THERMAL RADIATION PROPERTIES OF LARGE HYDROGEN LEAKS FROM GAS DISTRIBUTION NETWORKS

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ABSTRACT

Determination of the behaviour of hydrogen when leaking from pipework on gas distribution assets is essential in assessing the comparative risk associated with using pure hydrogen in place of natural gas in existing assets. Experimental work considering the behaviour of gaseous hydrogen when released in large volumes from gas distribution pipework at pressures of up to 7 barg through holes of up to 200mm in diameter in both buried and unburied scenarios is currently underway. The present paper presents and briefly discusses the results from a set of ignited 20mm diameter releases of hydrogen at pressures up to 7 barg vertically upwards from a pipe in an open excavation. Gaseous releases which find a direct route to atmosphere have the potential to create significant volumes of flammable gas and subsequently significant fires in the case of ignition. It is important to understand both the dispersion distances and thermal hazard field to be able to understand the comparative risk posed when compared to natural gas releases in similar situations. Results of current work completed to date are presented alongside comparisons with known properties of natural gas releases and the potential implications to the comparative risk of hydrogen network operation. The work has been conducted at the DNV GL Spadeadam Testing and Research Centre, UK as part of the UK Gas Distribution Networks and Ofgem National Innovation Competition funded H21 project.

1.0 INTRODUCTION

In line with the UK government's de-carbonisation strategy, the gas industry and Ofgem funded H21 Network Innovation Competition (NIC) [1] project aims to provide the necessary evidence base for a policy decision on the use of pure hydrogen in the UK's gas distribution network. After an initial feasibility study on the prospect of converting the city of Leeds [2], the NIC project was awarded funding to proceed with the necessary evidence gathering to be able to quantify the comparative risk of operating a pure hydrogen network when compared to that of the existing natural gas network. The present paper relates to research currently underway in the Phase1B part of the project.

The methodology in Phase1B is that of a Quantitative Risk Assessment (QRA) for the operation of a gas network on pure hydrogen. DNV GL's existing approach to the QRA procedure for existing natural gas infrastructure has been examined and a set of knowledge gaps identified for hydrogen operation. The H21 Master Testing Plan (MTP) was developed after this QRA review to detail which experiments need to be carried out to provide data and knowledge to help to fill the gaps in the QRA for transition to hydrogen operation.

The risks associated with a gas release from the pipeline network is quantified using a set of linked models to predict:

- the frequency of gas releases and the likely sizes of release holes due to different threats
- the outflow of the gas
- the dispersal and tracking of the gas if subsurface, either to the surface or into buildings.
- how it disperses or accumulates in the atmosphere

- if a flammable mixture is predicted, the likelihood of ignition
- explosion overpressure and thermal radiation from an ignited mixture
- response of buildings and structures from the fire / explosion
- the probability of casualties from the fire / explosion / building collapse

Some of these models are phenomenological and use an understanding of the engineering, physical and chemical formulae to model properties of the gas leak. Others are empirical and based on experimental and historical incident data. The models have been shown to be suitable within their scope of validation for Natural Gas releases against full scale experimentation and statistical analysis performed by DNV GL over the past 30 years. For a number of these models, the introduction of hydrogen in place of natural gas takes them outside of their validated scope.

One area where it was identified that information was required was of the radiative properties of ignited hydrogen releases of a scale appropriate for large releases from the network. Some information was already available from industrial scale (in excess of 60 barg) releases performed in 2009 for Air Products at the DNV GL Spadeadam Research and Testing Centre [3,4] and radiative properties of natural gas fires are well documented in the literature and summarized in Lowesmith [5] along with some guidance on assessing the thermal hazards posed.

Measurements from a sub-set of the hydrogen releases performed as part of the H21 Phase 1B project are presented here where release rates are typically below that of an industrial release. Some discussion on the fraction of heat radiated from the experiments is made and a short commentary on the applicability of the guidance in [5] is made.

