Hydrogen Flaring & High-Pressure Venting Demonstration Review: Technical Report

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Abbreviations	Meaning
AGI / AGIs	Above Ground Installation(s)
[redacted]	[redacted]
ATEX	Explosive Atmospheres (EU directives)
BLEVE	Boiling Liquid Expanding Vapour Explosion
BOS	Background-Oriented Schlieren (imaging)
CAB	Compressor Acoustic Building
CGA G-5.5-2021	Compressed Gas Association Standard for Vent Systems
CCR	Compressor Casing (Routine) Vent
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DBB	Double Block & Bleed Vent
DGS	Dry Gas Seal
ELD(s)	Engineering Line Drawing(s)
ESD / ESDV	Emergency Shutdown / Emergency Shutdown Valve
FLIR	Forward-Looking Infrared (thermal imaging)
GDNs	Gas Distribution Networks
GT	Gas Turbine
HAR	Hydrogen Area/Cluster projects
H_2	Hydrogen
IFC	International Fire Code
ISO 17776	International Standard for risk assessment
LTS	Local Transmission System
NB	Nominal Bore
NGT	National Gas Transmission
NIA	Network Innovation Allowance
Nm^3/h	Normal cubic metres per hour
NOx	Oxides of Nitrogen
NTS	National Transmission System
OEM / OEMs	Original Equipment Manufacturer(s)
P&IDs	Piping & Instrumentation Diagrams
PPE	Personal Protective Equipment
PRS	Pressure Reduction Station
QRA	Quantitative Risk Assessment
RFI	Request for Information
SCADA	Supervisory Control & Data Acquisition
SoW / SOW	Statement of Work
VDN	Vibration, Dynamics and Noise
WP	Work Package

1.0 Executive Summary

This report presents an integrated demonstration and modelling evaluation of the venting and flaring characteristics of hydrogen and hydrogen blends. The study was conducted under conditions reflective of National Transmission System (NTS) assets. Full-scale demonstrations were undertaken to measure noise, thermal radiation, and overpressure arising from controlled flaring and delayed-ignition venting events for 5%, 20%, and 100% hydrogen.

A quantitative assessment of typical vent types within the National Transmission System (NTS) was undertaken, through which three [redacted] venting scenarios were identified using a qualitative risk-ranking approach namely, the Pig Trap Vent, Compressor Casing Routine (CCR) Vent, and Double Block and Bleed (DBB) Vent. These scenarios were classified as [redacted] based on factors including vented inventory size, venting frequency, proximity to personnel, and the potential for high-momentum jet formation. Aspen HYSYS was used as an initial screening tool to generate blowdown profiles, recognising that results are sensitive to discharge coefficient variations and that subsonic flow is not well captured. These profiles were then passed to CFD for more detailed assessment of jet behaviour, dispersion, noise, flammable cloud formation, and overpressure effects. Additional risk modelling using HyRAM+ and FlareSim provided comparative insight into thermal radiation levels and exclusion-zone requirements. This analytical work was complemented by full-scale hydrogen and hydrogen–natural-gas blend venting and flaring demonstrations, which quantified thermal radiation and noise levels associated with both delayed ignition of vents and controlled flaring, as well as overpressure generated during delayed ignition events. Meteorological conditions during the demonstration programme were monitored and recorded to support interpretation of the test data and comparison with modelling results.

The demonstration used a 1-inch (pig trap) vent, 2-inch (double block and bleed, DBB) vent and a 4-inch flare. The hydrogen fuel tank was at 10barg with the natural gas flow at 8barg. Computational Fluid Dynamics (CFD) was used to predict flammable gas cloud volume, noise and overpressure providing the basis for hazard determination where direct measurement was not possible. It was determined in the previous report that even with the lower pressure systems hazard magnitudes were not drastically different (i.e., similar size gas clouds), therefore, the test conditions were concluded as acceptable.

The results demonstrate that noise is the dominant hazard for both venting and flaring, particularly for hydrogen-rich releases. For flaring, measured A-weighted noise levels at 15 m ranged from approximately 82–118 dB(A), attenuating by 3–13 dB(A) over 15–60 m. Even at the highest flows tested, flaring noise was generally manageable with appropriate exclusion zones and was driven primarily by flow rate and jet exit velocity. In contrast, delayed-ignition venting generated significantly more severe acoustic impacts, with peak A-weighted noise of ~120–127 dB(A) and linear levels exceeding 140 dB, extending beyond 60 m for high-hydrogen cases. These levels exceed occupational exposure limits and demonstrate that local or routine venting of hydrogen-rich gas is not tolerable except adequate acoustic mitigation measures are put in place, with noise rather than thermal radiation or overpressure, governing exclusion-zone requirements.

Thermal-radiation levels were significantly lower for venting than for flaring, reflecting the short-duration, localised combustion that occurs after delayed ignition of the vented cloud. Recorded heat-flux values for venting measured at approximately 15 m from the vent generally fell within 0.16–0.99 kW/m^2, well below common thermal hazard thresholds and significantly lower than the 0.75–2.63 kW/m^2 range measured at the same distance during flaring from the 4-inch flare tip. As expected, thermal radiation from flaring increased with natural gas concentration and flowrate but remained within acceptable limits at distances of 15 m and beyond. These findings show that thermal radiation-based exclusion zones established for natural-gas flaring, defined in SR-23 as areas where thermal radiation is below 6 kW/m^2, are conservative when applied to hydrogen and hydrogen–natural-gas blends. This reflects the lower emissivity and the reduced radiative intensity of hydrogen flames; therefore, thermal radiation is unlikely to govern exclusion-zone requirements for hydrogen flaring. For venting scenarios, thermal radiation is considered a secondary hazard, relevant only in the immediate vicinity (<5 m) following ignition.

Overpressure behaviour was evaluated using measured blast-pressure data from the delayed-ignition tests and model-based predictions informed by CFD-derived cloud volumes. Measured near-field peak overpressures reached approximately 4.5 kPa at 5 m for the highest-flow 100% hydrogen cases, decreasing rapidly with distance and remaining below structural-damage thresholds beyond 5–10 m. Lower-hydrogen blends (5% and 20%) produced lower overpressures due to their smaller flammable mass and lower flame speeds. Although overpressure at <5 m distance was not measured during the test, overpressure-scaling analysis and TNT/TNO ME-based modelling confirm that some scenarios particularly those involving high hydrogen content or larger vent geometries could exceed 6 kPa within 1–3 m of the vent for the flowrates considered. Due to the open field nature of the experiment a TNO ME Power class of 3 was utilised. This provided the most accurate overpressure predictions with class 7 significantly overestimating the free field overpressure and class 1 underestimating it. [redacted]

The project integrated Computational Fluid Dynamics (CFD) with full scale demonstration testing to establish a robust, evidence-based understanding of hydrogen and hydrogen-blend venting behaviour. Although gas cloud dispersion and flammable-volume formation could not be directly measured during the on-site tests, CFD was used to predict jet development, cloud structure, and flammable cloud mass for each vent configuration and hydrogen concentration. These predictions were then validated qualitatively using observed jet behaviour and quantitatively by comparing model-derived ignition-severity inputs with the recorded noise, thermal radiation, and overpressure measurements.

The hazard review confirms that local venting practices suitable for natural gas are not directly transferable to hydrogen-rich service. Pig traps and DBB vents are typically located in congested, personnel-accessible areas, which amplifies noise and safety impacts. Local venting of ≥20% hydrogen was shown to be impracticable due to excessive noise levels, even with access restrictions.
At 5% hydrogen, the results demonstrate that hydrogen introduction does not significantly increase hazard levels compared with methane; however, they highlight that existing local vent arrangements are already sub-optimal, with silencers or remote venting required to achieve acceptable noise and operational conditions. These findings indicate that low-percentage hydrogen blending represents an opportunity to improve and standardise venting practices rather than introducing a fundamentally new hazard.

The hazard review confirms that local venting practices suitable for natural gas are not directly transferable to hydrogen-rich service. Pig traps and DBB vents are typically located in congested, personnel-accessible areas, which amplifies noise and safety impacts. Local venting of ≥20% hydrogen was shown to be impracticable due to excessive noise levels, even with access restrictions. At 5% hydrogen, the results demonstrate that hydrogen introduction does not significantly increase hazard levels compared with methane, however, existing local vent arrangements are already sub-optimal, with silencers or remote venting required to achieve acceptable noise and operational conditions.

For planned operations, recompression of gas back into the system is therefore identified as the preferred option, minimising noise exposure, ignition risk, and gas wastage. Where recompression is not feasible, flaring provides a more controlled and predictable hazard outcome by fixing the ignition location and avoiding large unignited gas clouds; however, flaring introduces additional considerations related to noise, maintenance burden, siting constraints, and planning approvals, particularly at urban or space constrained sites. Where flaring is not practical, particularly on SGN sites, planned venting can be accommodated with appropriate mitigations including but not limited to sufficient exclusion areas, lower venting rates, flame arrestors and silencers as required. Based on the demonstrated and CFD-validated findings the disposal mechanism hierarchy is also extended to the full range of vent types identified in within the network.

The study also highlights important policy and standards implications. Existing guidance such as IGE/SR/23, while providing a robust foundation for natural gas venting, does not adequately address hydrogen behaviour. In the absence of a dedicated hydrogen flaring standard, broader regulatory frameworks such as the OGA Flaring and Venting Guidance (2021) and industry decarbonisation commitments provide the policy context, reinforcing that flaring and venting should be non-routine, minimised, and justified on a technically and economically defensible basis, consistent with net-zero objectives.

The findings from this project provide a robust technical and regulatory basis to support hydrogen readiness across existing and future gas infrastructure.

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2.0 Hydrogen Venting and Flaring Demonstration Background

As the UK progresses towards Net Zero targets, each operator within the energy market is looking into how their future and day to day operations could change as the targets are approached. Both NGT and SGN are investigating how gas networks will change when different gas flows through the network. For the scope of this project NGT and SGN are looking to understand how their gas release philosophies will change as hydrogen is introduced into the energy network.

Currently natural gas is vented and very little to no flaring is undertaken by NGT and SGN. However, in the previous phases of this project it has been identified that as hydrogen is blended into the network and potentially replace natural gas entirely new risks may arise due to unintended ignition of the venting gas as well as supersonic gas velocities. To validate the simulations models and to understand the effects of these hazardous events it is important to ground the theories in reality. Therefore, in an effort to do this a demonstration was undertaken.

Prior to the test a statement of work was created and sent out to various suppliers for quotation. Through a comprehensive technical and commercial assessment, a supplier was chosen to undertake the required demonstration activities. Once a vendor has been selected it was important to define the core aims/objectives the demonstration would help provide information to.

1. Help define the scale of hazards related to venting and unintended ignition of a vent.
2. Provide evidence for safe Flaring of hydrogen and hydrogen blends.
3. Support decisions on when to vent & flare.
4. Validation of modelling software's.
5. Inform policy and standard update.
6. Compare blend to 100% hydrogen operation.

2.1 Report Outline

This report outlines the key activities carried out during the demonstration, including the setup, environmental conditions, and testing procedure. The final instrumentation layout is presented with accompanying site photographs for reference. The results are provided alongside the test summaries prepared by [redacted] and Wood VDN. The test data served as a benchmark for CFD simulations, providing evidence of their effectiveness in replicating hazards related to gas venting. Table 2 1 below summarise the parties driving the various elements of the scope.

Table 2-1 : Project Team and Responsibilities

Project Stage	Party Responsible
Scenario development, Hazard Modelling and test planning	Wood Project team
Pre and Post demonstration CFD	Wood Project team
Demonstration Execution, weather and thermal radiation data recording	[redacted]
Noise and Overpressure data recording and processing during demonstration	Wood VDN team
CFD Validation (at the client's request)	[redacted]

A comparison of the MES CFD outputs is presented to assess the performance of different simulation tools and determine which is most appropriate for the required outcomes. Finally, the report discusses how relevant policies and standards may need to be updated, and new ones developed to address future gas flow scenarios.

2.2 Scope and Limitations

This study has been designed to evaluate the safety, feasibility and performance of hydrogen venting and flaring under representative National Transmission System (NTS) and Local Transmission System (LTS) conditions. This includes typical pressure ranges from 80 – 5 barg with ambient operating temperatures. However, several boundaries govern what is included within scope and what falls beyond the remit of this phase of work. The assessment focuses on modelling and measuring the consequences of hydrogen releases including flammable cloud formation, jet behaviour, thermal radiation, noise and overpressure but does not consider every aspect of hydrogen behaviour, ignition probability or operational risk. Understanding these boundaries is essential when interpreting results and planning future implementation activities.

Work undertaken within this study includes detailed CFD modelling of hydrogen behaviour across 5%, 20% and 100% hydrogen compositions. The modelling captures jet development, dispersion, flammable cloud size, and overpressure consequences for delayed ignition scenarios. These outputs are complemented by physical demonstrations measuring thermal radiation, noise levels and overpressure to validate key modelling assumptions. Structural loads on internal vent pipework particularly the high-momentum impulse loads acting on elbows were also assessed, as these loads directly affect the suitability of existing vent designs for hydrogen service. In addition, ignition reliability of the flare pilot system is included within scope, with demonstration results used to inform future flare system standards.

While demonstration records overpressure, radiation and noise, it does not include dispersion or concentration field measurements due to budget constraints, meaning that CFD remains the sole source of cloud size prediction. Furthermore, the [redacted] test facility could not fully replicate the peak transient flowrates that may occur on NTS sites. Instead, demonstrations employ constant flowrates to produce a conservative hazard plateau, which CFD analysis has shown to be representative of the sustained part of the hazard envelope once the brief NTS peak decays.

Although this study provides the engineering basis for defining sterile zones and hydrogen ready venting/flaring standards, the development of a full NTS wide hydrogen venting and flaring standard sits within the implementation phase. Likewise, detailed operational procedures and emergency response guidance will need to be produced by NGT using the data and conclusions from this study.

Table 2-2 captures the original Statement of Work sent out to the suppliers. Within the subsequent sections the full test conditions will be provided. For the reasoning to why there is a difference between the SoW and the test set up please see the previous report Ref. [3].

Table 2-2 Case Matrix

Based Scenario	Composition [Mol% H_2]	Flowrate [kg/s]	Time	Device	Delayed ignition?	Repeated
PIG Trap Vent	100	0.3	20s	Flare	No (pilots lit)	2x
	20	1.7				
	5	2.0				
Compressor Casing (Routine) Vent	100	1.5				
	20	4.6				
	5	5.5				
Double Block Bleed Vent	100	1.1				
	20	8.4				
	5	9.7				
PIG Trap Vent	100	0.3	15s then ignition	Pig trap vent	Yes	2x
	20	1.7				
	5	2.0				
Compressor Casing (Routine) Vent	100	1.5	15s then ignition	Compressor casing vent	Yes	
	20	4.6				
	5	5.5				

Based Scenario	Composition [Mol% H_2]	Flowrate [kg/s]	Time	Device	Delayed ignition?	Repeated
Double Block Bleed Vent	100	1.1	15s then ignition	Double block and bleed vent	Yes	

2.3 Qualitative Review

While developing the test plan, once the hydrogen venting and flaring scenarios were identified and a ranking methodology established, a workshop was held with key personnel from Wood, NGT and SGN to review the hydrogen venting and flaring scenarios to agree on:

- The validity of identified venting and flaring scenarios,
- The basis for the ranking of those scenarios (i.e. Inventory, Frequency, Location, etc please see Ref. 3 for more information),
- Quantification of any additional factors which should be considered,
- The ruling-out of any scenarios based on those previously performed by other demonstrations.

The outcome of the workshop and review can be found within Table 2-3, establishing that the top three scenarios that should be considered for further assessment are:

- Pig trap Vent,
- Compressor casing routine Vent, (note this vent was selected as it is similar in process condition to the startup purge vent but a better reference flowrate for the vent was available from the compressor OEM)
- Fuel Gas Vents on the Gas Turbine (Double Block and Bleed).

The starter vent was not considered for demonstration due to the move away from gas starters towards electric.

[redacted]

[redacted]

3.0 At site demonstration

The demonstration was undertaken on the WC 2nd of February 2026. The location of this test was [redacted] [redacted] [redacted] The demonstration included flaring and delayed ignition testing for hydrogen and hydrogen blends. The methodology integrates the engineered test scenarios defined in this study with [redacted]'s operational test capabilities and Wood's independent vibration, dynamics, noise, and overpressure measurement programme. This section describes the overall approach, test configuration, instrumentation strategy, and execution procedures for both flaring and delayed ignition events.

Three representative configurations were used for the test including:

- 4-inch flare tip (controlled flaring tests)
- 1-inch pig trap vent (open venting and delayed ignition)
- 2-inch double block & bleed (DBB) vent (open venting and delayed ignition)

Hydrogen and natural gas blends are prepared on site using dedicated hydrogen and Tulsa Natural Gas storage tanks. Composition is managed by metered flow control of each gas stream, ensuring adequate mixing lengths and bend induced turbulence before the test outlet. The test points have been presented Table 3-1 and

Table 3-2 below.

The flow rates proposed were specified within the original scope of work issued to [redacted]; however, these rates could not be fully achieved due to limitations in the capacity of the gas tankers available for the demonstration. CFD analysis detailed within the test plan [3] confirmed that there is no significant difference in the predicted hazard outcomes when comparing the NGT-specified flow rates with those achieved during the [redacted] testing campaign.

