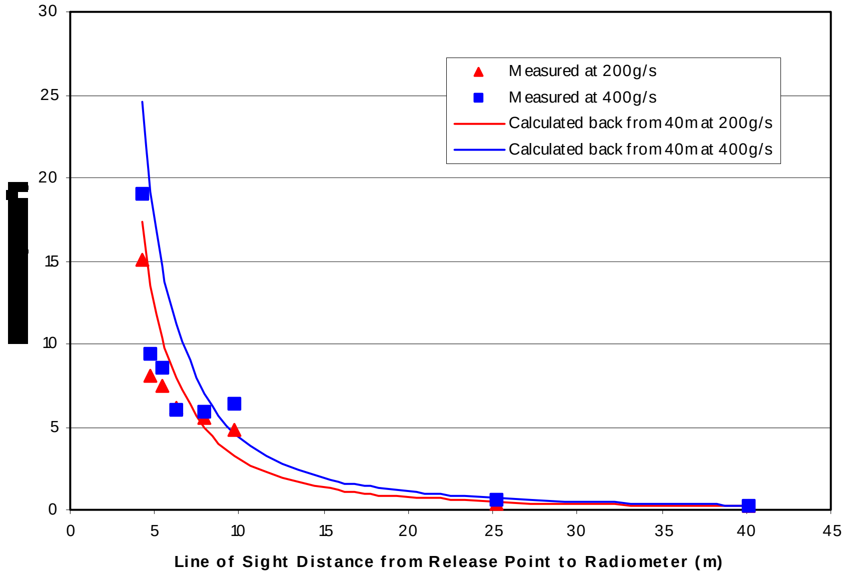


Figure 9. Measured heat flux intensity versus inverse square law calculation – 2” Pipe

The graphs shown in Figures 10 and 11 show the intensity of heat flux against distance from the bottom of the vent stack for the ¾” and 2” releases.