2.0 SCOPE OF PAPER

The experiments considered in this paper were all conducted by releasing hydrogen at different pressures through a 20mm hole in the top of an 8” NB steel pipe, set in an open excavation. Each release was oriented vertically upwards and an array of thermal radiation sensors used to assess the thermal field around each release. The outflow from the pipe was measured at a metering orifice.

The measurements of thermal radiation in each experiment are used to perform a simple calculation of the fraction of the power of the release (net calorific value multiplied by the mass release rate) which is radiated. This calculation is performed as an indicative assessment of the quality of the data recorded and assumes a point source in all cases. Transmissivity of the atmosphere is taken into account from local measurements of relative humidity and ambient temperature. Table 1 shows the four experiments considered here.

Table 1: Experiments Considered

Experiment ID	Fuel	Target Pressure (barg)	Hole Size (mm)	Orientation	Cover
LR051	Hydrogen	0.35	20	Up	Open Excavation
LR053	Hydrogen	2	20	Up	Open Excavation
LR055	Hydrogen	7	20	Up	Open Excavation

LR055R	Hydrogen	7	20	Up	Open Excavation

3.0 EXPERIMENTAL FACILITY

To perform releases of a sustained, nominally steady state pressure, it is required to pressurise a volume connected to the release point to a higher pressure than that required at the release and control the pressure at the release point with a pressure controlling device. In the case of these experiments; an existing pair of 36” NB storage reservoirs were used, interlinked with a 6” NB / 8” NB pipe and associated isolation valves having a total volume of approximately 170 m^3. The centre of the interconnecting pipe was fitted with an 8” NB tee section and 8” NB globe type flow control valve. The outlet pipework incorporating a metering orifice was fitted to the downstream side of the flow control valve. The release spool with the 20mm diameter hole in the side was also fitted with a pressure and temperature sensor. The pressure sensor used had a range suitable for the experiment being conducted. The temperature here was measured using a 1.5 mm diameter, stainless steel sheathed, mineral insulated, type ‘T’ thermocouple inserted into the pipe using a pressure retaining gland. All pipework instruments were calibrated in the field using standards traceable to national standards prior to commencement of the experimental programme. An arrangement of the pipework and instruments installed on it is shown in Figure 1.

The mass flow through the metering orifice was calculated from the measured differential pressure across the plate and the static pressure and temperature using the calculations and methods set out in BS EN ISO 5167 [6].