Table 3-1 Case Matrix for Flaring Demonstration

Based Scenario	Composition [Note 1]	Flowrate	Duration	Number of Runs	Inlet Pressure
Unit	Mol% H_2	Kg/s	Seconds	-	barg
Flare Tip [4-inch]	100	0.13	20	2	8
	20	0.35	20	2	8
	5	0.38	20	2	8
Flare Tip [4-inch]	100	0.49	20	2	8
	20	1.70	20	2	8
	5	2.00	20	2	8

Table 3-2 Case Matrix for Venting Demonstration

Based Scenario	Composition [Note 1]	Flowrate	Duration	Number of Runs	Inlet Pressure
Unit	Mol% H_2	Kg/s	Seconds	-	barg
Pig Trap Vent [1-inch]	100	0.13	20	2	8
	20	0.33	20	2	8
	5	0.35	20	2	8
Double Block and Bleed	100	0.49	20	2	8

Based Scenario	Composition [Note 1]	Flowrate	Duration	Number of Runs	Inlet Pressure
Vent [2-inch]	20	1.27	20	2	8
	5	1.37	20	2	8

The compressor casing vent was not considered during demonstration due to budget constraints. A single 4-inch flare was used based on the assumption that local flaring is impracticable and gas for flaring will be channelled to a collection header and then flared which is why there is a low rate and high-rate flaring matrix.

3.1 Test site conditions

During the testing campaign the achieved conditions have been presented in the tables below.

Table 3-3 : Flaring Demonstration Conditions

[redacted]

Table 3-4 : Venting Demonstration Conditions

[redacted]

3.1.1 Wind and Environmental Conditions

Wind direction and speed play a vital role in the propagation of both acoustic and blast pressure waves in the open field environment. The sensor arc orientation was selected to account for the wind direction on site. Initial setup had sensors lined in exactly the North-East, East, and South-East directions, however, they were modified to appropriate downwind direction after discussions on site. The onsite weather station was mounted 10m off the ground.

[redacted]

Figure 3-1 Physical Layout – Field Setup Images

3.2 Equipment Set up

All upstream pipework from the flange connection of the vent/flare was kept constant during the testing programme. The system incorporated a 4-inch vertical take-off, with each test burner tip connected to the runner via a 4 inch flanged connection. Each burner tip was fitted with a single pilot, supplied with [redacted] Natural Gas (TNG) and hydrogen gas mixture from a common pilot gas header. For the delayed ignition test cases, the pilot was initially unlit while the gas was supplied continuously. Ignition was initiated at the 15 second mark once steady flow is achieved using a high energy ignition (HEI) system, which subsequently ignited the vented gas at the test tip.

For test points involving hydrogen and natural gas mixtures discharged through the 1-inch vent (VT 1) and 2-inch vent (VT 2) vent tips, the high exit velocities necessitated installation of the pilot at an elevated position approximately 1.02 m above the vent tip to ensure reliable ignition of the vented gas. All other test cases were conducted with the pilot positioned directly at the exit of the respective test tip.

The natural gas was supplied from the local municipal natural gas network, while hydrogen was provided via third party compressed tube trailers. Dedicated orifice meter runs were installed for both hydrogen and natural gas to measure test fuel flowrates, with the metering systems designed and constructed in accordance with ASME MFC 3M 2004.

During each test point, noise and thermal radiation measurements were recorded. Thermal radiation measurements were taken at a distance of approximately 15.2 m from the flare or vent stack, while noise measurements were conducted at a distance of approximately 28.0 m from the stack exit in additional to the series of microphones discussed in Section 3.3.1.

[redacted]

Figure 3-2 : 1" Vent Arrangement

Figure 3-2 presents the 1" vent arrangement for the delayed ignition tests. Similarly to all the runs the ignition source has been kept consistent and can be seen sitting higher than the vent pipe. The vent utilises a 4-inch flange connection which reduces into a 1-inch pipe. The connection set up presented above is very similar to the pig trap cases which was trying to be recreated. This helped ensure the results were representative of actual operation. Furthermore, the vent exit is sat at height 3 m of the ground.

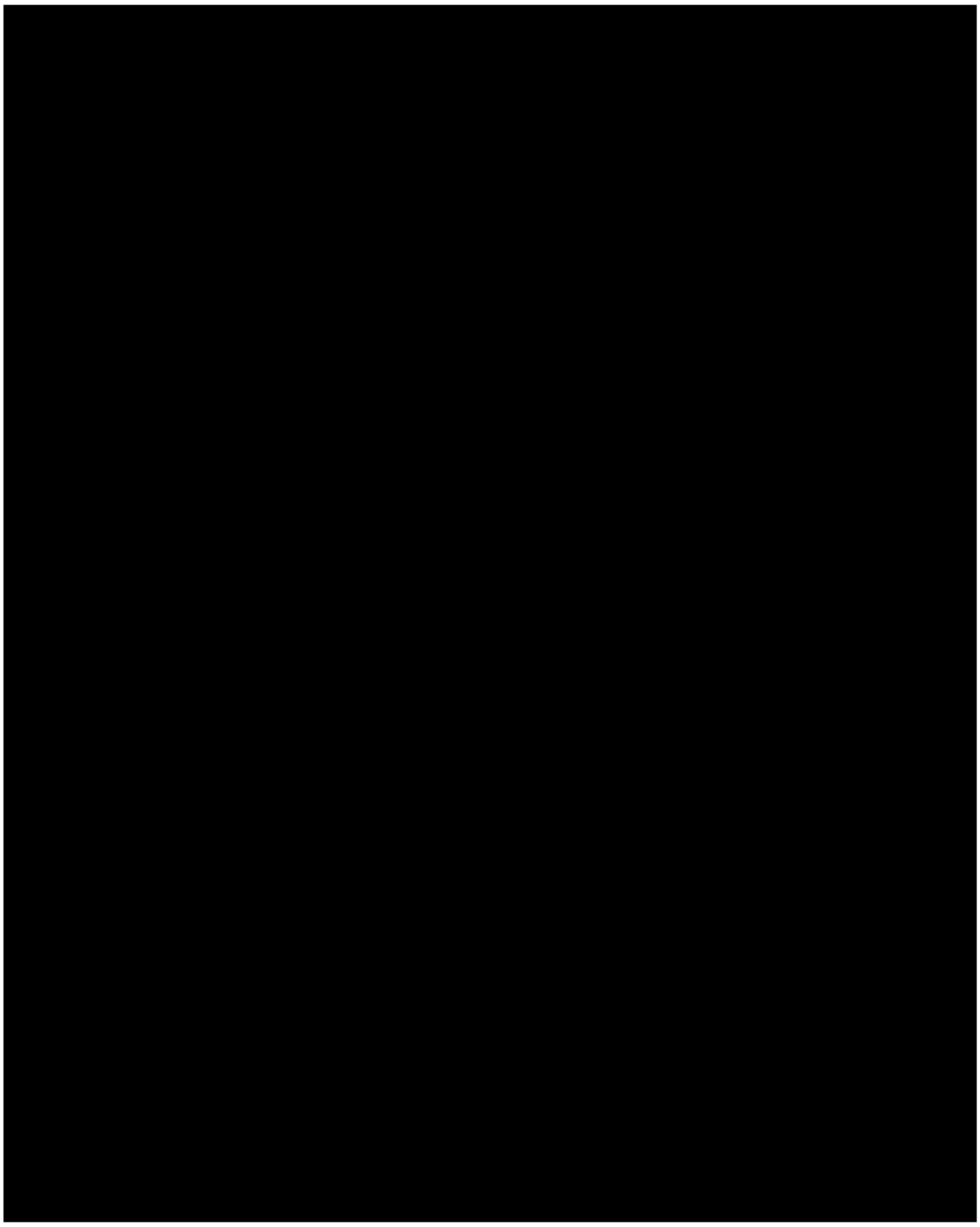


Figure 3-3 : 2" Vent Arrangement

Figure 3-3 presents the 2" vent arrangement for the delayed ignition test. The only difference between this and the 1" is the size of the vent pipe and the reducer final diameter. The Figure above demonstrates the open field nature of the test with little to no obstructions which could impact recorded data. In line with the 1" the vent exit is sat at height 3 m off the ground.

[redacted]

Figure 3-4 4" Flare Test Arrangement

Figure 3-4 presents the flaring demonstration test set up. Similarly to the 1" and 2" vent set ups all equipment is identical up to the 4" flange. After this a straight 4" section of pipework has been fitted in line with the burner height. For the 4" vent pipe the gas exited at 4 m above the ground level.

[redacted]

Figure 3-5 : Open field overview Demonstration site

In the figure above the full expanse of the test facility has been presented. Yellow circle on the far left shows the vent location with the 4" shown. Various measurement location has also been circled at varying distances from the vent location. It is important to note that during the test a 60 m safe distance was enforced around the test location as well as informing all site personnel of ongoing tests. Furthermore, it was ensured that other tests at the facility would not take place within the exclusion zone to ensure reliability of data produced.

3.3 Instrumentation Layout

3.3.1 Noise and Overpressure Measurements

IEPE Brüel & Kjær Type 4954 microphones and IEPE Kistler Type 6233B Pencil Probes were calibrated and arranged radially at distances of 5 m, 10 m, 15 m, 30 m, 45 m, 50 m, and 60 m from the vent/flare source as shown in Figure 3-6. This sensor array was designed to capture both near-field blast pressure (pencil probes) and the far-field acoustic signature (microphones) simultaneously for each test event. Additionally, noise measurements were carried out using a free field microphone positioned at 28 m from the vent tip for validation purposes.

[redacted]

Figure 3-6 Physical Layout – Approximated Locations Based on Field Measurement

IEPE Bruel & KJAER Type 4954 Microphones were deployed for acoustic pressure measurement at 1.6 m elevation above ground, while IEPE Kistler Type 6233B Pencil Probes for blast pressure measurement deployed at 1.6 m and 3.0 m elevation above ground as shown in Figure 3-6 . All signals are then fed to a PC-based data acquisition and analysis system for display and storage. The noise and overpressure data was recorded at a sampling rate of 50kHz, providing sufficient resolution to capture the shock front arrival time and pressure rise characteristics across the sensor array.

Table 3-5 : Measurement devices exact positionings

Test Point	Type	Distance from Source (m)	Elevation (m)	Direction
BP 5m E	Pencil Probe	5	3.0	E (68°N)
BP 5m S	Pencil Probe	5	1.6	S (159°N)
BP 10m SE	Pencil Probe	10	1.6	SE (115°N)
BP 15m SE	Pencil Probe	15	1.6	SE (115°N)
Mic 15m E	Microphone	15	1.6	E (68°N)
Mic 15m SE	Microphone	15	1.6	SE (115°N)
Mic 15m S	Microphone	15	1.6	S (159°N)
Mic 30m E	Microphone	30	1.6	E (68°N)
Mic 30m SE	Microphone	30	1.6	SE (115°N)
Mic 30m S	Microphone	30	1.6	S (159°N)
Mic 45m E	Microphone	45	1.6	E (68°N)
Mic 45m SE	Microphone	45	1.6	SE (115°N)
Mic 45m S	Microphone	45	1.6	S (159°N)
Mic 60m E	Microphone	60	1.6	E (68°N)
Mic 50m SE	Microphone	50	1.6	SE (115°N)
Mic 60m S	Microphone	60	1.6	S (159°N)

3.3.2 Thermal Radiation Measurements

Radiation measurements were taken 15 m directly east from the flare/vent stack with a MEDTHERM Radial Thermopile as detailed in Ref. [4]

3.4 Sensor Calibration

Before testing, the team verified sensor connectivity, calibrated all microphones, confirmed system timing, and checked field sensor placement using a range finder and compass tools. iCalibration of other instruments used during the test are shown in the test report Ref. [4]

Table 3-6 – Microphone Field Calibration

Test Point	Amp (Pa) RMS @1000Hz	Amp (dB)	Deviation from Calibration (dB)
Mic 15m E	10.42	114.33	+0.33
Mic 15m SE	10.26	114.20	+0.20
Mic 15m S	10.26	114.21	+0.21

Test Point	Amp (Pa) RMS @1000Hz	Amp (dB)	Deviation from Calibration (dB)
Mic 30m E	10.28	114.22	+0.22
Mic 30m SE	10.27	114.21	+0.21
Mic 30m S	10.41	114.33	+0.33
Mic 45m E	10.28	114.22	+0.22
Mic 45m SE	10.34	114.27	+0.27
Mic 45m S	10.11	114.07	+0.07
Mic 60m E	10.56	114.45	+0.45
Mic 50m SE	10.34	114.27	+0.27
Mic 60m S	10.35	114.27	+0.27

Data from all channels was recorded simultaneously during each test, then processed by reviewing waveforms, extracting and converting peak pressures, averaging results, and generating visualizations. Post-processing also included creating radial heat maps and waveform overlays to illustrate spatial sound distribution and blast wave propagation.

Calibration of the thermal radiation instrumentation is detailed within the [redacted] test report Ref. [4]

4.0 Results

4.1.1 Flaring Tests

All six flare test points were carried out with a 4-inch flare tip. TP1, TP2 and TP3 were the low flow tests for 100%, 20% and 5% hydrogen respectively while TP4, TP5 and TP6 were at significantly higher flowrates for 100%, 20% and 5% hydrogen respectively. Full description of the flaring case matrix which includes the flowrates and composition for each test point is detailed in Table 3-3

4.1.1.1 Noise Measurement

Sound pressure levels measured during the flaring tests varied significantly across the different test point configurations, primarily reflecting differences in gas compositions and flow rate. The general trend across the test configurations showed a decrease in dB SPL with increasing radial distance from the flare source, consistent with expected geometric spreading and atmospheric absorption losses. Increased hydrogen composition led to higher acoustic levels which also increases with flowrate. All flaring tests were conducted at constant flow rates, as defined in Table 3-3, with the influence of flow rate on acoustic output examined by comparing low-flow and high-flow test cases.

Due to the pencil probes located at 5m and 15 m away from the flare being heat saturated from the flare, and low transient pressure forces, peak measurements from the pencil probes as shown in Figure 4-3 are not reliable for sound amplitudes and do not reflect the test conditions on site. Representative noise measurements were recorded from the microphones instead.

Noise data from the demonstration tests were post-processed and analysed using both linear (unweighted) and A-weighted [dB(A)] metrics to provide a comprehensive characterisation of the acoustic emissions. The linear noise levels capture the full sound pressure field, including low-frequency and impulsive components associated with high-velocity gas release and delayed ignition, which are substantially de-emphasised by A-weighting. Comparison of the two datasets shows that linear noise levels are consistently higher, reflecting the true physical intensity of the events, while the A-weighted results are more representative of human hearing response and are therefore appropriate for occupational exposure assessment.

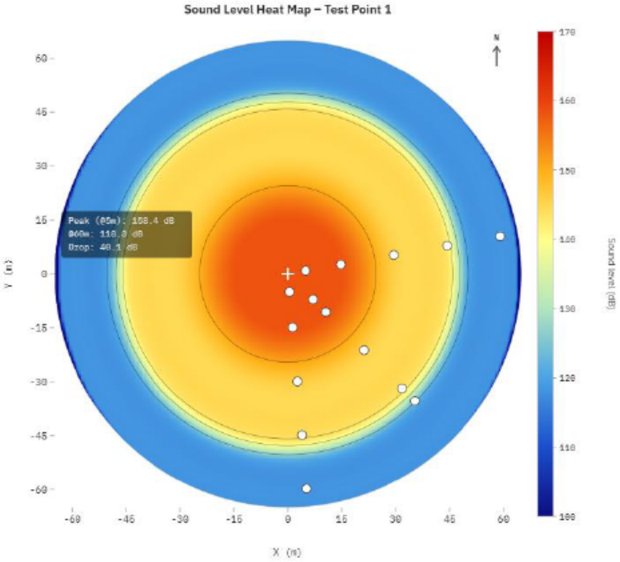
Table 4-1 presents the peak noise level in dB(A) at different distances during the flaring test while the noise contours showing the linear un-weighted noise levels are presented in Figure 4-1. Although flaring generally produces lower noise levels than venting systems, the flaring test results show the peak A-weighted noise levels depends on both flow rate and hydrogen concentration, with a consistent reduction in noise observed with increasing distance from the flare. TP1, TP2, and TP3, representing the low-flow tests for 100%, 20%, and 5% hydrogen respectively, exhibit comparatively lower peak noise levels at 15 m, ranging from 82.5 to 104.9 dB(A), with measured reductions of between 3.4 and 11.2 dB(A) over the 15–60 m range. The elevated values observed for TP3 in this group are noted to be influenced by external site noise.

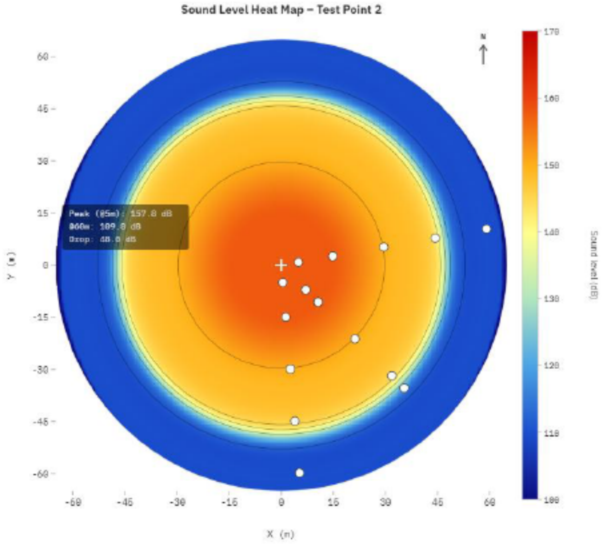
In contrast, TP4, TP5, and TP6, corresponding to significantly higher flow-rate tests for 100%, 20%, and 5% hydrogen, record substantially higher peak noise levels, reaching up to 117.7 dB(A) at 15 m for TP4. The larger noise difference observed between TP3 and TP2 arises because, at low flow rates, flaring noise is strongly influenced by gas density, buoyancy, and flame jet interaction, with the denser 5% hydrogen blend generating higher aerodynamic jet noise than the 20% case. At higher flow rates, however, the flaring regime becomes momentum dominated, and noise generation is controlled primarily by mass flow rate and exit velocity, causing compositional effects to become secondary. As a result, TP6 exhibits only a marginal increase in noise relative to TP5, whereas the TP3–TP2 contrast remains pronounced.