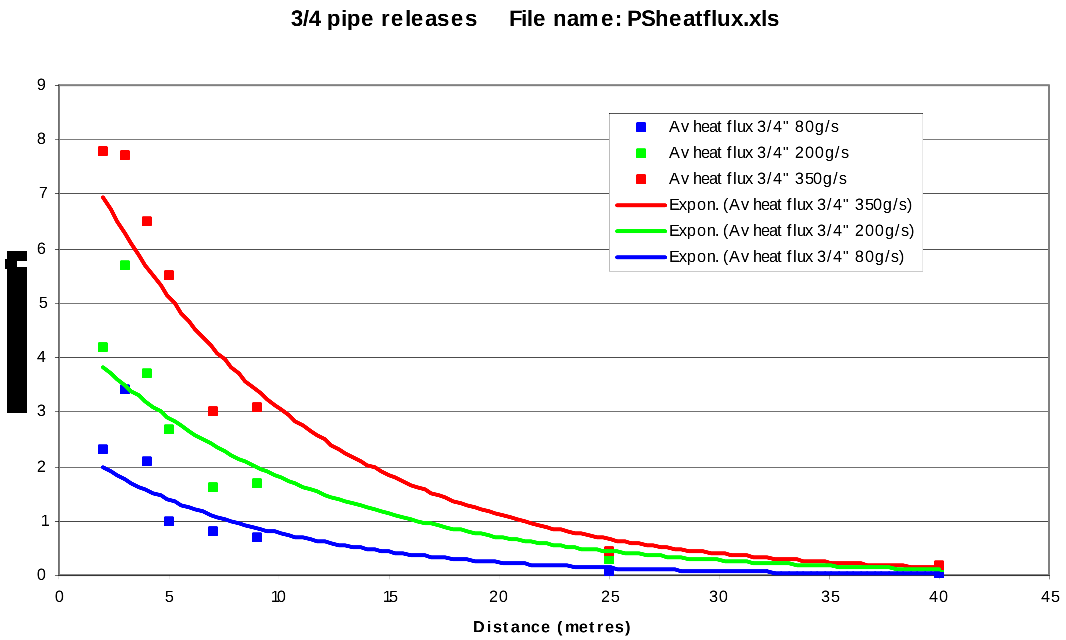


Figure 10. Heat flux intensity against distance – ¾” Pipe

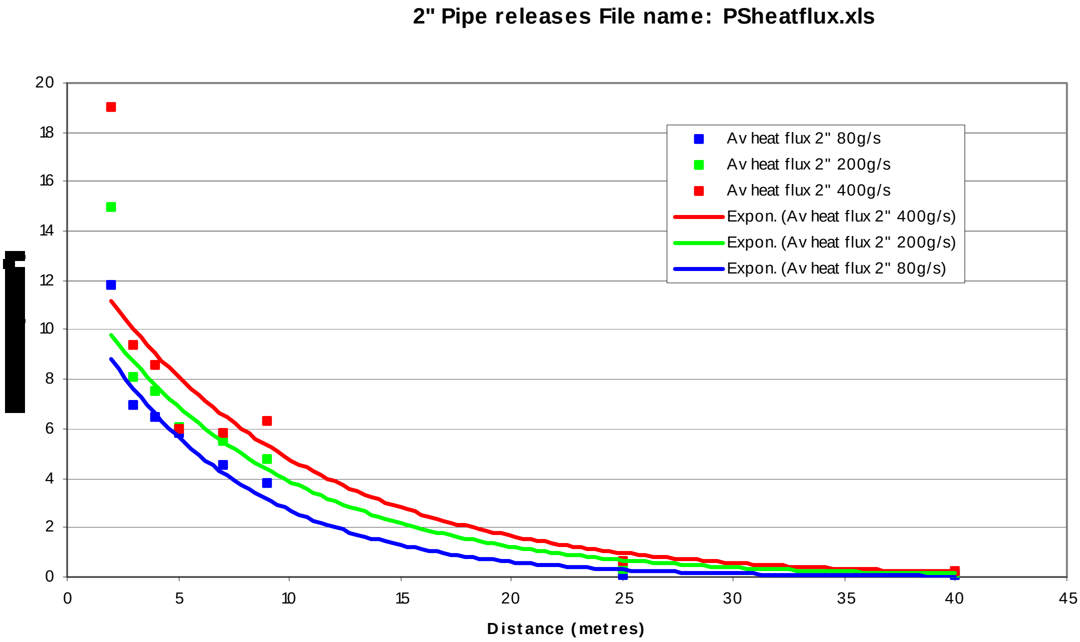


Figure 11. Heat flux intensity against distance – 2” Pipe

A suggested no harm level for long exposure to radiation from a jet fire is 1.6 kW/m^2 [1], however, at this level a normally clothed person could withstand an extended period of exposure without being harmed. Setting safety distances based on this level would therefore be overly cautious.

The level of harm from thermal radiation is not simply a matter of the level of radiation experienced, the time for which it is experienced is also a factor. For this reason levels of harm are usually related to a thermal dose unit (TDU) expressed as:

$$TDU = I^{4/3}\, t \qquad (1)$$

Where I - thermal radiation intensity in kW/m^2; and t - time in seconds.

Table 11 shows the range of selected experimental burn data for infrared radiation.

Table 11. Burn versus thermal dose relationship

Harm caused	Infra-red radiation thermal dose (TDU) $(kW/m^2)^{4/3}$ s	
	Mean	Range
Pain	92	86-103
Threshold first degree burn	105	80-130
Threshold second degree burn	290	240-350
Threshold third degree burn	1000	870-2600

Plotting the dose v time relationship for 2 kW/m^2 and 5 kW/m^2 of thermal radiation intensities gives the graph shown in Figure 10. The horizontal line on the graph indicates the mean data for the harm criteria “pain” as shown in Table 11 and taken from Stoll and Green[2]. This indicates that for a 5 kW/m^2 thermal radiation intensity, an exposure time of 10 seconds is necessary to produce pain. It can also be seen that an exposure time of 35 seconds is required to produce pain at a thermal radiation intensity of 2 kW/m^2.

EIGA use a pain threshold of 8 seconds at 9.5 kW to calculate their safety distances, this equates to 160 TDU whereas the data used from Stoll & Green gives an average pain threshold of 92 TDU. The different figures can be justified by the target populations in each application; EIGA guidance is aimed at industry and a largely protected population of workers. In this case, hydrogen flares on public facilities with an unprotected target population were being addressed.

The definition of a safety distance taken from EIGA IGC 75/07[3] is as follows:

The safety distance is the minimum separation between a hazard source and an object (human, equipment, environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a major incident.