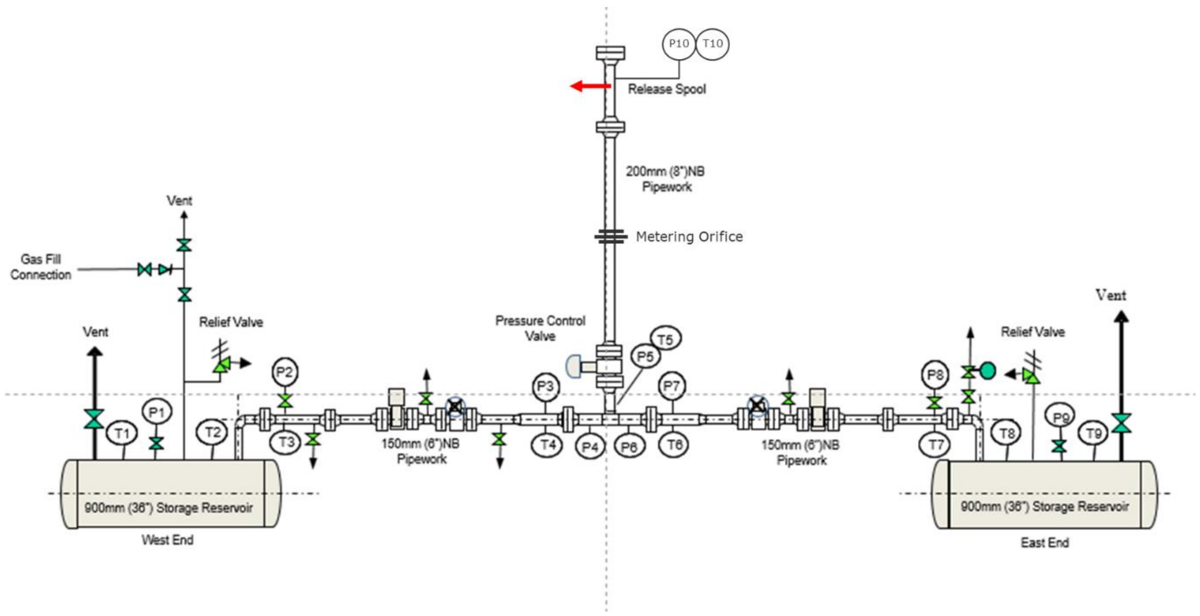

Figure 1. Pipework Arrangement

The release spool was installed into the base of a pre-formed steel trench, as shown in Figure 2. This trench was prefabricated and installed in the local clay and was used to allow the flanges of the release spool to be accessed for turning or replacement for later experiments. The trench was 0.5 m wide and 1.1 m deep. The dimensions were chosen to be typical of a trenching bucket on an excavator and the release pipe was installed into one end to mimic the relative geometry which might be encountered in an interference damage type situation. A photograph of the release point within the trench is shown in Figure 3.

Figure 2: Pre-formed 'Open Excavation'

Figure 3. Release pipe in 'Open Excavation'

The incident thermal radiation flux was measured in each experiment using an array of 15 wide angle radiometers. The radiometers were mounted on tripods or steel uprights on one of five bearings around the release point and were moved closer or further from the release point depending on the expected release rate. An example layout is shown in Figure 4. The field of view of each radiometer is 150° and the centre of view was angled at the expected jet centre in each experiment. The radiometers consist of a calorimeter mounted behind a calcium fluoride window transmitting light in the range 0.3 to 11.5 µm. These devices have a response time in the region of 1 second and a full-scale accuracy in the region of 5% of the reading. Each sensor was calibrated across its measuring range in a black body furnace prior to commencement of the experimental programme.