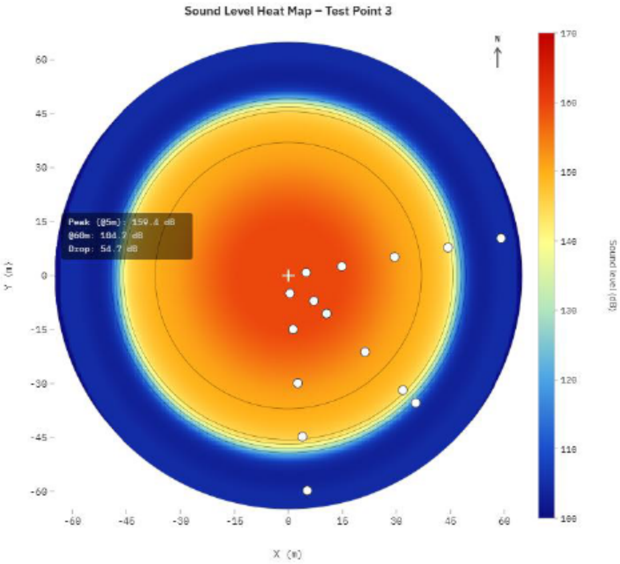
Although noise levels attenuate with distance for all high-flow cases, reductions of 12.2–13.0 dB(A) over the 15–60 m range indicate that elevated noise persists at substantial distances from the flare. The flaring noise results demonstrate that flow rate is the dominant driver of flaring noise, while hydrogen concentration introduces secondary variation, and confirm that noise remains a governing factor for exclusion-zone definition, particularly under high-flow flaring conditions.

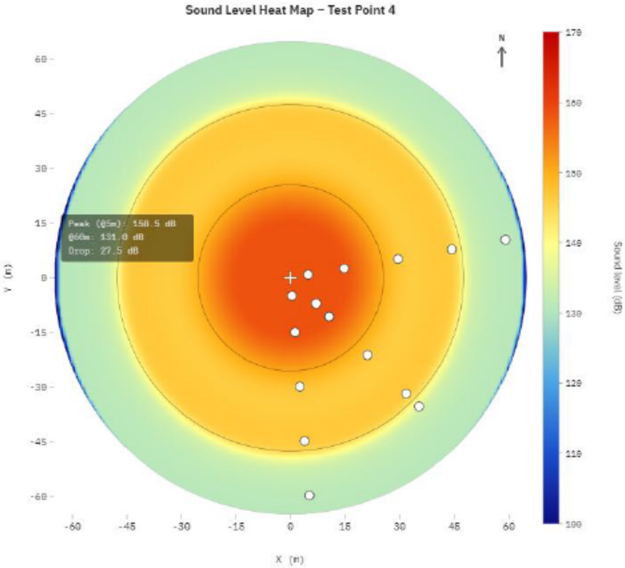
Table 4-1 : Flaring Test Results Summary – Peak Db(A) at Microphone Locations

[redacted]


Sound Level Heat Map – Test Point 1
Peak (@5m): 158.4 dB
@60m: 118.3 dB
Drop: 40.1 dB
N
Y (m)
X (m)
Sound level (dB)


Sound Level Heat Map – Test Point 2
Peak (@5m): 157.8 dB
@60m: 109.8 dB
Drop: 48.0 dB
N
Y (m)
X (m)
Sound level (dB)


Sound Level Heat Map – Test Point 3
Peak (@5m): 159.4 dB
@60m: 104.7 dB
Drop: 54.7 dB
N
Y (m)
X (m)
Sound level (dB)


Sound Level Heat Map – Test Point 4
Peak (@5m): 158.5 dB
@60m: 131.0 dB
Drop: 27.5 dB
N
Y (m)
X (m)
Sound level (dB)

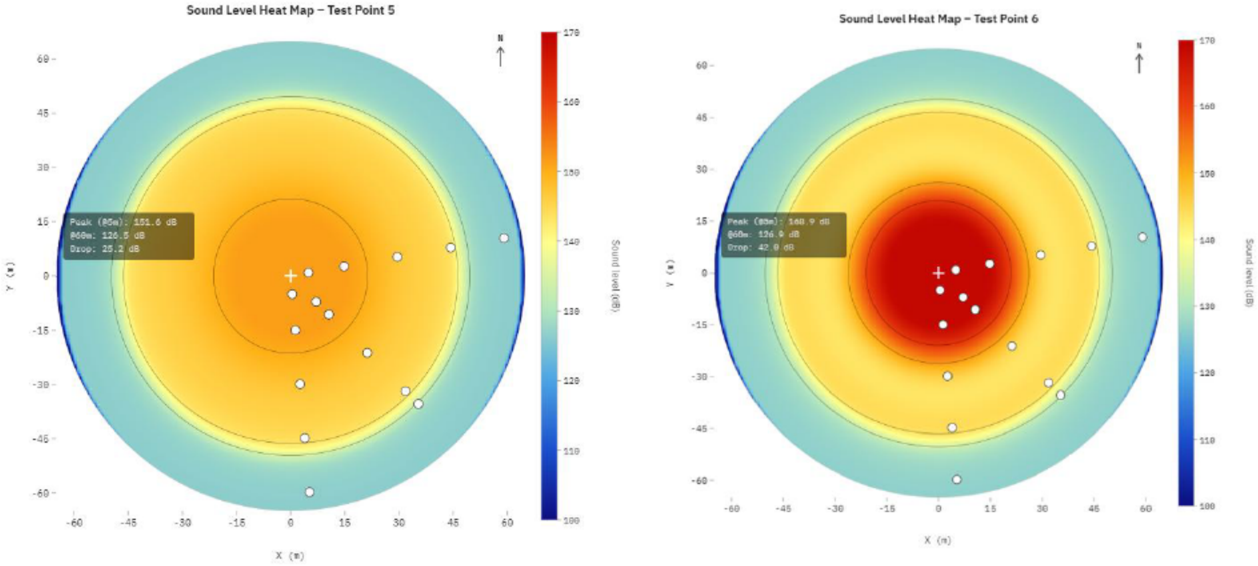


Figure 4-1 Sound Level Heatmap for Flaring (Test point 1 to 6)

[redacted]

[redacted]

4.1.1.2 Thermal Radiation Measurement

Table 4-2 summarises the measured thermal radiation levels recorded during the flaring trials performed using a 4-inch flare tip across three hydrogen compositions i.e., 5%, 20%, and 100% H_2. For each hydrogen fraction, two test runs were conducted to assess consistency and capture natural variability in flame behaviour and atmospheric conditions. The recorded heat flux values represent the peak thermal radiation measured at the specified monitoring locations. Thermal radiation from flaring increases with flow rate across all compositions, at high flow conditions, the highest radiation levels were measured for the 5% hydrogen cases. At low flowrate, no significant difference between the measured thermal radiation for 5% and 20% H_2. Regardless of the flowrate, pure hydrogen has the lowest thermal radiation due to its low emissivity.

Table 4-2 : Flaring Thermal Radiation Results

[redacted]

[redacted]

4.1.1.3 Flaring Review

Flaring demonstrations were undertaken as part of this project to provide evidence that flaring is a safe technique that could be utilised if venting of pure hydrogen or hydrogen blends was deemed too high risk. The objective was to record noise and thermal radiation values which could help inform design decisions. In terms of thermal radiation, each flaring test took measurements at 15 m from the stack.

Based on the results presented in Table 4-2 the thermal radiation experienced is more dependent on the gas flowrate than the composition of the gas. This is to be expected as the emissivity of the flame when burning natural gas is greater than that of hydrogen. This is positive confirmation that flare systems designed for natural gas service, would have reduced thermal contours as methane is replaced with hydrogen for the same operating condition. The largest value recorded in Table 4-2 was 2.63 kW/m^2 at 15m. Based on the thermal radiation exposure limits presented in Appendix A, the recorded radiation levels are considered acceptable. It is therefore anticipated that, if a temporary flare which is a portable, short duration flaring system installed to safely combust gas of similar size with the same flow rate were used on site, the maximum thermal radiation exclusion zone would be limited to several meters base on not breeching the 6.3 kW/m2 thermal radiation exposure limit.

Table 4-3 : FlareSim predictions vs hand measurements for thermal radiation

[redacted]

The table above presents both the demonstration recorded thermal radiation levels at 15.24m for test points 1 – 6 and the Flaresim predicted thermal radiation data for the corresponding test points. The test conditions were replicated in FlareSim for review. It can be seen that FlareSim overpredicts the thermal radiation exposure by at least 31% for all test points. Therefore, for future flare system design FlareSim can be utilised as the software will provide conservative estimates needed for design purposes. The reason the demonstration results present considerably lower thermal radiation levels is likely due to the weather conditions i.e., fluctuating wind speed and direction which could cause cross winds.

Test 6 was conducted using a 4-inch flare with a flow rate of 2 kg/s and pressure of 8 barg. When this is compared with the compressor casing scenario, which considers a 10-inch stack operating at 10 kg/s, the recorded thermal radiation data indicate that exclusion zones based on thermal radiation would be less than 50 m from the flare stack.

These findings have been corroborated using FLARESIM. For the 10-inch, 10 kg/s case, the thermal radiation at 50 m was found to be 1.58 kW/m² with the 16m height of the flare playing a significant role in the thermal radiation contour. Furthermore, exclusion zones defined based on 6.3kW/m2 where personnel can work safely for up to 5 mins with aluminized clothing was not breached.

When the pig trap and double block and bleed scenarios were modelled in FlareSim a 6.3 kW/m2 exposure level was experienced within 5 – 10 m of the flare with flowrates up to 2 kg/s due to the low heights of these vents. Whereas for the compressor casing at a gas flowrate of 10kg/s 6.3 kW/m² was not breached at any distance at ground level from the flare.

In summary, from a thermal radiation perspective, deploying a small portable flare necessitates identifying suitable space on site. Exclusion zones should be established based on FlareSim predictions to ensure safety and compliance. These are estimated for the pig trap and double block and bleed flowrates to be no greater than 20m (greater than this 6.3kW/m2 would not be experienced). If the large compressor casing stacks were converted to a flare system with similar height current exclusions zones at sites would be sufficient to protect against thermal radiation. On a thermal radiation basis, flaring hydrogen is less hazardous than natural gas, so this is not a limiting factor to utilising flares, but noise is.

Noise is a slightly more challenging. Figure 4-2 indicate that noise levels peak at approximately 120 dB(A) within a distance of 5 - 10 m. It should be noted, however, that the blast pressure sensors located at <15 m were adversely affected by the flare and flame body, resulting in distorted readings. Consequently, the data recorded at distances of 15 m and greater are considered more representative.

When compared with venting, flaring produced lower noise levels despite the higher mass flow rates involved. This is considered likely to be a consequence of differences in gas flowrate and exit velocity between the two scenarios.

In accordance with SR23 [5], personnel should not be present in areas where noise levels of 120 dB or greater may be experienced. Based on a review of the data provided by [redacted] for the higher flow-rate cases, the corresponding noise-based exclusion zone would therefore extend up to 10 m.

High flaring noise is dominated by high jet exit velocity and turbulence at the flare tip, particularly for hydrogen were choked or near-supersonic flow is common. The most effective mitigation measures therefore act at the noise source, including reducing exit velocity by increasing flare-tip diameter, implementing staged or controlled depressurisation to avoid large instantaneous flow rates, and optimising flare-tip design (for example, low-noise or multi-port tips) to disrupt coherent jet structures and minimise shock formation. For smaller or frequent flaring duties, especially in areas of high societal sensitivity, ground or enclosed flares may be considered, provided they are purpose-designed with adequate purge, ventilation, and ignition safeguards to prevent flammable gas accumulation.

Conventional noise silencers are not suitable for direct application at flare tips, as flare noise is generated by combustion and high-velocity jet effects rather than pipework flow, and the extreme thermal and flow conditions would compromise silencer function and flame stability. Noise mitigation approach may be applied upstream of the flare, for example to mitigate valve or restriction noise, but overall noise control is more effectively achieved through flare design and flow management. Where residual noise remains high, noise-based exclusion zones and operational controls should be applied, and for large or repeat releases recompression remains the most effective mitigation option, as it eliminates the atmospheric noise source entirely.

These findings indicate that, for flaring operations, noise exposure is the governing factor when defining exclusion zones, rather than thermal radiation. Under normal operation, flaring does not result in flammable cloud formation and, therefore, does not present an overpressure hazard, as combustion is established immediately at the flare tip. In addition, flaring systems are designed and operated with multiple layers of protection to manage ignition reliability, including continuous or redundant pilots, flame detection, and automatic re-ignition systems.

However, under abnormal conditions such as flame-out followed by subsequent re-ignition, a limited volume of unignited gas may be released prior to ignition, potentially generating a short-duration overpressure event upon re-ignition. Owing to the elevated discharge height, high buoyancy, rapid dispersion, absence of confinement or congestion, and the presence of engineering and procedural safeguards to limit the duration of unignited release, any resulting overpressure is expected to be spatially limited and transient and is not anticipated to govern exclusion-zone requirements for flaring.

4.1.2 Delayed Ignition Tests

A major hazard associated with venting hydrogen is the transient overpressure generated following delayed ignition. This is not a significant concern typically associated with methane in unconfined environment. These overpressure peaks are critical inputs for defining hazard exclusion zones, assessing personnel safety risks, and supporting quantitative hazard modelling. Test Points TP7, TP8, and TP9 were performed using a 1-inch vent tip for 100%, 20%, and 5% hydrogen mixtures, representing conditions typical of a pig-trap vent. Test Points TP10, TP11, and TP12 used a 2-inch vent tip for corresponding hydrogen mixtures and delayed-ignition scenarios, representative of a double-block-and-bleed vent configuration.

The delayed ignition tests produced transient overpressure events that are visually distinct from the steady-state flaring results when examined in the time-history waveforms. Figure 4-4 shows an example multi-channel waveform plot from a delayed ignition event, illustrating the sequential arrival of the shock front at sensor locations at increasing distances from the source.

The shock front propagation is clearly visible as a sharp high-amplitude spike progressing in time from the nearest Pencil Probe channels to the more distant microphone channels. The time delay between successive arrivals allows the shock propagation velocity to be estimated.

The magnitude and temporal characteristics of the overpressure signal reflect the transient nature of the delayed ignition event, with peak pressures occurring over very short durations before rapidly decaying. Unlike confined explosions or congested environments where sustained flame acceleration can occur, the unconfined geometry limits both pressure build-up and impulse duration. As a result, while measurable overpressures are generated, the events remain short-lived and spatially attenuated with distance, as indicated by the diminishing peak amplitudes observed across the sensor array. This will not be the case when there is confinement.

The delayed ignition overpressure behaviour is governed primarily by flammable cloud size, composition, dispersion prior to ignition, and ignition timing. This explains why delayed ignition represents a major hazard for hydrogen venting scenarios but is not typically associated with controlled flaring, where immediate combustion at the source prevents flammable cloud accumulation.

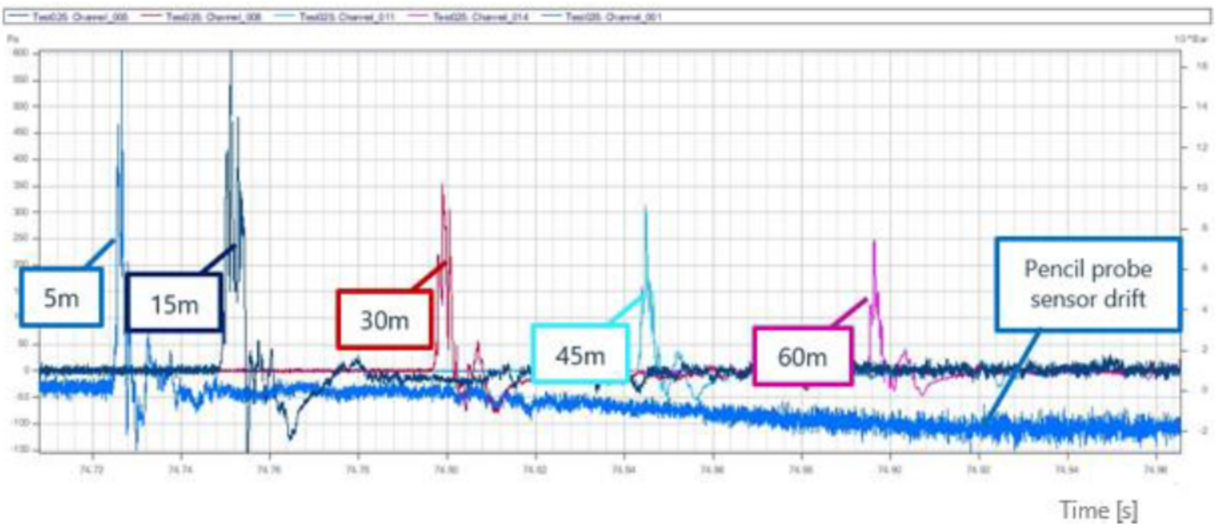


Figure 4-4 Multi-Channel Waveform Showing Shock Front Propagation Through Sensor Array (Delayed Ignition Test)

4.1.2.1 Noise Measurement

The peak noise data at various distances for the delayed ignition test is shown in Table 4-4. Although noise data are reported from the blast pressure sensors these is not entirely reliable as the only useful data from these sensors aligns with the blast pressure wave. The peak noise measurement is shown in Figure 4-5 and Figure 4-6

Table 4-4 : Venting Test Results Summary – Peak Noise data

[redacted]

Figure 4-5 shows the maximum noise levels averaged linearly to show recorded following delayed ignition of vented gas from a 1-inch pig trap vent to show the noise level that will be experienced by mechanical devices when the vented gas is ignited. Across all compositions, the delayed-ignition event generates very high initial noise levels, with peak values at short distances (5–10 m) typically exceeding 140dB for most of the cases. Noise levels decrease with distance, but even at 60 m remain well above 140 dB for pure hydrogen case. The decay profile shows a rapid reduction within the first 10–15 m, followed by a more gradual decline out to 60 m.