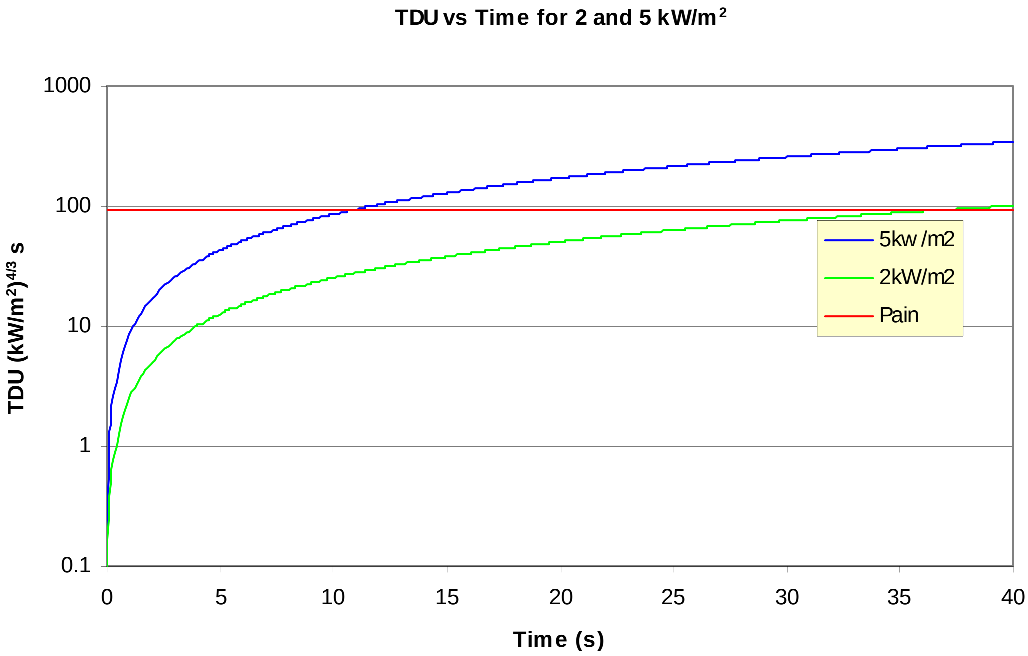


Figure 10. Dose versus time relationship

Using the results obtained from the experiments and exponential fit, Table 12 shows the distances at which a thermal radiation intensity of 5 kW/m^2 would be experienced.

Table 12. Distance to 5 kW/m^2 intensity of each release

Nominal flow rate (g/s)	Distance (m) 2" vent	Distance (m) 3/4" vent
80	6.0	N/R
200	7.5	2.3
400	9.5	4.7

N/R = level not reached

Table 13 shows distances at which a thermal radiation intensity of 2 kW/m^2 would be experienced.

Table 13. Distance to 2 kW/m^2 intensity of each release

Nominal flow rate (g/s)	Distance (m) 2” vent	Distance (m) 3/4” vent
80	12.0	2.0
200	14.0	9
400	18.5	14.2

6.2 Ignited T piece effects

This type of vent termination resulted in increased thermal radiation at ground level when compared to a vertical vent, due to the production of an almost horizontal jet from each end of the T. An interesting effect was observed when hydrogen was released from the ¾ pipe at 350 g/s; the resulting jet flames were not horizontal as they were with the 2 inch pipe but were deflected towards the ground.

Comparing the heat fluxes measured for the 2” and ¾” releases, the thermal radiation for the 2” release is slightly higher than for the ¾” even though the ¾” flame is closer to the sensors, due to the downward trajectory. This is most probably due to the greater flame thickness which is apparent in the 2” releases.

6.3 45° shrouded vent termination - ¾ inch pipe ignited release

The shrouded vent termination resulted in higher heat fluxes than a release from a vertical pipe in the plane of the vent. This is because the sensors were deliberately positioned in line with the flame projection in order to measure the worst-case scenario. The extent of the flame projection was 5.6m long and 1.9m wide but this will be wind dependent to some extent.

6.4 Un-ignited releases 3/4” vent pipe – T piece

Two tests at the maximum release rate were performed but gave differing results in terms of measured hydrogen concentrations. Results from the test which gave the highest concentrations are given in this paper.This is due to the weather conditions and the changing wind speed and wind direction. With an almost co-flowing wind direction (3° deviation) a maximum hydrogen concentration of 5.9% was recorded 10m from the T-piece and 2m above the ground. This shows that for high velocity releases through a T-piece, flammable concentrations of hydrogen are present near to ground level.

7.0 MAIN FINDINGS

A safety distance of at least 10 metres is recommended to restrict the thermal radiation intensity to a level of 5 kW/m^2 for a 5.5 m high 2” vertical vent at a release rate of 400 g/s.

A safety distance of at least 5 metres is recommended to restrict the thermal radiation intensity to a level of 5 kW/m^2 for a 5.5 m high 3/4” vertical vent at a release rate of 350 g/s.

A safety distance of at least 18.5 metres is recommended to restrict the thermal radiation intensity to a level of 2 kW/m^2 for a 5.5 m high 2” vertical vent at a release rate of 400 g/s.

A safety distance of at least 14.2 metres is recommended to restrict the thermal radiation intensity to a level of 2 kW/m^2 for a 5.5 m high 3/4” vertical vent at a release rate of 350 g/s.

EIGA IGC 15/06[4]. recommends a safety/separation distance of 8 metres for a gaseous hydrogen installation from the site boundary and areas where people are likely to congregate, this distance does not conflict with the findings from these experiments.

The shrouded vent termination would appear to be preferable to the T-piece termination. It does not produce a downward deflection of the jet flames.

Some form of vent end termination is required to prevent the ingress of water into the vent pipe. Comparing the designs tested so far (end flap, T-piece and shrouded), the shrouded design would appear to be the most satisfactory. Further design development and refinement is recommended.

T-piece vent terminations are not recommended for use on hydrogen vent pipes due to the downward deflection of the gas stream at high exit velocities.

REFERENCES

(1) Lachance, J.L.J., et al. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure, 3rd International conference on hydrogen safety, 2009

(2) Stoll, A.M., Green, L.C., The production of burns by thermal radiation of medium intensity, ASME58-A-219, (1958)

(3) EIGA IGC Doc 75/07/E - Determination of safety distances. European industrial gases association AISBL 2007 Avenue des Arts 3-5 B 1210 Brussels

(4) EIGA IGC Doc 15/06/E Gaseous hydrogen filling stations. European industrial gases association AISBL 2007 Avenue des Arts 3-5 B 1210 Brussels