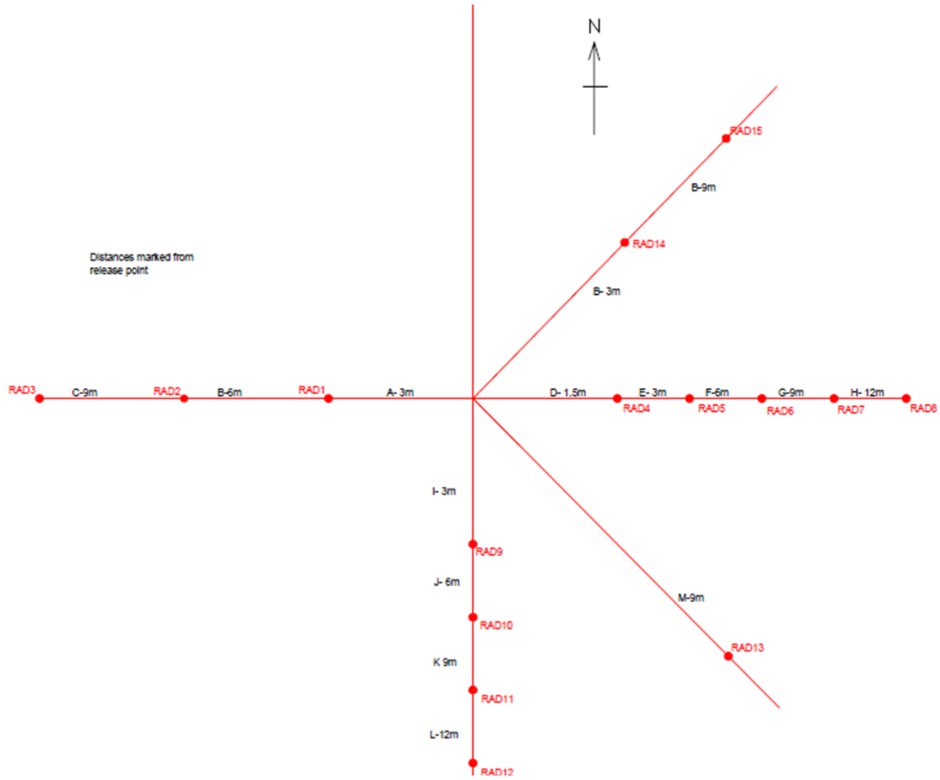

Figure 4. Example radiometer layout

The wind speed and direction were measured at two heights (5 m and 10 m from local ground level) in one location approximately 50 m from the release point using sonic anemometers.

To perform an experiment, the reservoirs were charged to a pressure above the required release pressure calculated to accommodate a minimum of 60 seconds of run time at the expected outflow but low enough to allow control of the flow using the flow control valve. After enforcement of an exclusion zone and confirmation of all instrumentation and video recording equipment recording, the release was initiate by operation of the isolation valves and then the flow control valve. The flow control valve was manually operated to control to the required pressure in the downstream pipework. Once a nominally steady flow was obtained, the hydrogen was ignited using an incendiary firework placed close to the release point. The firework burned for a number of seconds after initiation. On extinguishment of the firework, the release was allowed to continue for some tens of seconds before once again being isolated. Some adjustments of the release pressure may have been made after ignition by operation of the flow controller.

4.0 RESULTS

Table 2 shows the headline outflow measurements for each experiment for a 20 second averaging period chosen to start after the incendiary firework has extinguished and end before the flow is isolated. Standard deviation through the averaging period is also given as an indication of the variation in pressure and flow across the period. Note that LR055 was conducted as a direct repeat of LR055 excepting that only one of the two storage reservoirs was opened. This was intended as a commissioning of the system for operation at smaller volume, higher storage pressure conditions. Moderately lower stability of the control mechanisms was observed and this is evident in the slightly lower test pressure (and higher standard deviation) reported. The power of each release quoted in the table is calculated using a net calorific value of 119900 kJ.kg^{-1} for gaseous hydrogen. Figure 5 shows a set of photographs, one from each of LR051, LR053 and LR055. The camera in LR055 was positioned further from the release point for protection. It can be noted that there appears to be very little visible radiation from these releases but little quantitatively can be deduced given that the iris and ISO settings on the video camera were set automatically by the camera.

Table 2. Results

Test ID	Diameter (mm)	Orientation	Outlet Pressure (barg)	Outlet Pressure (stdev)	Mflow (kg/s)	Mass Flow (stdev)	Power (kW)
LR051	20	Up	0.355	0.003	0.019	0.0002	2482
LR053	20	Up	1.973	0.014	0.048	0.0005	6055
LR055	20	Up	7.447	0.080	0.146	0.0031	17245
LR055R	20	Up	6.684	0.100	0.135	0.0019	15679

Figure 5. Photographs of LR051, LR053 and LR055(left to right)

Figure 6 through Figure 9 show the thermal radiation measurements made by each of the radiometers in each experiment. The wind speed and direction are also shown in the same figures. Note that the wind direction is as approaching the release from a bearing between 0 and 360 such that a measured bearing of 270° can be interpreted as the flame being blown away from the radiometers on the 270° line. Also on each plot are a set of contours for different point source radiation assumptions. These contours have not taken into account the transmissivity in the atmosphere and can be described by Equation 1:

$$I = \frac{QF_r}{4\pi r^2}, \tag{1}$$

where I – incident radiation, kW.m^{-2}; Q – total power of flame, kW; F_r – fraction of heat radiated, unitless; r – radius (distance to receiver), m.