100% hydrogen cases produce the highest noise levels at all distances, 20% hydrogen exhibits intermediate behaviour, louder than the 5% case but significantly below pure hydrogen. 5% hydrogen produces the lowest noise levels, with peak values at short range closer to 133 dB(A) and far-field values around 111–118 dB at 60 m.

Figure 4-6 shows the background ambient dB(A) noise prior to venting, noise generated during venting, and the peak noise associated with delayed ignition of the vented gas for test point 10. Prior to gas release, measured noise levels across all microphones remain relatively stable, in the range of approximately 75–80 dB(A). These levels reflect the ambient acoustic conditions at the test site on the day of testing and slightly on the high side because of the continuous background from the highway close to the test site.

At approximately 110 s, a clear step increase in noise is observed at all measurement locations, corresponding to the onset of venting across all venting tests. The majority of the acoustic contribution arises from the venting phase, with noise levels increasing by approximately 25–45 dB(A) above the ambient baseline. During this phase, noise levels increase to approximately 95–110 dB(A) depending on distance, indicating that the dominant acoustic contribution arises from the high-velocity jet formed at the vent outlet. The relatively flat plateau during venting is when the gas release has reached steady state with noise generation governed primarily by jet momentum and turbulence. As expected, measured noise levels decrease with increasing distance from the vent, demonstrating geometric spreading and atmospheric attenuation.

It is noted that in some venting applications, silencers can achieve noise reductions of the order of 20 dB, and the use of such mitigation, together with double hearing protection for personnel, can significantly reduce individual exposure during controlled manual venting activities. Where venting operations can be managed such that point exposure remains significantly below 120 dB(A) and the duration of exposure is short, venting may be tolerated under tightly controlled conditions. However, the acceptability of such activities is highly dependent on both noise level and exposure duration and requires strict procedural control.

At approximately 120–130 s, coincident with delayed ignition of the vented gas cloud, a short peak in noise level is observed. At this point, all microphones record a pronounced peak in noise, exceeding 133 dB(A) at closer locations for test point 10 and remain > 90dB(A) at the furthest measurement distances. This peak reflects the impulsive nature of delayed ignition, where rapid energy release and flame establishment generate a short-duration but high-intensity acoustic event. Following ignition and cessation of venting, noise levels rapidly decay back to baseline values, confirming that the high noise exposure associated with delayed ignition is transient in nature. Nonetheless, the magnitude of the recorded peak levels demonstrates that such events would exceed typical occupational noise thresholds and therefore have direct implications for personnel exclusion zones and operational controls.

Levels recorded at 5–30 m are well into the red zone of the HSE noise exposure limit [9] for all delayed ignition cases tested, therefore, no safe standing exposure for personnel, even for short durations within this distances from the vent because hearing protection alone is not sufficient mitigation. Noise Levels at 45–60 m are still above lower action values and exposure must be time-limited and controlled with exclusion enforced.

The results indicate that both pig trap and double block and bleed venting generate high noise levels, making it unsuitable for operation near personnel. Pig traps are typically located in congested areas of sites, often near access points and maintenance zones, which further exacerbates the risk to personnel from excessive noise exposure during venting activities. The gas from the pig trap can be vented using a portable vent located far away from personnel or alternatively, gas can be captured and recompressed back into the system, avoiding both excessive noise exposure and unnecessary gas wastage. Double block and bleed fuel gas vents are typically higher than 3m, however this will have marginal effect on exposure at ground level.

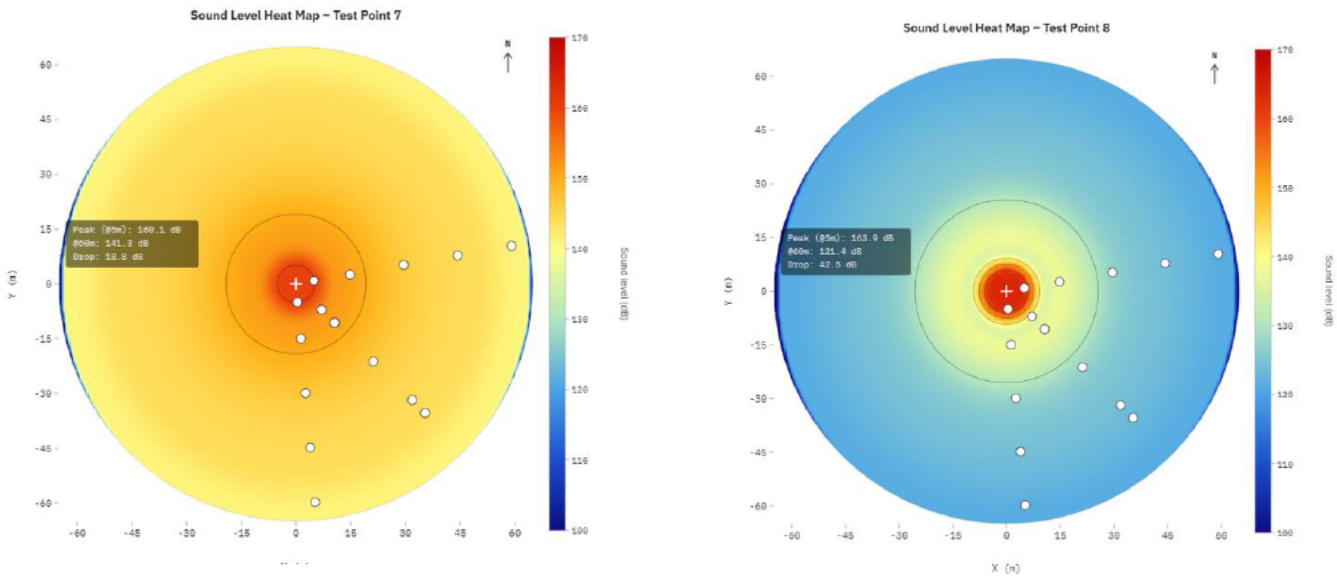
[redacted]

Figure 4-5 : 1" Delayed Ignition Maximum Noise Exposure Plot

[redacted]

Figure 4-6: Example Delayed Ignition Noise Exposure Plot

The linear (unweighted) sound-level heat maps shown in Figure 4-7 illustrate the spatial distribution of true acoustic pressure generated during the tests, capturing the full frequency content of the noise, including low-frequency and impulsive components mostly experienced by mechanical devices



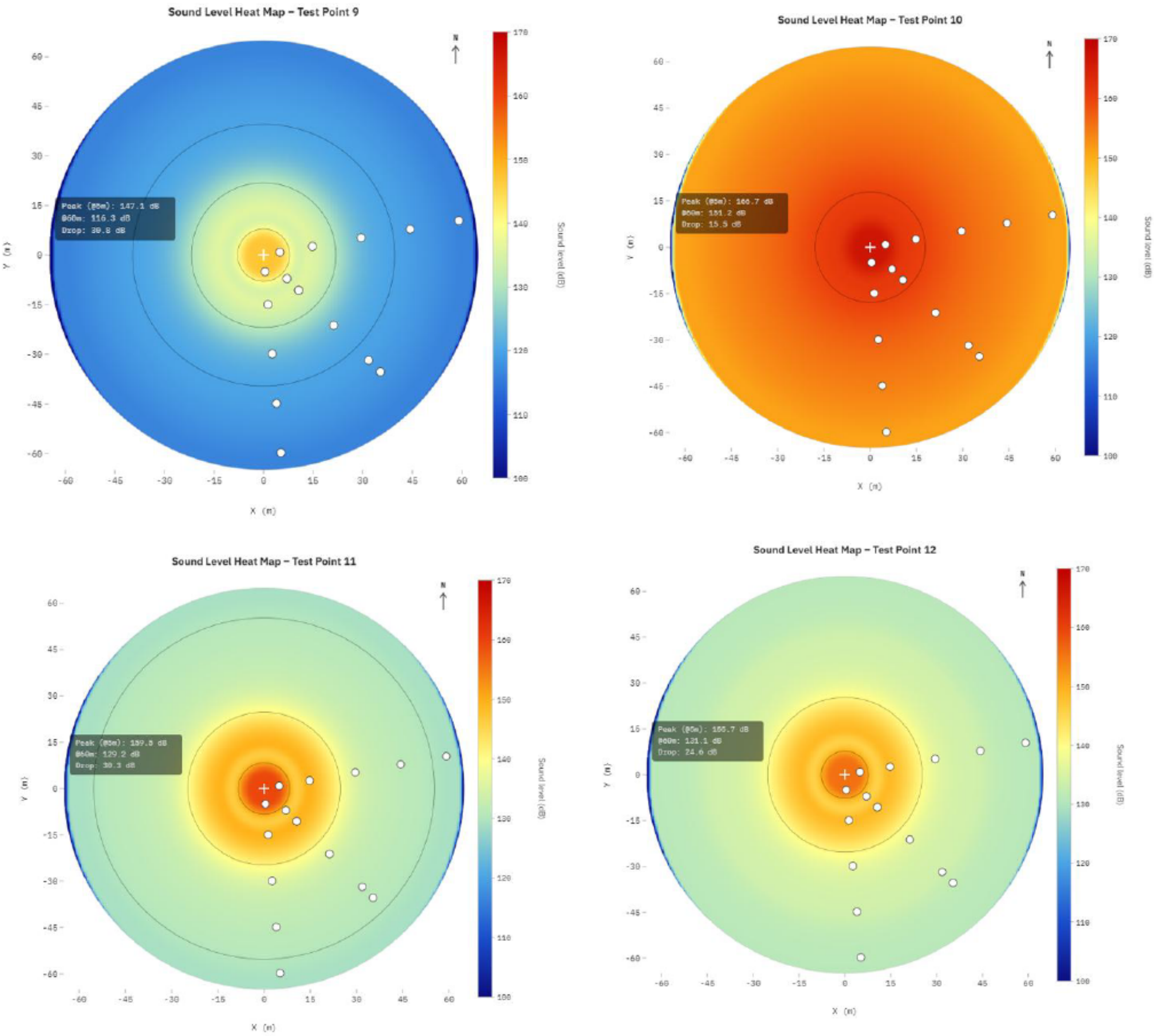


Figure 4-7 Sound Level Heatmap for Delayed Ignition of a Vent (Test point 7 to 12)

4.1.2.2 Overpressure Measurement

[redacted]

Figure 4-8: 1”, 5%,20%,100% Delayed Ignition Maximum Overpressure

The delayed-ignition results show a clear dependence of blast overpressure on hydrogen concentration. Higher hydrogen content consistently produced higher overpressures, particularly in the near-field (5 m). For both vent-tip sizes, the 100% hydrogen cases (TP7 and TP10,) generated the highest blast loads, with peak levels around 146 dB, while the lower-concentration cases (20% and 5% hydrogen (TP8, TP9, TP11 and TP12) produced significantly lower near-field levels in the range of 131–132 dB. This represents a reduction of approximately 14–15 dB compared with the pure-hydrogen events. Mid-field microphone levels showed the same trend, with higher-hydrogen mixtures retaining higher overpressures at distance.

Figure 4-9 and Figure 4-10 below shows the maximum overpressure levels recorded during delayed-ignition tests for releases of 5%, 20%, and 100% hydrogen from the 2-inch vent tip, with measurements taken along two separate downwind directions: easterly and southerly. Full instrumentation layout is shown in Figure 3-6. These directions were selected based on prevailing wind conditions during testing to ensure that sensors were positioned within the primary path of the vented gas cloud at the time of ignition.

In the easterly direction, the overpressure curves demonstrate the typical behaviour of an outdoor hydrogen-air overpressure, with the highest peak values occurring close to the vent (within ~10 m) followed by a rapid decay as distance increases. The 100% hydrogen cases generate the most significant overpressures, reflecting the higher flame speed and energy release associated with pure hydrogen. The 20% and 5% blends exhibit progressively shorter decay profiles and lower peak pressures, consistent with their reduced reactivity.

The southerly direction plot shows similar decay characteristics, though the absolute magnitudes is slightly smaller than the easterly results. This is due to the wind direction, turbulence, minor cloud-shape variations, and local atmospheric disturbances, all of which influence how the combustible mixture forms and propagates prior to ignition. The repeatability between Run 1 and Run 2 for each composition demonstrates good consistency in measured behaviour despite natural variability in outdoor conditions.

[redacted]

Figure 4-9 : 2", 5%,20%,100% Delayed Ignition Maximum Overpressure in easterly direction

[redacted]

Figure 4-10 1", 5%,20%,100% Delayed Ignition Overpressure in southerly direction

Figure 4-9 and Figure 4-10 illustrate the maximum overpressure measured during delayed-ignition tests for hydrogen releases at different compositions (5%, 20%, and 100% H_2). Each curve represents the peak overpressure captured at increasing distances from the vent, enabling direct comparison of how vent size and hydrogen concentration influence the severity of the blast wave.

Figure 4-11 below shows the maximum overpressure levels measured during delayed-ignition tests for 100% hydrogen released from both the 1-inch and 2-inch vent tips. The curves show how peak overpressure decays with increasing distance from the vent, illustrating the influence of vent size and release characteristics on the resulting blast wave. As expected, the 2-inch vent generates consistently higher overpressures at close range due to the larger mass flow and greater jet momentum at ignition. All test runs exhibit a rapid reduction in overpressure within the first 10–15 m, followed by a more gradual decline out to 60 m, indicating that the blast effects become significantly less severe with distance.

[redacted]

Figure 4-11 : 1" & 2" Maximum Overpressure Delayed Ignition Tests

Figure 4-12 presents the time-history pressure waveform recorded by the 5 m blast sensor during a delayed-ignition event for the 2-inch DBB vent operating with 100% hydrogen. For most of the recording period, the signal remains close to ambient, indicating a stable pre-ignition condition with no significant pressure disturbances. This is followed by a single, sharp pressure excursion at approximately 160 s, corresponding to the moment of ignition of the accumulated hydrogen cloud.

The waveform is characterised by a very steep pressure rise, reaching a peak overpressure of approximately 0.8–0.85 psi (~5.5–5.9 kPa), followed by a rapid decay and a short-duration negative phase.

Although the measured peak overpressure at 5 m approaches commonly cited damage thresholds for glazing and light structures, the rapid decay of the pressure wave suggests that structural damage potential reduces quickly with distance. However, the magnitude of the near-field peak confirms that personnel located close to the vent would be exposed to hazardous blast loads, reinforcing the need for exclusion zones and for avoiding local venting of hydrogen-rich gas from DBB configurations.

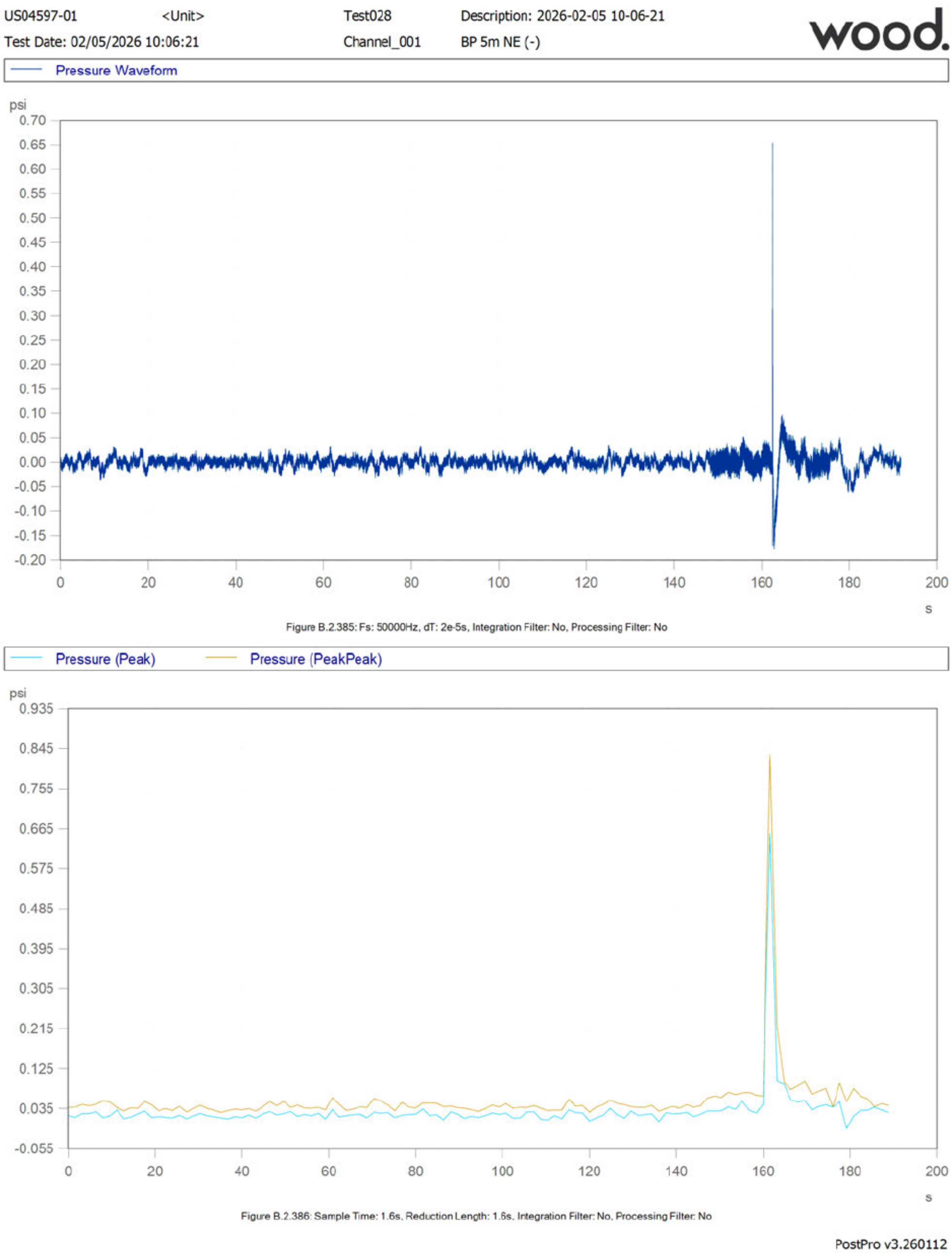


Figure 4-12 : 2" Delayed Ignition 5m blast sensor 100% hydrogen overpressure pressure results

Table 4-5 summarises the thermal radiation measurements recorded during the hydrogen venting trials for both the 1-inch and 2-inch vent tips, across hydrogen concentrations of 5%, 20%, and 100%. Unlike flaring, where combustion takes place at the flare tip, venting releases unignited gas, and any measured thermal radiation is solely due to delayed ignition of the accumulated jet cloud. As expected, the recorded heat flux levels are significantly lower than those observed in flaring scenarios, reflecting the smaller flame size and shorter combustion duration following ignition of the vented cloud. The results show consistent trends across repeated runs, with slightly higher thermal radiation associated with the 2-inch vent tip due to the larger release rate and greater combustible cloud volume. These values are well below typical thermal hazard thresholds, but they provide important empirical data for validating dispersion and ignition modelling, and for assessing the potential thermal exposure to personnel and nearby equipment during vent-related ignition events.

[redacted]

The thermal radiation values recorded during venting are significantly lower than those measured during flaring, this is because in flaring, hydrogen is intentionally combusted at the flare tip, producing a stable flame with a sustained heat release rate and a corresponding radiative footprint. In flaring, thermal radiation values range from approximately 0.75 to 2.63 kW/m^2, with higher values observed at 20% and 5% blends in some runs due to local flame behaviour and atmospheric effects.

Thermal radiation is a measure of energy transfer rate (joules per second) per area (m^2), and in venting scenarios any radiative exposure associated with a transient ignition would be extremely brief typically less than one second. In addition, the high venting velocity rapidly disperses the gas and flame, causing high dispersion of the gas cloud which reduces the thermal radiation exposure at a single point. Consequently, the overall thermal radiation exposure from venting is substantially lower than that associated with sustained ignition events. The venting results reflect this behaviour, with measured thermal radiation generally between 0.16 and 0.99 kW/m^2, depending on vent size and hydrogen fraction. Even the highest observed venting values associated with the 2-inch vent tip at 100% hydrogen remain well below the lowest radiation levels recorded during flaring.

Delayed-ignition flames resulting from hydrogen venting are inherently limited in size and duration because the flammable cloud formed prior to ignition is finite, unconfined, and rapidly consumed. Consequently, thermal radiation is low, however, venting remains hazardous due to the potential for transient overpressure and elevated noise following delayed ignition. Operational controls should therefore focus on managing overpressure and noise risks, through ignition-source control, minimisation of vent inventory and duration, personnel access management, and exclusion-zone definition based on these effects rather than just thermal radiation.

4.1.2.3 Delayed Ignition Review

Delayed ignition testing was initially scoped to enable estimation of realistic overpressures arising from credible venting scenarios. The outcomes of this testing were intended to inform both design conditions and the definition of site exclusion zones. Based on the tests conducted on site, and with reference to Figure 4-8 and Figure 4-9, the maximum overpressure recorded was 4.5 kPa. A limit of 6 kPa defined in Appendix A, is generally considered the threshold at which structural damage may occur due to overpressure. Consequently, none of the data recorded at distances of 5 m or greater from the stack exceeded this limit. Nevertheless, the dataset reveals several notable trends.

Firstly, the results indicate that increasing the hydrogen fraction in the gas mixture leads to an increase in overpressure. This trend is evident in Figure 4-8, Figure 4-9 and Figure 4-10. One exception to this general behaviour is observed in the 20% hydrogen, 1-inch case. During the two repeated delayed ignition tests for this condition, the overpressure measured at 5 m exceeded that recorded for the 100% hydrogen case. It is suspected that challenges associated with gas mixing, or residual gas remaining in the line, may have resulted in a locally increased hydrogen concentration, thereby generating higher overpressures than anticipated. Alternatively, the anomaly may be attributable to deviation or uncertainty in the blast pressure sensor measurements. Notwithstanding this outlier, the overall dataset supports the conclusion that overpressure increases with increasing hydrogen content. While the overpressures associated with both 20% and 100% hydrogen remain acceptable at distances greater than 5 m, it is possible that limits could be exceeded closer to the vent.

Figure 4-11 presents the overpressure results for all 100% hydrogen flow-rate cases. The data clearly demonstrate that overpressure increases with increasing mass flow rate. The maximum flow rate tested during this programme was 0.5 kg/s; consequently, it is expected that a 10-inch stack operating at 10 kg/s could generate substantially higher overpressures than those measured during the tests.

In addition to overpressure, noise levels were measured extensively during the venting tests. Preliminary CFD analysis predicted that the vented gas would achieve choked or near-supersonic exit velocities, and this behaviour is corroborated by the measured noise data presented in Figure 4-5 and summarised in Table 4-4. Peak A-weighted noise levels measured at 5 m and 10 m exceed 125–130 dB(A) for all test cases, with maximum values reaching approximately 133 dB(A) during the 100% hydrogen delayed-ignition tests. Noise levels reduce with distance but remain significant, with values still greater than 110 dB(A) at 60 m for the highest-hydrogen cases.

The magnitude and spatial persistence of these noise levels are consistent with supersonic or highly under-expanded jet flow, confirming the CFD prediction of high exit velocities. Importantly, the results show that the majority of the noise increase is associated with the venting phase itself, rather than ignition, as indicated by the sustained high noise plateau prior to delayed ignition. The measured data also demonstrates a clear increase in noise with increasing hydrogen content, with the 100% hydrogen venting cases consistently producing the highest acoustic levels at all measurement distances.

Under SR-23 criteria, noise levels of this magnitude are not acceptable for routine venting operations, particularly within 60 m of the vent, which represents the maximum measurement distance deployed during the testing programme. These findings are consistent with independent noise measurements recorded by [redacted] and reinforce the conclusion that local venting of hydrogen-rich gas, and especially 100% hydrogen, is impractical for many NGT sites, as the resulting noise-based exclusion zones would be difficult to manage operationally.

The final delayed ignition review was to replicate the demonstration conditions within HyRAM+ to understand if the tool can be utilised for design purposes. The first pass was to review the case with the largest overpressure recorded at the demonstration; this was the 100% 2” case. As HyRAM+ is designed for hydrogen and hydrogen jets the simulated results for this case should be the closest. The result has been shown below.

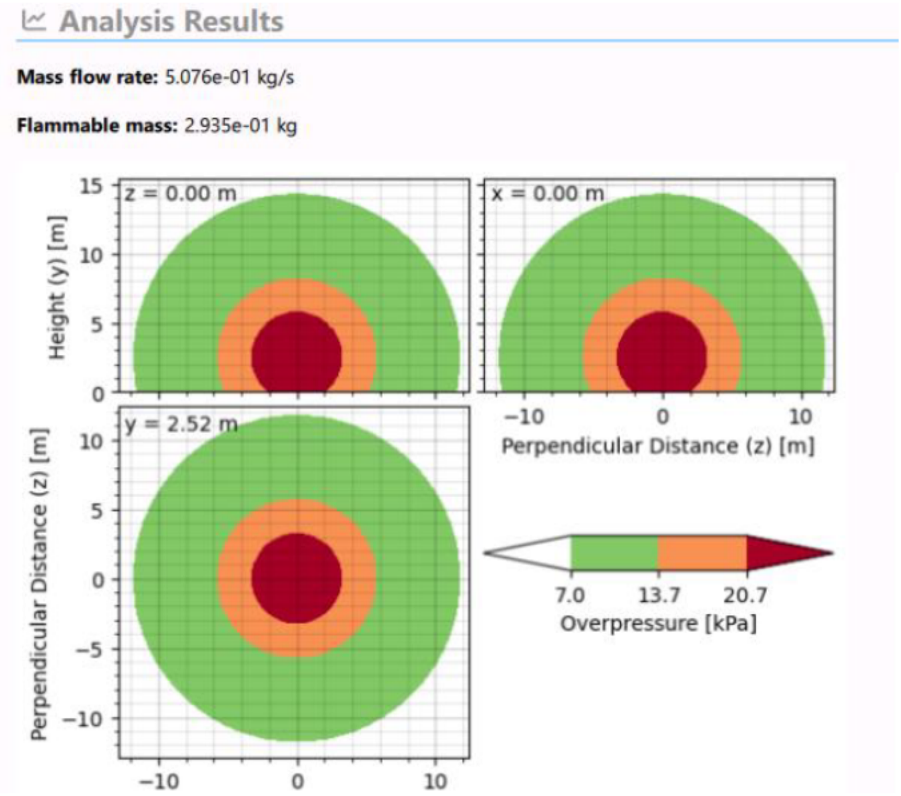


Figure 4-13 : HyRAM+ replication of Test Point 10 Run 1

To match the demonstration conditions to the HyRAM the mass flowrate of the vent had to be matched. For test point 10 run 1 the mass flowrate achieved was 0.49k/s which is very close to 0.51 kg/s passed into HyRAM+. Figure 4-13 estimates that an overpressure of 7kPa or greater is experienced within 12 meters of the vent stack. With regards to Figure 4-9 the test did not record above 4kPa at any distance. This highlights that HyRAM+ tends to overestimate overpressure quite significantly. It is important to mention that HyRAM has limited functionality to input weather conditions which has large effect on overpressure. In summary HyRAM+ is a good first pass tool to understand the scale of a hazard however, it is too conservative to be utilised as a design tool.

4.1.3 Comparison to similar work

To critically review the work completed here it was important to compare test results against similar tests undertaken. Furthermore, the comparisons made between the work can be used to infer conclusions on untested events.

For the overpressure hazard assessment one other project has been completed that recorded delayed ignition tests. The venting and flaring test completed for SGN can be used for comparisons with this project. The first step was to find a like for like case to compare results from. Based on recorded data of the [redacted]s test only one case is comparable. This has been shown in the table below.

[redacted]

[redacted]

Table 4-6 presents the 4 cases with similar conditions, overall, the demonstration work presented in this report tested points at a lower mass flowrate than the [redacted]s work with faster gas velocity due to smaller pipe diameters. Since the cases had been chosen the next step was to compare results with the [redacted]s test overpressure readings which were taken from 5 – 28m with 4 sensors in this range. The Wood test recorded overpressures at 5m, 15m ,30m, 45m and 60m. Therefore, peak overpressure measurements are directly comparable at 5m. It is unknown at exactly what height [redacted]s set the instruments to, however, from images they look to be comparable heights to the demonstration work conducted for this project. Based on these assumptions the peak overpressure measurements for these test cases could be compared. This has been highlighted in the table below.

[redacted]

Table 4-6 presents the 4 cases with similar conditions, overall, the demonstration work presented in this report tested points at a lower mass flowrate than the [redacted]s work with faster gas velocity due to smaller pipe diameters. Since the cases had been chosen the next step was to compare results with the [redacted]s test overpressure readings which were taken from 5 – 28m with 4 sensors in this range. The Wood test recorded overpressures at 5m, 15m ,30m, 45m and 60m. Therefore, peak overpressure measurements are directly comparable at 5m. It is unknown at exactly what height [redacted]s set the instruments to, however, from images they look to be comparable heights to the demonstration work conducted for this project. Based on these assumptions the peak overpressure measurements for these test cases could be compared. This has been highlighted in the table below.

Table 4-7 shows that during comparable test the Wood cases generated greater overpressure at 5m as well as 28 – 30 m. If the highest measurements are taken for each set the Wood demonstration recorded 64% greater overpressures at 5 m and 41% at 28 – 30m. Furthermore, with review of Table 4-6 both Wood cases achieved 30% less flowrate that the [redacted]s results. This is likely due to the wind conditions. The wind speed for the Wood cases were nearly 50% lower. This would lead to less gas cloud dispersion, greater accumulation and larger gas clouds.

The results above highlight how environmental conditions could play a vital role when defining hazard from a gas cloud type event. As wind speed drops the overpressures increase. Therefore, on a still day with little to no wind peak overpressure could be greater that the values recorded above. The cases compared above are for 100% hydrogen, however, with regards to blends the wind will have less of an effect on the overpressure from scenario to scenario due to the higher density of the natural gas leading to less dispersion. However, there will still be an increase in overpressure as wind falls which must be factored in during design. The [redacted]s stack was only 1 m taller than the [redacted] set up and is unlikely to have significant effect.

Table 4-8 : Further [redacted] Cases

[redacted]

With referenced to the original scenario list through the demonstration direct conclusion can be drawn for the pig trap and double bleck and bleed cases. However, large gas flowrates were not tested such as the compressor casing of 10kg/s. Table 4-8 show a 10" , 10kg/s compressor casing case in a low wind speed conditions would see considerably higher overpressures at 5m then any of the test presented above. A conservative estimate would be Peak overpressure could surpass 12kPa within proximity to a 10" vent. This pressure wave would seriously damage equipment and people and must be avoided. Consequently, a dedicated demonstration campaign for the 10" compressor casing vent should be undertaken to better characterise and manage these risks.

4.1.4 Ignition location

During the demonstration conducted as part of this project, the vented gas was ignited using a flare pilot. This led to the gas cloud igniting from the base. This is repetitive of unintended ignition of a gas cloud as the vent tip location is the most likely location ignition could occur. This is due to the mechanisms such as static which can generate when very high velocity gas passes through a vent. However, from literature it is understood that in an open-air experiment ignition in the centre of the gas cloud would generate greater overpressures. Most overpressure experiments use stationary bags with ignition at the bag's centre.

Ignition at the base of the gas cloud will cause pressure waves to generally travel in the direction of the moving venting gas. The pressure waves will move in a circular patten, however, as there is little gas below the ignition point much less pressure moves in a downward direction. This will reduce the amount of overpressure that is reflected off the ground and subsequently produce smaller peak overpressure recordings [13].

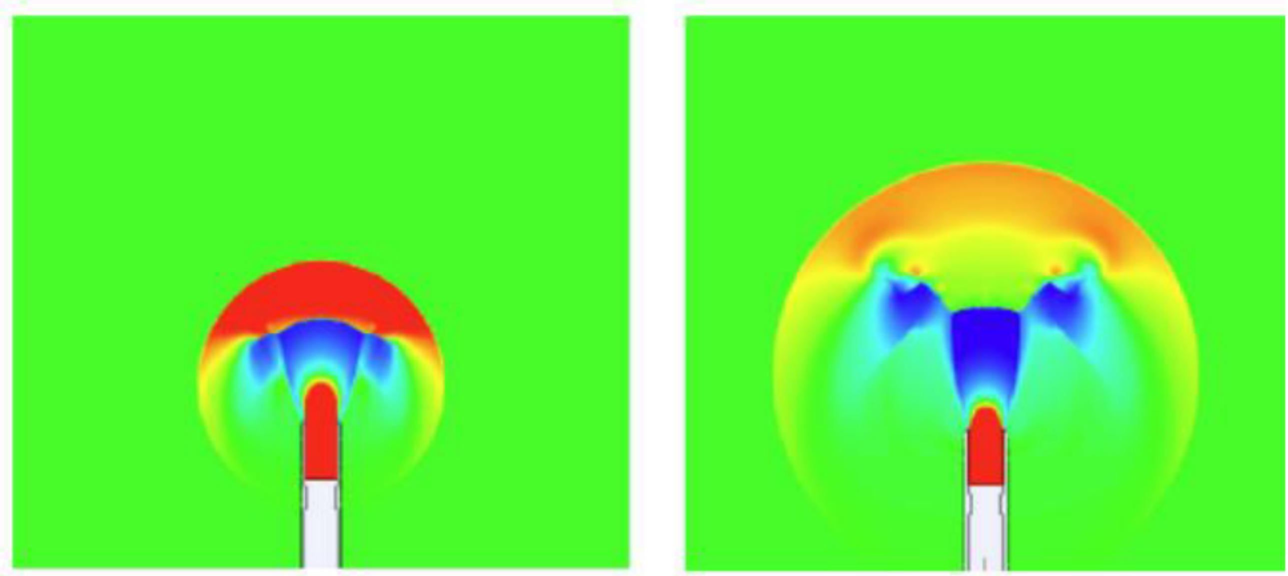


Figure 4-14 : Jet Overpressure Contour [14]

Figure 4-14 presents the pressure generated by an explosion from a jet. The darker contours are more prevalent towards the top of the gas cloud whereas to the sides the pressure is not as significant. This demonstrates the comments made above.

This was likely the case with regards to the experimental work conducted in this study. Overpressure is a function of flame speed. The more time and distance the flame front travels the faster it gets, the higher the overpressures. Thus, with regards to the demonstration it was likely that the peak overpressure was present above the gas cloud with a base ignition. However, this basis allows conclusions to be drawn with regards to hydrogen gas clouds. As hydrogen is added into the gas mixture the gas velocity increases, the density decreases. This leads to much more narrow and straight gas clouds in comparison to natural gas.