It is noted that the general trend for I is on the expected 1/r^2 relationship for all measurements and that there is little influence of the wind speed or direction on these results.

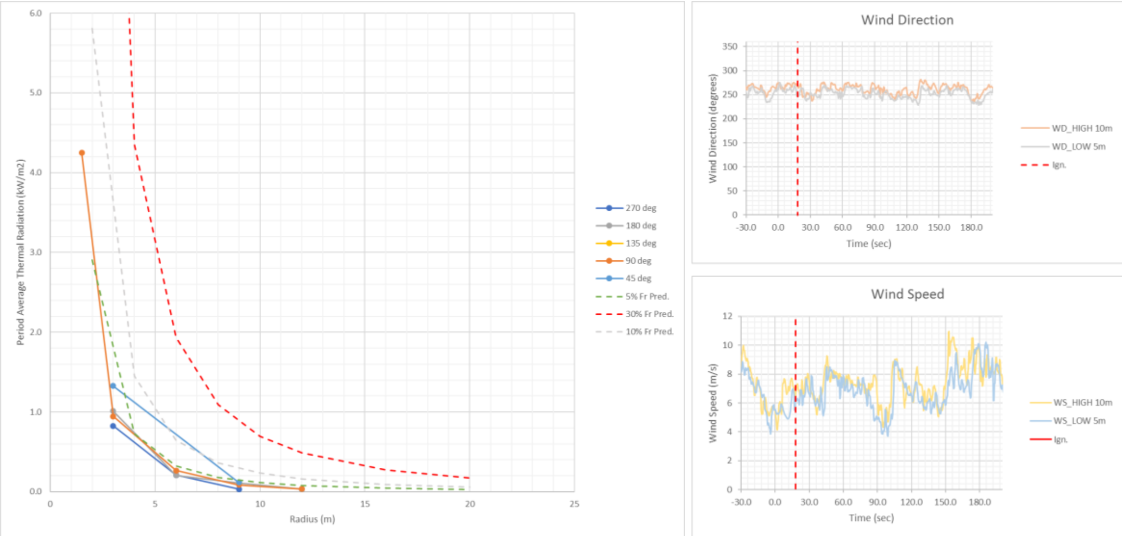

Figure 6. Thermal Radiation measurements from LR051

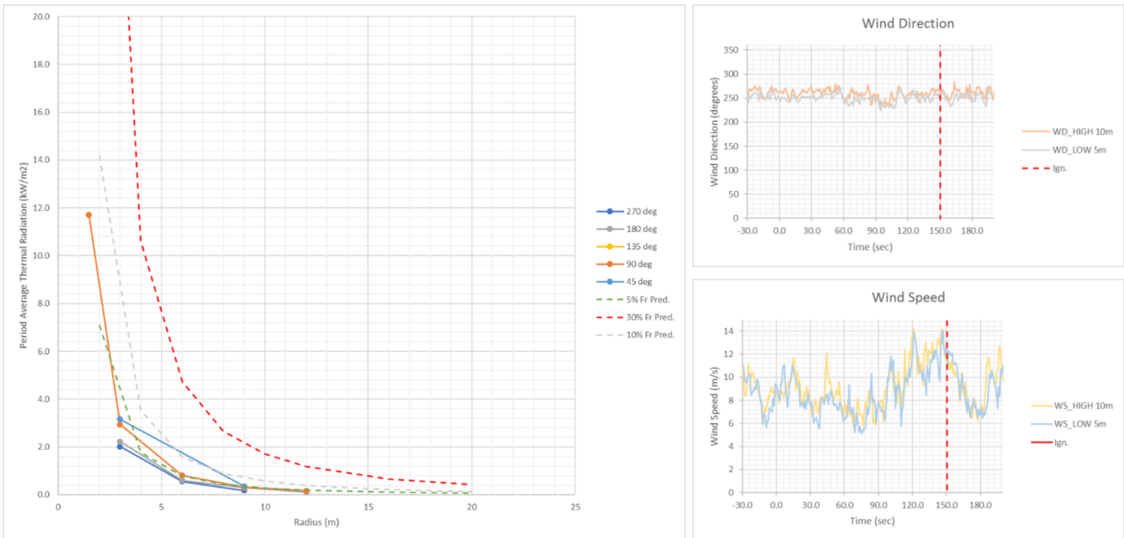

Figure 7. Thermal Radiation measurements from LR053

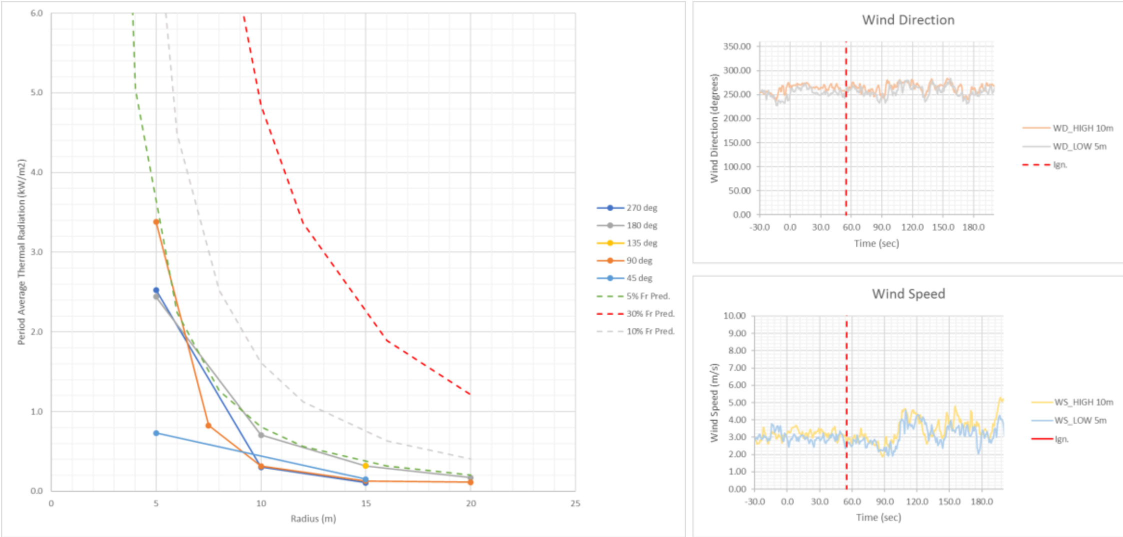

Figure 8. Thermal Radiation measurements from LR055

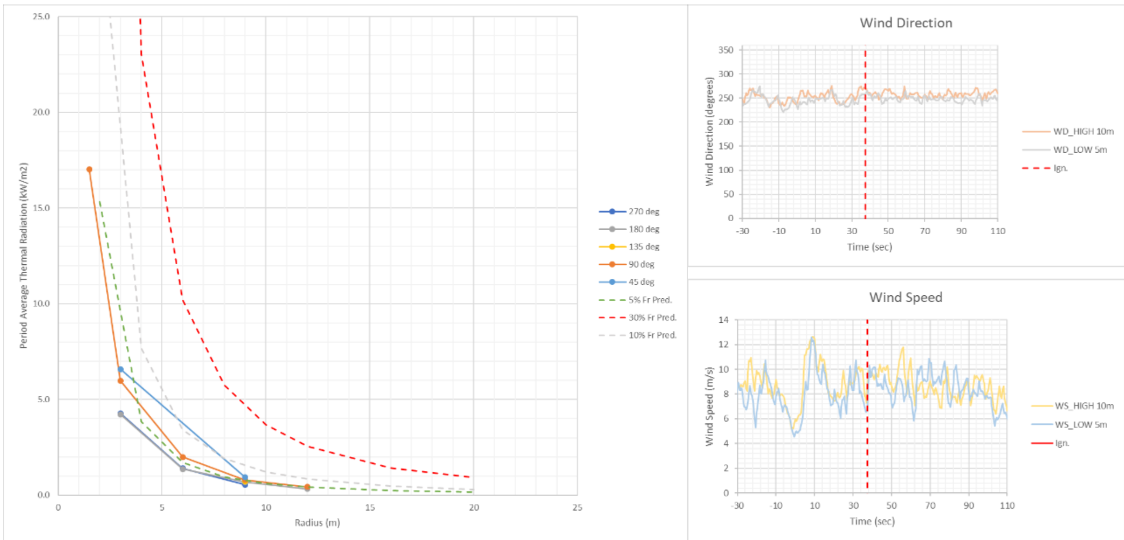

Figure 9. Thermal Radiation measurements from LR055R

5.0 DISCUSSION

This paper is primarily concerned with conveyance of the measured results, but as an exercise in quality checking of the data, the measured values were compared with those that would be predicted from a point source of equivalent power to the release power. Here the transmissivity of the atmosphere has been taken in to account as follows in Equation (2):

$$I = \frac{\tau Q F_r}{4\pi r^2}, \qquad (2)$$

where I – incident radiation, kW.m^{-2}; τ – transmissivity, unitless; Q – total power of flame, kW; F_r – fraction of heat radiated, unitless; r – radius (distance to receiver), m.

The transmissivity is calculated using established formulae taking into account the relative humidity and temperature measurements, averaged during the same period as that for the thermal radiation measurements.

The fraction of heat radiated, F_r, is given in [5] as guidance for different mass flow rates of hydrocarbon gas jet fire in its Table 1. For a mass flow of 0.1 $kg.s^{-1}$, closest to the values in the experiments reported here, $F_r = 0.05$.

Figure 10 shows the resulting comparison between the predicted point source radiation and the measured using the value of 0.05 chosen for F_r. The predictions generally overpredict and could be deemed conservative in most cases for the data considered.