In conclusion the demonstration work conducted in the project was representative of NGT and SGN onshore transmission operations as an ignition source are likely to be found at the base of a gas cloud closest to site equipment and personnel. Therefore, the findings can be used to inform safety decisions, however, the results do not show the worst-case hazard potential. For both hydrogen and natural gas, ignition of a gas cloud from the top or centre of the cloud would result in downward propagation of the pressure wave and reflection from the ground, leading to higher local overpressures over a short distance.

Conservative guidance for gas-cloud explosions, derived largely from natural-gas experience, suggests that ground-contact cloud ignition can result in overpressure amplification by a factor of up to two.. With this conservatism in mind if the ignition location was more favourable for higher overpressure, the overpressure limit of 7-8 kPa would be broken.

However, this type of ignition may be plausible on an FPSO, offshore platform or other such structure, it is not likely to occur from NGT assets which typically operate in open, ground-based, uncongested environments. As such, while worst-case ignition scenarios should be acknowledged for completeness, the base-ignition configuration used in this study provides an appropriate and realistic representation of hydrogen venting hazards for onshore transmission infrastructure.

4.1.5 Congestion

It is well understood that congestion increase the overpressure of a gas cloud explosion. This is due to two main factors, the first is pressure wave reflection and then flame path length. During the experimental work conducted in this project it was decided after deliberation to remove any congestion from around the vent location. This would allow overpressures to be recorded at their minimum with lowest interference within the results pool.

With regards to the initial case matrix the double block and bleed location could lead to gas cloud congestion and accumulation either within the ventilation system or due to the flame arrestor or compressor cab. This would change the direction of gas flow as well as increase the flame path length. Both factors would increase overpressure. It is difficult to say by how much overpressure would increase when congestion is added. However, it is safe to say that any congestion that could confine the gas cloud would increases local overpressures and must be avoided. This further justifies moving away from local venting and ensuring gas is vented/flared within a designated safe area.

4.2 Practical Demonstration Challenges and Lessons learnt

- **Sensor Array Orientation and Wind Adjustment -** The initial sensor array layout was designed prior to arrival at site based on anticipated wind conditions and the sensors were laid out based on this plan. On the day of testing, the prevailing wind direction differed from the original assumption, necessitating a rotation of the sensor arc to ensure the primary measurement locations remained in the downwind direction. This reorientation was completed prior to testing, and the adjusted layout is shown in the Physical Layout section of this report.

  For future campaigns, it is recommended that the sensor layout design include a contingency arc rotation plan, or that a more flexible anchoring system be used to allow rapid field reorientation without full re-staking of sensor positions.

- **Pencil Probe Measurements -** While it was noted that blast overpressure measurements were not required for flaring tests, it should be noted that measurements from the pencil probes are most suited for very specific use cases. Generally, these sensors are suited towards measurement of propagating blast pressure waves and did not show any useful data for the flaring tests. Additionally, these sensors are temperature sensitive, and there were noticeable fluctuations in the waveform when the flare would blow directly towards the pencil probes.

  Kistler recommended using thermal protection foil, which was installed on the sensors according to the instructions provided. These thermal foils are likely only tested for transient blast events as opposed to sustained flaring conducted on site.

- **Flame Lift off** - During pre-testing, it was discovered that the 5% hydrogen and 20% hydrogen cases on the vent tip could not be ignited due to high exit velocity and lack of flame stability. The ignition source was elevated above the tip exit which allowed for delayed ignition of these test points during the customer witness test.

  This is an important point to note as it helps justify that the additional of hydrogen does not automatically make the vent gas more ignitable. Furthermore, solidifies that's due to the added velocity with the increasing hydrogen content the likelihood of ignition does not increase when hydrogen is added with regards to the scenarios tested here. Following on this allows suggestions to be made for blended option up to 20% to not change procedures around limiting ignition sources and extra strict requirements will not be required.

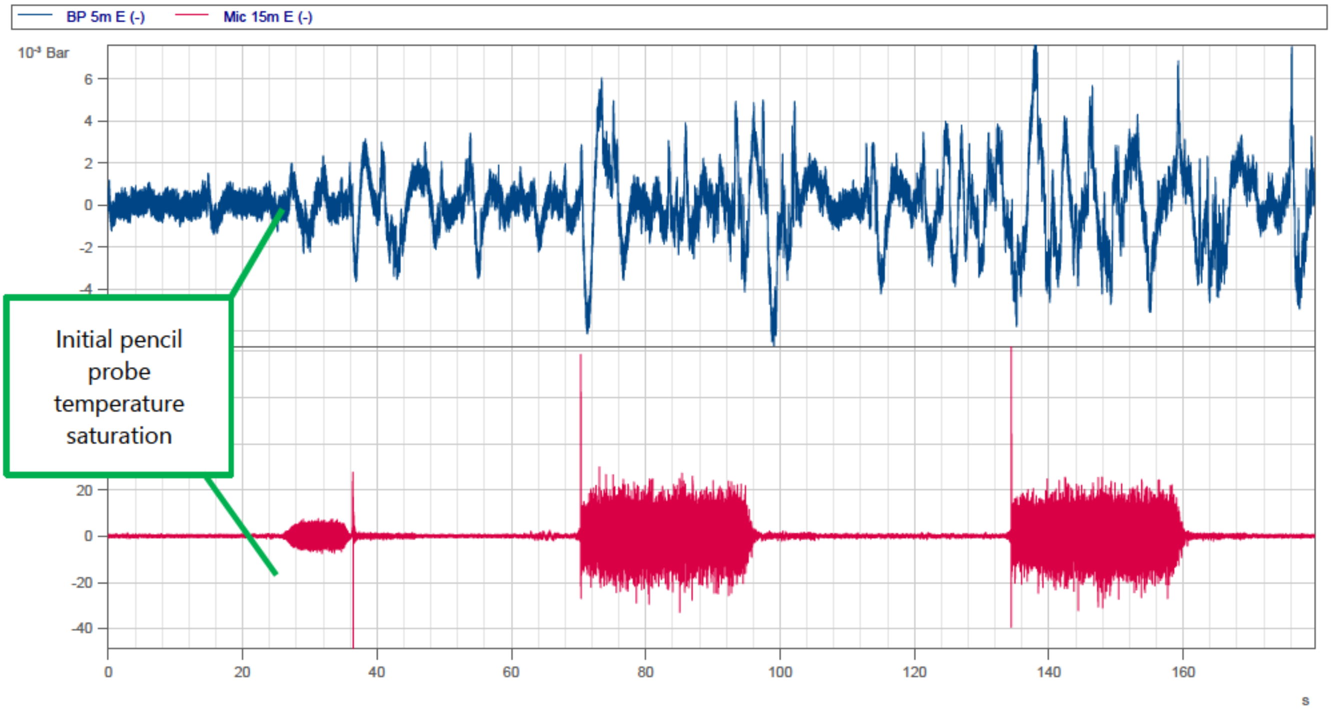


Figure 4-15 : Pencil Probe and Microphone Waveform Comparison for Flare Testing

- **3m Elevation Sensor Mounting** - The 3.0 m elevation Pencil Probe at the 5 m location required a non-standard mounting arrangement. Standard instrument tripods used for the 1.6 m sensors are not designed to extend to 3 m and do not provide sufficient rigidity at that height, particularly in wind-exposed conditions.

  A custom mounting solution was fabricated on site, in which a second tripod was mounted on top of the first to achieve the required elevation. While functional, this arrangement required additional time to assemble and is not ideal from a stability and repeatability standpoint. For future tests, a purpose-built elevated sensor mount or a lightweight mast system with ground anchoring is recommended.

- **Tripod stability in wind conditions** - Wind conditions at the site presented a significant challenge to sensor stability throughout the testing period. On multiple occasions, instrument tripods were displaced or knocked over by wind gusts prior to or during testing. This required re-levelling and repositioning of affected sensors. The primary contributing factor was the difficulty of anchoring tripods securely in frozen, uneven ground, which prevented the use of standard ground stakes.

- **Ground Anchoring in frozen terrain** - The test site ground was frozen and uneven, preventing secure installation of standard ground stakes and resulting in limited success with improvised anchoring methods. For future cold-weather campaigns, sensor stability can be improved by using sandbag ballast on tripod legs, screw-type anchors suitable for frozen ground, or low-profile weighted mounts where height permits, alongside scheduling tests during lower-wind periods and allowing additional setup time for anchoring challenges.

- **Orange hue from 100% hydrogen tests** – During the delayed ignition and flaring test it was noted that during the 100% hydrogen test, an orange hue originated from the burning gas cloud. [redacted] commented that the orange colour of the 100% hydrogen test points is expected to be produced by superheated water vapor and/or H-alpha emission in the combustion zone. Given the flare piping was purged with nitrogen between test points, the large flare gas flowrates, duration of the test points, and two performances per test point, residual natural gas would have been swept out of the flare piping. The observed flame appearance does not indicate incomplete combustion, increased thermal radiation, or elevated emissions and does not represent a safety or environmental concern. No mitigation or design change is required, and the behaviour is considered intrinsic to high-intensity hydrogen combustion. The only circumstance where this phenomenon may be a concern is human perception and flame visibility.

5.0 CFD Re-evaluation

The initial CFD assessment in the H_2 Test Plan used Ansys CFX. It estimated hazard levels and forecasted hydrogen dispersion patterns for specific geometries and flow rates, as agreed with NGT. A comprehensive CFD re-evaluation was then performed to refine and validate these preliminary results based on the demonstration results.

This extended analysis was initiated to ensure that the modelling accurately reflected the tested physical configuration, operational conditions, and atmospheric environment encountered during the live demonstration campaign. To achieve this, the CFD model was updated to include the precise vent configuration used by the testing vendor, replacing the generic or representative geometries utilised during earlier scenario screening. The re-evaluation used the measured and confirmed gas flowrates, including the actual hydrogen–natural gas blend fractions recorded during the testing programme. The CFD inputs were further refined by integrating meteorological data captured during the test periods, including wind speed, wind direction and ambient temperature.

5.1 Results

5.1.1 1-inch (Pig Trap) Vent

The first cases to be modelled were the 1” venting demonstration cases. For the basis of the simulation a straight vent pipe was modelling in the CFD with a height of approximately 6 meters from ground level to vent exit. Utilising the recording test data as well as measured wind conditions from the onsite weather station the demonstrations were replicated within CFD. Below presents the gas cloud formations for the 1” tests.

[redacted]

Figure 5-1 : 1" Venting Gas Cloud CFD Simulations

Figure 5-1 presents each of the three-gas composition and their representative gas clouds. The Blue shading denotes the hydrogen gas cloud above 4% mol fraction in air which is based on the LFL of the gas. The Red shading denotes the natural gas portion of the gas cloud. For the CFD simulations the natural gas was assumed at 100% methane. A scale bar has also been provided to demonstrate the height and width of the gas cloud at various stages in the jet.

The gas cloud volume is a critical safety parameter as it directly influences both the ignition likelihood and the consequence severity of a delayed ignition event. A larger flammable cloud contains more premixed, combustible mass, which can produce higher overpressures, greater thermal radiation, and larger hazard distances upon ignition.

[redacted]

Figure 5-2 : 1", 100% Hydrogen Pig Trap Venting Demonstration Replication

Figure 5-2 presents the 100% hydrogen gas cloud which was generated from the 1" vent with a flowrate of 0.14 kg/s. This formed a volume of 18m^3 with a gas cloud height of over 10m from the vent tip ~ 16 m from ground level.

[redacted]

Figure 5-3 : 1", 20% Hydrogen Pig Trap Venting Demonstration Replication

Figure 5-3 shows the CFD-predicted gas cloud for the 20% hydrogen blend released through the 1-inch vent at a flowrate of 0.44 kg/s. The resulting flammable cloud contains only 0.008 m^3 of hydrogen, indicating that the hydrogen fraction rapidly dilutes below its flammability limit due to its high buoyancy and fast dispersion. In contrast, the methane component forms a much larger 1.3 m^3 flammable cloud, which is expected because methane is heavier, entrains air more slowly, and therefore remains within flammable concentrations for longer. The cloud reaches 6 m in height approximately 11 m above ground level and remains compact, with the overall hazard dominated by methane, which has a lower flame speed and reduced explosion severity compared to hydrogen.

This behaviour differs significantly from the pure hydrogen case, where flammable cloud volumes were much larger (16–18 m^3) and posed a higher ignition-consequence risk. As a result, hydrogen-blend venting behaves more like natural-gas venting, whereas high-hydrogen releases favour flaring due to the substantially larger flammable cloud and associated hazard envelope.

[redacted]

Figure 5-4 : 1", 5% Hydrogen Pig Trap Venting Demonstration Replication

Figure 5-4 illustrates the flammable gas cloud formed during the 5% hydrogen blend release at a flowrate of 0.52 kg/s through the 1-inch vent. The resulting cloud is narrow, vertically elongated, and low in overall volume, with minimal horizontal spread. The hydrogen component of the cloud is extremely small at 0.009 m^3, demonstrating that hydrogen disperses below its flammability limit almost immediately after release. In contrast, the methane portion dominates the flammable volume at 1.2 m^3, consistent with methane's heavier density and slower mixing characteristics. The cloud reaches an elevation of approximately 11–12 m above ground level, reflecting the combined effects of jet momentum and buoyancy.

5.1.2 2-inch Double Block and Bleed

[redacted]

Figure 5-5 : 2" Venting Gas Cloud CFD Simulations

Figure 5-5 presents the CFD generated results for the 2" venting delayed ignition test. Similarly to the plots above the blue shading denotes the hydrogen gas cloud above 4% mol fraction in air which is based on the LFL of the gas. The red shading denotes the natural gas portion of the gas cloud. For the CFD simulations the natural gas was assumed at 100% natural gas.

For pure hydrogen, the release generates a very large flammable cloud of approximately 110 m^3, driven by hydrogen's high release velocity, rapid air entrainment, and wide flammability range. In contrast, the 20% hydrogen blend produces a smaller flammable hydrogen cloud (0.1 m^3) with the hazard dominated by the methane content, which accounts for roughly 6.1 m^3 of the cloud. At 5% hydrogen, the hydrogen contribution falls to effectively zero, and the flammable cloud is almost entirely methane-driven, with a volume of 7.1 m^3. The reduction in hydrogen-controlled cloud volume as concentration decreases reflects the lower reactivity, reduced buoyancy effects, and narrower flammable limits of the blended gases.

[redacted]

Figure 5-6: 2", 100% Hydrogen Pig Trap Venting Demonstration Replication

[redacted]

Figure 5-7 :2", 20% Hydrogen Pig Trap Venting Demonstration Replication

[redacted]

Figure 5-8 : 2", 5% Hydrogen Pig Trap Venting Demonstration Replication

Figure 5-6 presents the 100% hydrogen gas cloud which was generated from the 2" vent with a flowrate of 0.50 kg/s. This formed a volume of 110m3 with a gas cloud height of over 20m from the vent tip ~ 26 m from ground level.

Figure 5-7 shows the CFD simulation for the gas release with a 20% blend. Like above the set up a 2" vent was utilised, however, the flowrate of the blended gas was 1.30 kg/s. This generated a gas cloud with a hydrogen volume of $0.1m^3$ and a natural gas content of $6.1\ m^3$. The maximum height reached was just under 10m which is approximately 16m above ground level.

Figure 5-8 highlights the size of the natural gas and hydrogen gas cloud with a 5% blend, 1.40kg/s flowrate through a 2" vent. The hydrogen gas cloud volume was $0.1m^3$ and the natural gas $7.1m^3$. With a total gas cloud height of 14 – 15 m above ground level.

[redacted]

Figure 5-9 : 100% Hydrogen gas cloud for 2" and 1" releases at 0.5kg/s and 0.15kg/s respectively

Figure 5-9 presents the gas cloud formations with the 2" and 1" releases. The mass flowrate difference between the two cases is 3.3 times with the gas cloud size varying by 6.1 times. This indicates a strong positive correlation between hydrogen mass flow and gas cloud size. However, this is also dependent on gas velocity, therefore, for gas releases with similar size vent pipes, the larger the hydrogen content the larger the gas cloud. This is further confirmed by the blend case results, which show that as more hydrogen is released, the gas cloud becomes larger.

As shown above in Figure 5-8 and Figure 5-7 the 20% and 5% gas cloud volumes are close in size. Even as the total mass flowrate is less and the natural gas mass flowrate is reduced the slight increase in hydrogen mass flowrate maintains the gas cloud to a similar height as the 5% case.
These results align with the overpressure findings in that the 100% cases produce the largest overpressure due to the larger gas clouds and greater length ignition pathways to generate overpressures. Combined with the fact that the CFD indicated the gas velocity for both the 100% hydrogen release cases would be supersonic, this is in line with the very high noise levels recorded by the demonstration equipment.

During the demonstration, the flowrates for the gas mixtures was slightly less than operational flowrates for the scenarios which this work is based on. Therefore, it is safe to say that under similar environmental conditions the gas cloud would be larger for real world pig trap and DBB venting systems.

Additionally, the peak flammable gas cloud volume exists only for a short duration, typically lasting a few seconds, as shown by the CFD results presented in the Hydrogen Test Plan [3]. While this transient nature limits the duration of exposure, ignition of the cloud at or near its peak volume could still result in a short-duration but high-intensity combustion event, potentially generating elevated noise and localised overpressure. Additionally, the peak flammable gas cloud volume only last for a few seconds as shown in the CFD results presented H2 test plan document [3]

5.2 Overpressure estimation

Predicting overpressure can be carried out using several established methods, with the choice of technique depending on the nature of the explosion scenario. For solid fuels and high-energy explosives, the TNT-equivalence method is typically used, whereas vapour-cloud explosions are more suitably assessed using the TNO Multi-Energy (ME) model [10].