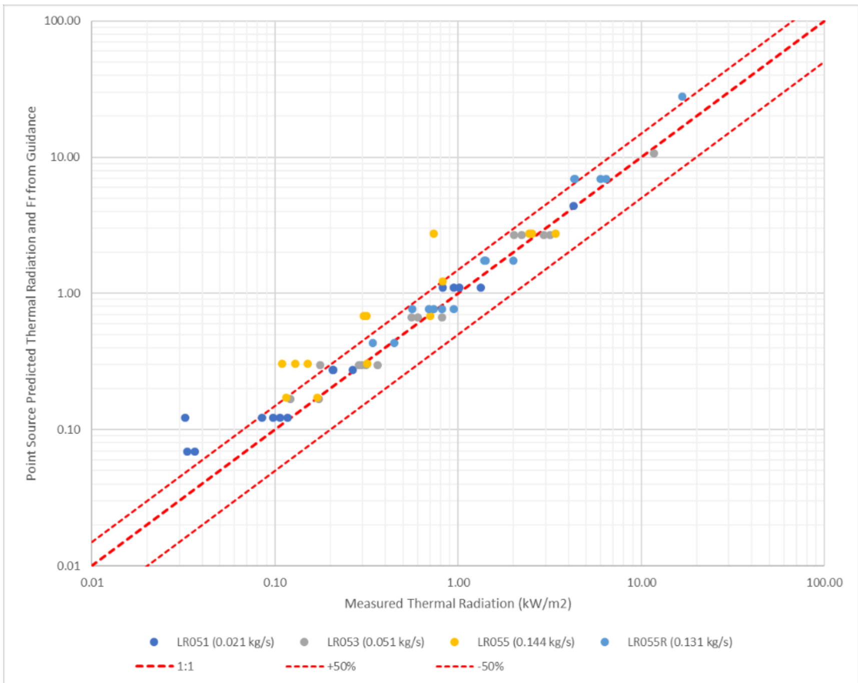

Figure 10. Point source predicted thermal radiation versus measured

The publications in [3] and [4] include thermal radiation data from much larger releases of hydrogen, typically in excess of 1 $kg.s^{-1}$ (122 MW) with some as high as 24 $kg.s^{-1}$ (2900 MW). Updating the plot in Figure 10 to include both measured and predicted values for these higher release rates gives the comparison shown in Figure 11 where the data has been separated by those with power below 16 MW (this work) and those with power above 100MW (larger, industrial scale). For these higher power releases, it is apparent that the point source assumption is not adequate given the potentially larger under prediction. This is as would be expected given the large size of the flames and potential impact of flame tilt, view factor, etc. A much more in-depth analysis of some of these larger releases is conducted in [4].

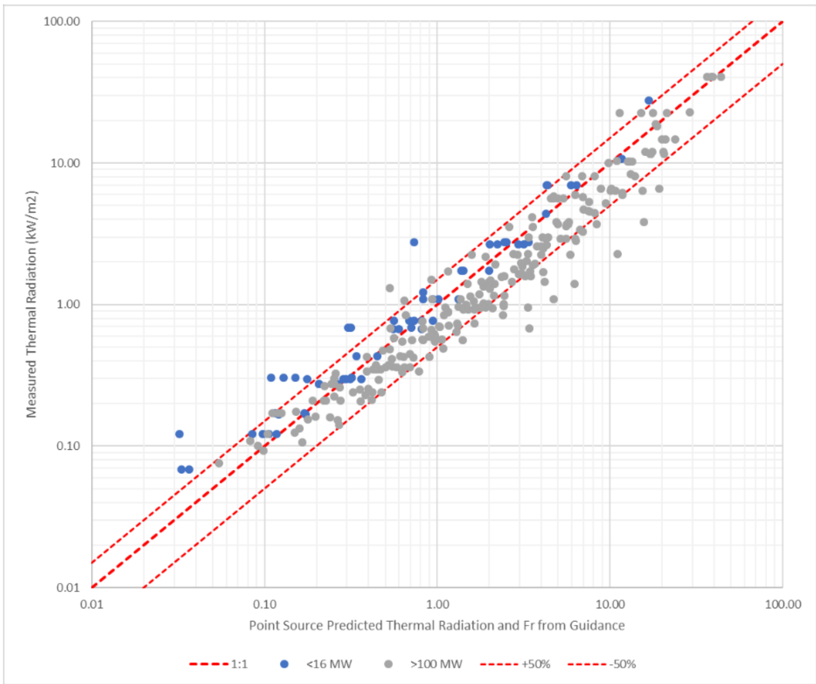

Figure 11. Point source predicted thermal radiation versus measured including large experiments

6.0 CONCLUSIONS

A sub-set of thermal radiation data for steady state hydrogen releases from an underground but uncovered pipe release have been presented along with some limited analysis of the results. This subset includes only vertically upwards releases and not impacting, buried or large holes. Experiments in these variants are planned for the remainder of the project and comparisons of resulting thermal radiation field will be performed.

For the scale of experiments considered here (<16 MW, that is), following the guidance available for hydrocarbons in [5] and making simple assumptions about the point-like nature of the source gives reasonable predictions of the thermal hazards expected.

Given the aim of the H21 project is to determine relative risk of releases from hydrogen distribution networks in comparison from the known risk from that of a natural gas network, the next steps in this analysis will be to compare the thermal radiation results here against similar outflow power for historic natural gas experiments.

7.0 ACKNOWLEDGEMENTS

The work has been conducted at the DNV GL Spadeadam Testing and Research Centre, UK as part of the UK Gas Distribution Networks and Ofgem National Innovation Competition funded H21 project.

8.0 REFERENCES

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