Both approaches begin by converting the flammable gas cloud into an equivalent mass of explosive material. This mass is then either translated into an equivalent TNT charge using conversion factors or adjusted using an "energy-level" multiplier, as defined in the TNO ME framework. Each method provides families of curves that relate scaled distance (derived from the equivalent explosive mass) to predicted overpressure. Once the appropriate curve is selected based on the test conditions or explosion severity class, overpressure estimates can be obtained for the scenario under consideration.

Both the TNT curves and TNO ME curves have been fitted for explosions with different composition to the demonstration undertaken here. However, as the demonstration presented here recorded and measured overpressures, curve fitting could be undertaken to characterise the specific gas releases of this nature to allow overpressure to be predicted over a range of scenarios which NGT and LTS could face.

5.2.1 Methodolgy

Using the gas cloud volumes calculated from CFD the gas mixture mass and explosion energy was generated. These have been presented below.

Table 5-1 : Gas cloud volumes, mass and explosion energy

Test Point	Gas cloud combined volume (m3)	Gas cloud mass (kg)	Explosion Energy (MJ)
1" 5% Venting Test Run 1	1.702	0.1702	62.47
1" 20% Venting Test Run 1	1.308	0.1308	37.52
1" 100% Venting Test Run 1	18.0	1.8	181.03

Test Point	Gas cloud combined volume (m3)	Gas cloud mass (kg)	Explosion Energy (MJ)
2" 100% Venting Test Run 2	110	11	1106.32
2" 5% Venting Test Run 1	7.1	0.71	228.46
2" 20% Venting Test Run 2	6.12	0.612	175.55

The next step was to calculate scaled distance. This allows the recorded overpressure data to be plot against the calculated scaled distance values which in turn allow two constants to be precited which can be utilised to predict overpressure close to the vent stack. The scaled distance equation is shown below.

$$Z = \frac{R}{(\frac{E}{Pa})^{1/3}}$$ (Equation 1)

In equation 1, Z is scaled distance, R is actual distance which overpressures were recorded, and E is the explosion energy and Pa being atmospheric pressure. This allows a graph to be generated; an example plot has been presented below.

[redacted]

Figure 5-10 presents the 5% 1" venting maximum overpressure recordings. Utilising curve fitting, a power law relationship can be drawn with a line equation present within the figure. Utilising this equation, them allows overpressure to be calculated at distances of 1,2,3 m away from the vent stack.

[redacted]

Figure 5-11 : Overpressure measurement with fitted power law result

The graph above shows the power law relationship predictions compared to the operational recordings. Before this can further be progressed it was important to check the accuracy of this method. Using the equations generated through curve fitting the average deviation can be calculated between the real recorded overpressure data and the calculated values. The table below presents the results of this.

Table 5-2 : Power Law Deviation Maximums from Real recorded data points

Test Point	Deviation
1" 5% Venting Test Run	± 8%
1" 20% Venting Test Run	± 78%
1" 100% Venting Test Run	± 8%
2" 100% Venting Test	± 10%
2" 5% Venting Test	± 20%
2" 20% Venting Test	± 40%

As both the TNO ME and TNT methods for predicting overpressure utilise curve reading to predict overpressure there is an inherent amount of inaccuracy. Currently it is uncertain what level of deviation is acceptable as sources still doubt the accuracies of these types of models [11]). Utilising this method the curve fitting underpredicted in the short range and overpredicted in the long range. This highlights the importance of repeats and test points relatively close to each other to allow conclusions to be still drawn.

For all of the cases, CFD predicted a gas cloud width between 0.5 and 1.5 m for flowrates and pressures as stated in Table 3-4 . As it is known that the pressure builds up as the ignition passes through the gas cloud it is not suitable to take an overpressure prediction at 1m. However, a 2m distance would be much more suitable to represent overpressure exerted on objects and personnel close to the vent stack. The table below presents these estimations.

Table 5-3 : 2m Overpressure Estimations based on Curve fitting exercise

[redacted]

The results above would suggest that at 5% blend even close to the stack the 6kPa breaking glass overpressure limit would not be reached. However, for each of the other cases the 6kPa limit is breeched or nearly reached. Based on the 2" data the overpressure estimations follow the expected trend that as more hydrogen is added the experienced overpressure is greater.

On the other hand, for the 1" case for 20% blend the results do not follow this trend. This is likely due to an anomaly in the results. One suggestion could be that that line had excess hydrogen still within it left over from the 100% test. This combined with the higher flowrate of the 20% case could have led to very high overpressures. It is also possible that the flame front of the gas cloud came into contact with the sensor if the wind direction was in perfect direction to the sensor. This event was actually experienced during the flaring tests which suggest the likely culprit for the 20%'s very high overpressure in a single direction at 5m.

In summary, the CFD simulations, gas cloud volume and overpressure estimate suggest that at short distance from the vent pipe the overpressures experienced are greater than that expected for natural gas. 4 of the scenarios tested either breached or approached the 6kPa breaking glass overpressure limit. The flowrates tested on the day were less than typical NGT operations. Therefore, real world over pressure in the near field are likely higher.

5.2.2 TNO ME Model

Typically, the TNO ME model would be utilised to predict overpressure. Therefore, for completeness a review below has been provided looking into the accuracy of the prediction if the model was used to estimate the demonstration overpressures.

The first step was to determine the class number. This class number defines which curve is utilised to interpolate overpressures at a chosen distance. The demonstration was conducted in an open field with no confinement and low to no obstacle density. Combined with the fact that both natural gas and hydrogen have medium and low ignition energies respectively it is safe to say the strength class maximum would be 3. This reinforced by the Table 5-4 shown below.

Table 5-4 : Guidelines by Kinsella (1993) for choosing class number (10)

Ignition energy		Obstacle density			Confinement		Strength
Low	High	High	Low	No	existing	no	
	x	x			x		7 – 10
	x	x				x	7 – 10
x		x			x		5 – 7
	x		x		x		5 – 7
	x		x			x	4 – 6
	x			X	x		4 - 6
x		x				x	4 – 5
	x			X		x	4 – 5
x			x		x		3 – 5
x			x			x	2 – 3
x				X	x		1 – 2
x				X		x	1

Figure 5-12 shows the curve at which overpressures were predicted. The methodology for predicting overpressure involves calculating scaled distance. To calculate scaled distance the first step was to determine the gas cloud volume in CFD. This is then converted into a flammable mass, which allows the energy of combustion to be calculated. Finally actual distance is divided by the energy term to achieve scaled distance. Then using Figure 5-12 and the strength class, interpolation is undertaken. This then predicts scaled peak overpressure which can be converted to none scaled overpressure utilising the equation below. Ps is peak overpressure; Pa is atmospheric pressure with P's being scaled overpressure (which is read from the figure below).

Equation 2: Scaled Overpressure $P_S = P'_S \times P_a$

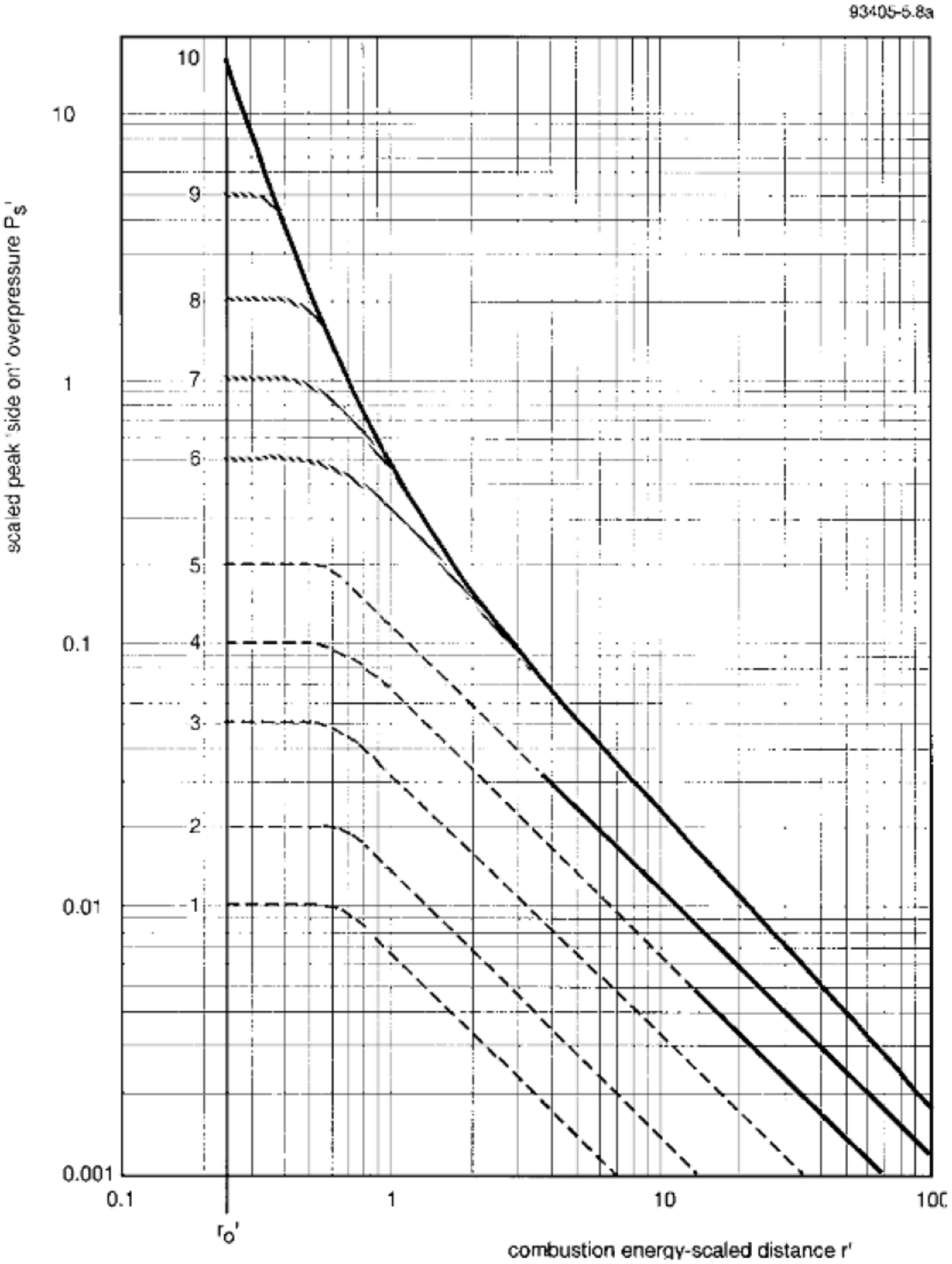


Figure 5-12 : Multi-Energy method blast chart: peak side-on overpressure (12)

For each of the tests conducted during the demonstration the overpressure was then estimated based the class 3 strength curve. The results have been presented in Table 5-5 below.

Table 5-5 : TNO ME Overpressure Predictions

[redacted]

The TNO ME curves used to interpolate overpressure are derived from experiments conducted with hydrocarbon gases, where overpressures were measured directly. The TNO ME method estimates overpressure using a scaled distance, defined as the physical distance divided by the explosion energy. In this method, explosion energy is calculated using the lower heating value (LHV) of the fuel–air mixture.

Table 5-5 compares the overpressures predicted using interpolated TNO ME curves with the overpressures measured during testing. The results show that the Class 3 power curve predictions do not vary significantly across the cases tested, however, all predictions deviate from the measured values to some extent. It is important to note that although the gas cloud volumes for the hydrogen releases were more than ten times larger, the corresponding gas cloud masses were only two to three times greater. This results in very similar overpressures prediction across the scenarios.

In terms of accuracy, the TNO ME method performed best for the largest 100% hydrogen releases, although it generally overestimated overpressure. Because the vent geometry did not change between tests, it was not possible to reduce the TNO ME power class for individual scenarios. Nevertheless, the results suggest that a lower power class may have been more appropriate for some measurement locations, though not for all.

These findings highlight several limitations of the TNO ME model. First, the selection of the TNO ME power class is highly subjective and dependent on user judgement. To investigate this strength class 1 and 7 were also tested to see what the overpressure predictions would be. These have been summarised in the table below.

Table 5-6 : Class 1 and 7 TNO ME results

[redacted]

When the estimated overpressure in Table 5-6 for class 1 and class 7 is compared to the recorded results during the demonstration campaign, it is observed that within 5 m the Class 1 significantly underestimates overpressure and the class 7 significantly over estimating it. Class 1 seems more appropriate for the 5% blends which indicates that the strength class used for the TNO ME model cannot be blanketly applied to any gas system. Although adjustments can be made for other gases, such as hydrogen, this implicitly assumes that explosion behaviour and overpressure are governed solely by the heat of combustion and ignition energy. The curve-fitting approach produced more accurate overpressure predictions, and future work should focus on applying the fitted equations directly to predict overpressure in similar scenarios.

5.2.3 Overpressure Estimation Review

Two primary methods were used to predict overpressure in this work described above. The first method used measured data from the demonstration to generate overpressure contours based on a power-law relationship combined with explosion energy. The second method used the same explosion energy and scaled-distance formulation but estimated overpressure by interpolating values from the TNO ME curves using an assumed explosion power class.

As shown in Table 5-3 and Table 5-6, curve fitting to the recorded experimental data produced the most accurate overpressure predictions. However, this method was not without limitations. In particular, predictions for the 20% hydrogen blend exhibited higher percentage variance than the other cases. This discrepancy highlights an important outcome of the project, based on existing estimation tools, the 20% blend was expected to generate significantly lower overpressures, yet the demonstration results showed considerably higher overpressures than anticipated which makes the result a possible outlier.

A further limitation of both prediction methods is their reliance on gas cloud volumes generated by CFD simulations. To fully validate these approaches for broader application in typical overpressure assessment scenarios, experimental gas cloud measurements are required to confirm the accuracy of the CFD-predicted cloud sizes. This would necessitate the use of gas cloud visualisation techniques, however, which were considered too costly to implement during the demonstration phase of this project.

6.0 Hazard Review

During the initial phases of this project several HAZID actions had been identified during previous project that looked into the hazards of venting hydrogen and hydrogen blends. The full table has been provided in the Test plan report. For this phase it was important to revisit these events to investigate if the work completed has answered any question or filled in areas of uncertainty. The table below has been colour coded to highlight which actions have informed, the green shows directly that the work conducted can inform that Event and action requirement. The orange shading is where conclusions can be inferred with the red denoting no new findings.

[redacted]

[redacted]			
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	To be reviewed in this project

[redacted]	[redacted]	[redacted]	[redacted]
		[redacted]	
[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	

[redacted] comments below show how findings from this project can help inform each of the safety actions/ areas of investigation presented above.

No. 1.41

Video evidence from the demonstration testing, supported by CFD analysis, confirms that hydrogen releases form tall, slender gas clouds. This behaviour is primarily driven by the high exit velocity and the physical properties of hydrogen. Depending on the release rate, these gas clouds can extend approximately 50–60 m vertically. In the event that such a cloud ignites with delayed ignition, the resulting overpressure would be generated from the base of the cloud, with the peak overpressure occurring predominantly in the direction of the gas cloud trajectory.

As to how significant this overpressure is, it is still unlikely to cause injury based on the measurements taken in these demonstrations.

No. 1.46

The findings from this work broadly align with the safety guidance outlined in CGA G-5.5-2021, however CGA G-5.5-2021 is extremely limited in its depth. Work from this demonstration and the CFD work developed from it will allow development of hydrogen supplement for SR/23. SR/23 is a detailed standard that allows operations and engineering to design and install vents on site that comply with NGT's understanding of Natural gas. To replace good technical standard with something limited like CGA G-5.5-2021 would be a downgrade and require significantly more engineering and dispersion study

No. 1.47

In the event of delayed ignition during venting, the required sterile or exclusion zones are dependent on both the gas flow rate and the vent configuration. For 5% hydrogen operation, the results indicate that overpressure levels are not hazardous to site personnel. For 20% hydrogen blends, however, the demonstration recorded overpressures of up to 3.1 kPa at a distance of 5 m. Extrapolation suggests that the 6 kPa overpressure limit could be approached or exceeded at distances of less than 2 m from the vent stack.

Accordingly, for 20% hydrogen venting activities, local or manual venting should be avoided. In such cases, exclusion zones are expected to be governed primarily by noise exposure rather than overpressure or thermal radiation. For larger gas releases, which would typically be routed to a station vent and already subject to defined exclusion zones, these zones are unlikely to be significantly affected, although a reassessment based on noise exposure limits would still be required. FlareSim is the industry standard tool for predicting safe limits for flaring activities. Therefore, it is recommended to use FlareSim to generate sterile areas for flaring activities. The figures below demonstrate some realistic expected safe distances for noise and overpressure from delayed ignition.

[redacted]

Figure 6-1 : 2" Recorded Noise Exposure extrapolated for 120db limit

Figure 6-1 presents the proposed sterile areas defined by noise exposure. The inner red circle represents the venting sterile zone determined by noise limits in accordance with SR23 for hydrogen blended with natural gas. As shown by the demonstration results (refer to Figure 3-18), noise levels for both 5% and 20% hydrogen blends exceed 120 dB at distances of up to approximately 70 m from the vent. For 100% hydrogen venting, the distance at which noise levels fall below 120 dB is estimated to exceed 140 m, as indicated by the outer yellow ring in the figure.

In comparison, sterile areas driven by overpressure effects are significantly smaller, extending only a few metres from the vent stack. Although the demonstration flow rate for the 2-inch DBB cases was lower than would be expected under normal operating conditions, a conservative overpressure-based exclusion zone of 5 m has been adopted.

The figure clearly demonstrates that noise exposure, rather than overpressure, is the governing criterion for defining sterile areas during venting operations. To protect personnel, no personnel should be present within the noise-based sterile zones while venting is underway. Overpressure limits primarily influence mechanical design requirements, as excessive overpressure may result in damage to equipment and pose a risk to personnel.

[redacted]

Figure 6-2 : 1" Recorded Noise Exposure extrapolated for 120db limit

Similarly to Figure 6-2, a 120db limit, noise exposure plot has been generated above for the 1" case. As can be seen for blends a sterile distance of 60m must be applied based on SR23 with 100% hydrogen jumping to 120m. As the 10" cases were not demonstrated through experimental experiments there is no data to extrapolate against. However, it is well known from the CFD from the previous report that the 10" cases have lower velocity even subsonic with the low rates which would reduce these noise exposure contours.

No 1.48

The table below summarises key design considerations with regards to the venting scenarios to provide basis to the solutions.

Table 6-2 : Gas System design changes for blend and pure Hydrogen operation

Scenario	5% Blend Design changes	20% Blend Design changes	100% Design changes
Pig Trap Venting	• Hydrogen introduction at this blend does not increase hazard levels significantly. However, current design is not ideal for methane. Remote vents (tripod type) would be significant improvement and are already used but not universally required. • Considering adding silencers to vent pipe	• Local venting with manual vent pipes should be avoided. • Increase vent pipe diameter • Inline regulators	• Collect vent gas to comment header and send to large 10" vent or flare stack • Inline regulators • Flame arrestors • Nitrogen snuffing if gas is vented
Double Block and Bleed	• No required design changes. • Considering adding silencers to vent pipe	• Remove 90º bends from vent pipes. • Increase vent pipe diameter to reduce gas velocity. • Inline regulators	• Collect vent gas to comment header and send to large 10" vent or flare stack • Inline regulators • Flame arrestors • Nitrogen snuffing if gas is vented
Compressor casing	• No required design changes.	• Flame arrestors • Inline regulators	• Swap to flaring if sterile areas to small compared to gas flowrate. • Nitrogen snuffing if gas is vented • *Demonstration campaign is recommended to better characterise the resulting overpressure and dispersion behaviour, and to support robust risk management for compressor casing scenario

No. 1.49/2.03

6.1 Venting and Flaring Philosophy

1. Purpose

This philosophy defines the basis for selection between flaring and venting for hydrogen transmission systems, including pure hydrogen and hydrogen–natural gas blends (5% and 20% H_2 by volume), covering both permanent and temporary facilities. The objective is to ensure risks to personnel, environment, and assets are ALARP, while recognising the specific flammability, dispersion, and ignition characteristics of hydrogen.

2. Definitions

- Flaring: Controlled combustion via flare or burner system.
- Venting: Controlled atmospheric release without combustion.
- Legacy Asset: Existing installation not originally designed for hydrogen flaring.
- New Asset: Installation designed or significantly modified for hydrogen service.

3. General Principles

- 5% hydrogen blends are treated as equivalent to existing natural gas service.
- 20% hydrogen blends require equipment modifications, but no fundamental change to disposal philosophy.
- 100% hydrogen requires a differentiated approach for new vs existing assets.
- Venting solutions must demonstrate control of explosive atmospheres.
- Flaring solutions must demonstrate acceptable social, environmental, emission, and flame-stability performance.
- Temporary installations follow the same philosophy, with proportional engineered solutions.
- Guidance is based on safety concerns only. It is beneficial in terms of CO2e to flare natural gas, hydrogen and any blend.

4. Allowable Venting cases

Table 6-3 : Allowable Venting cases assessment

Gas Case	Change Required	Venting Permitted	Comments
5% Hydrogen Blend	No change to the natural gas venting philosophy is required; however, existing vent designs are already sub-optimal, and remote (e.g., tripod-type) venting is recommended as an improvement.	Remote venting for improved personnel safety. Typical activities such as routine maintenance, general depressurisation and commission and purging	Existing vent systems deemed acceptable subject to standard site safety assessments
20% Hydrogen Blend	Venting philosophy unchanged, however equipment modifications and noise mitigation required	Use of vent silencers, pipe widening and inline flow control to reduce noise and gas cloud development. Ignition sources must be controlled	Venting release should be short and controlled to limit site noise exposure, recompression strong candidate to offset venting hazards.
100% Hydrogen –	Venting permitted for	To manage risk, use of flame	Routine venting shall be

Gas Case	Change Required	Venting Permitted	Comments
Legacy assets	small inventory, low frequency vents e.g ball valve cavities. Venting must be engineered to manage hazards	arrestors, nitrogen snuffing, pipe widening and velocity reduction. Furthermore, if vent points can be elevated this would be advantageous.	minimised and justified. Emergency venting shall be supported by: Defined exclusion zones, Enhanced gas detection, Strict ignition source control

5. Non-allowable venting – De-inventory

Flaring Philosophy (100% Hydrogen – new assets)

For new assets designed for 100% hydrogen, routine or large-scale venting for de-inventory is not recommended due to the associated safety, noise, and environmental risks. In line with the findings of this study and the Recompression Project, recompression should be the preferred disposal method wherever practicable, as it avoids atmospheric release, eliminates ignition and noise hazards, and aligns with net-zero objectives. Note that the recompression project has recommended that CH4RGE be expanded to allow recovery of other vented gasses, not just compressor seal gas.

Where recompression is not practicable, flaring should be adopted as the secondary disposal option. Flaring is preferred to venting as it provides a controlled combustion outcome, avoids delayed-ignition risk and uncontrolled dispersion, and mitigates the extreme noise associated with supersonic hydrogen venting. Flare system design will account for hydrogen's low ignition energy and high flame speed, with thermal radiation and noise-based exclusion zones defined using appropriate industry-standard tools.

For smaller gas flowrates or locations with high societal sensitivity, ground or enclosed flares may be considered to reduce noise, visual impact, and planning constraints, provided they are purpose-designed to prevent flammable gas accumulation through continuous purge, reliable ignition, and appropriate ventilation. Venting of 100% hydrogen should be avoided except in very limited, low-inventory cases subject to specific justification and control.

Venting Philosophy (100% Hydrogen – Legacy assets)

When flaring is not reasonably practicable venting may be accepted with layered safeguards. This includes:

- Flame Arrestors
- Nitrogen Purging
- Gas Velocity reduction
- Elevated vent stacks

Venting must demonstrate acceptable vent gas size, exclusion of ignition sources and controlled operational procedures with site staff adequately protected. However, how these systems are controlled depends on if they are permanent to temporary fixtures. The ESD initiation philosophy below has suggests some principles to follow.

Table 6-4 : ESD Philosophy Summary

ESD Philosophy	
Automatic Initiation (permeant instillations)	**Manual Initiation (temporary installations)**
• Activation on hydrogen gas detection • Fire detection • Gas velocity excursion • Loss of containment in congested areas	Manual ESD push buttons should be: • Clearly marked, • Located near access and collection points and • Should be available locally and remotely
Venting ESD Requirements	**Flaring ESD Requirements**

ESD Philosophy	
• Automatic isolation prior to vent opening • Automatic nitrogen snuffing • Permit control to ensure hot work lockout • Potential interlocks to prevent venting in low wind scenarios	• Pilot availability • Flame detection operational • Air assistance available

This philosophy is a baseline and can be used to build on to generate a full philosophy for venting and flaring hydrogen and its blends safety. Once the philosophies are endorsed by HSE deviations from them must pass formal risk assessments, technical authority approval and HSE endorsement.

6.2 Flaring Basis of Design

Designing a flare system is heavily dependent on its requirements as well as size and space limitations. However, utilising similar test set up conditions to the demonstration, findings can be drawn around approximate flare system heights that would be suitable for NGT/SGN sites. A sensitivity assessment was then undertaken to determine at which height a 4-inch flare could be utilised at various flowrates to avoid any thermal radiation exposure greater than the 6.3 kW/m2 defined by SR/23 at ground level. The table below presents the results.

Table 6-5 : Flare size sensitivity for 5% H_2 Concentration

Flowrate (kg/s)	Flare size (")	Stack Height at which thermal radiation exposure everywhere is less than 6.3 kW/m2 (m)	90db Noise exposure limit distance	120db Noise exposure limit distance
10	10	14	180	~
10	4	14	>200	~
5	4	10	150	~
1	4	6	60	~

Table 6-4 presents the results of the FlareSim analysis. For the 10 kg/s case through a 4-inch flare, a flare height of 14 m was required to fully remove ground-level thermal radiation exposure exceeding 6.3 kW/m^2. The required flare height decreases with reducing flow rate, falling to 6 m for a gas flow of 1 kg/s. It should be noted that all cases were modelled using a 5% hydrogen blend, which is expected to provide results comparable to a 100% natural gas case. Furthermore, as discussed above, the addition of hydrogen to the flare reduces emissivity and, consequently, thermal radiation contours and flare height requirements on this basis. However, operation with 100% hydrogen results in significantly higher noise levels. While the 10-inch case presents similar noise contours, the 4-inch case shows the 90 dB contour extending considerably further, with the 120 dB limit exceeded near the flare. For a 100% hydrogen flare the height is less important compared to the diameter of the flare stack and the subsequent flowrate through the flare, whereas for natural gas dominated flares, height is a more critical parameter to determine system design.

6.3 Disposal Mechanism

The demonstration campaign focused on pig trap and double-block-and-bleed (DBB) venting and assumed a single representative flare configuration, and the resulting disposal mechanism hierarchy extends these demonstrated and CFD-validated findings to the full range of vent types identified in the qualitative analysis. This section categorises the assessed typical vents across NGT And LTS assets and defines the appropriate gas disposal mechanism for hydrogen and hydrogen-natural gas blends as shown in Table 6-6. Recommended disposal route, venting, flaring, or recompression has been assigned for 5%, 20%, and 100% hydrogen based on the demonstration results and supporting modelling. In particular, the categorisation reflects that low-flow vents can generally remain vented, whereas high-flow vents increasingly require flaring or recompression as hydrogen content increases with adequate mitigations in place.

This classification is intended to support practical operational decision-making and to inform policy and standards development, including updates to guidance such as IGE/SR-23, which was developed for natural-gas service and does not explicitly address hydrogen-specific behaviours and new flaring standards and policies. The table should therefore be read as a decision-support tool, to be applied in conjunction with site-specific risk assessments, confirming that hazards related to noise, thermal radiation, overpressure, dispersion, and ignition are adequately controlled for the chosen disposal method.

Table 6-6 Recommended Disposal Routes for various Vent Types

Type of vent	5% H_2	20% H_2	100% H_2
Starter vent	No mandatory design change relative to natural gas, however, existing local vent designs are acoustically sub-optimal and silencers and remote venting should be considered to improve personnel safety	Likely to be phased out by this point.	N/A (starter vents being phased out)
Pig Trap vent	No mandatory design change relative to natural gas, however, existing local vent designs are acoustically sub-optimal and silencers and remote venting should be considered to improve personnel safety	Utilise a vent collection system, flare on a new asset or recompression.	Collect vent gas to collection system and dispose via recompression or flare
Fuel gas vents at GT - DBB	No changes to venting procedures except noise control considerations (e.g. silencer, controlled depressurisation, double ear protection)	Venting could be acceptable if pipe diameter increased, 90-degree bends removed and pipe height increased,	Collect vent gas to collection system and dispose via recompression or flare
Dynamic seal vent /Degasser Tank Vent	Follow CH4RGE recommendations. Otherwise, no changes required	Vent (with monitoring/silencing/pipe diameter increase if required) Follow CH4RGE recommendations	Should be CH4RGE compliant
Gas actuated valves	No changes to venting procedures.	Vent preferred short-term because of the low inventory, valves being phased out	N/A (valves being phased out)
Static seal vent	No changes to venting procedures.	Venting preferred due to small inventory	Venting preferred due to small inventory
Fuel gas skid - Trip	No changes to venting procedures except noise control considerations (e.g. silencer)	Venting preferred due to small inventory (consider pipe widening and flow control)	Collect vent gas to collection system then either recompress or flare
PRS (Pressure Reduction System/Station) relief valve	No changes to venting procedures except noise control considerations (e.g. silencer)	Vent with elevated discharge with noise control considerations	Collect vent gas to collection system and route to flare

Type of vent	5% H_2	20% H_2	100% H_2
vent/bursting disk on pre-heat exchanger			
Compressor Casing vents - routine	No changes to venting procedures except noise control considerations (e.g. velocity reduction through flowrate reduction)	Flare or recompression(CH4RGE)	Flare or recompression(CH4RGE)
Compressor Casing vents - ESDV	No changes to venting procedures except noise control considerations (e.g. silencer)	Flare or recompression (CH4RGE)	Flare or recompression (CH4RGE)
Relief valves of condensate tanks and scrubbers	No changes to venting procedures except noise control considerations (e.g. silencer)	Vent with elevated discharge and exclusion control	Route to flare
Temporary Planned/ Emergency Pipeline vents	No changes to venting procedures except noise control considerations (e.g. silencer, controlled depressurisation, double ear protection)	Erect temporary flare or temporary vent if recompression not utilised	recompress or flare
Process vent – station	No changes to venting procedures except noise control considerations (e.g. velocity reduction through flowrate reduction)	Vent with controls for noise	Assess case by case. Flare preferred
Start-up Purge Vent	No changes to venting procedures except noise control considerations (e.g. silencer)	Venting preferred due to small inventory (consider pipe widening and flow control)	recompress or flare
Body Ball Valve Cavity	No changes to venting procedures except noise control considerations (e.g. silencer)	Vent due to low volume but consider widening temporary vent pipes and reduce 90-degree bends	Vent due to very low inventory

7.0 CFD Review

[redacted]

7.1 Dispersion Modelling and Jet Behaviour

[redacted]

[redacted]

7.2 Flammable Cloud Extent and Composition Effects

[redacted]

7.3 Delayed Ignition and Explosion Modelling

[redacted]

[redacted] r

8.0 Policy and Standard Updates

8.1 Venting

IGE/SR/23 Ref. [5] was written to guide venting of natural gas, it explicitly scopes "liquid-free natural gas" and excludes other gases and detailed flare design. As we repurpose assets for hydrogen and H_2–NG blends, several SR/23 principles still help, but others require material updates due to hydrogen's different jet acoustics, buoyancy/entrainment, flame emissivity, and ignition behaviour.

Sections requiring modification include:

- **Section 2- Scope:** SR/23 limits scope to natural gas (≥ 89% methane) and excludes "other gases". new clauses for H_2 and H_2–NG blends should be added, clarifying where SR/23 methods hold and where hydrogen specific rules such as acoustic control, jet Mach control, overpressure checks apply.
- **Section 6.5 – Dispersion and exit velocity guidance:** The design for ≥ 60 m/s exit velocity principle originally to promote dispersion must be conditional for hydrogen. Hydrogen jets readily become under-expanded/choked upstream, and our measurements show extreme far-field noise measurements even when exit velocities are modest, therefore, exit-velocity targets must be traded against acoustic limits. Guidance should include silencers and increased pipework diameter. The limitations of venting designs become clear here as there is a trade-off between noise and dispersion efficiency. Flares do not need to consider dispersion of large clouds as the assumption is full combustion. Therefore, lower velocities can be accepted resulting in lower noise.
- **Section 6.6 and 6.7 – Sterile zone basis**: For hydrogen systems, noise, not thermal radiation, governs personnel exclusion. Update SR/23 to define noise-based sterile zones (e.g., no personnel where SPL ≥ 120 dB) and to require demonstration that community/occupational limits are met for hydrogen venting and delayed-ignition scenarios. Our data show ≥ 120 dB well beyond 60 m in several hydrogen venting cases.
- **Appendices 4-5- Noise Prediction and Control:** The Appendix 5 estimator (built around NG, subsonic outlets) is not reliable for hydrogen jets that can be significantly faster and thus quite different in shape. Methods capable of predicting noise levels associated with hydrogen releases or measurement-based characterisation should be adopted. It is also important to make acoustic mitigation such as rate reduction, larger outlet, silencers with ~15–20 dB attenuation a default for hydrogen and ≥ 20% H_2- NG blends.

  Larger outlet diameters Should be permitted or preferred to reduce exit Mach for hydrogen, explicitly allow trade-off of dispersion velocity vs. acoustic limits, complemented by stack height to manage dispersion.
- **Add New Section for overpressure:** SR/23 lacks near-field blast guidance for delayed ignition of vent. This is because there is no overpressure risk associated with natural gas releases. For H_2/H_2–NG, require check of 1–3 m stand-off against 6 kPa using TNO-ME/TNT-equivalence with CFD-derived cloud mass. Our tests measured ~4.5 kPa at 5 m and modelling indicates > 6 kPa closer in several cases.

  For any hydrogen case with credible delayed ignition, it is important to assess 2–3 m overpressure vs 6 kPa glazing/light equipment threshold using CFD cloud mass + vapour-cloud models. Supports/clearances should be updated accordingly. This could be risk assessed to reduce the number of cases. Criteria such as vent height, vent geometry and proximity to equipment and people could be used to reduce the number of cases in a similar way that this project did.

  Wind speed has been found to have significant effect on overpressure generation with no wind condition been the worst-case scenario, extra precautionary measures should be taken while venting under such condition. NGT and LTS can design for still conditions as a worst case. Making certain environmental conditions mandatory for venting operations may be challenged as not a reliable risk reduction mechanism.

  Additionally, overpressure severity increases significantly in the presence of congestion or confinement therefore, best practice is to locate vent outlets away from pipe racks, structural steel, buildings, and equipment, avoid venting within partially enclosed spaces or near solid surfaces that can reflect pressure waves, and ensure clear, open surroundings in the near field of the vent.
- **Section 7.2- Vent-line Layout and Mechanical Loads:** Hydrogen note should be added stating elbows such as 90° bends should be avoided. The DBB arrangement with two elbows showed high forces on the elbows and stronger acoustic lobes, even at 20% blends.

- **Section 8-Temporary Flares:** For hydrogen and blends, make silencing and exit-Mach control mandatory (not optional). If space/planning constraints prevent compliant venting, require recompression or routing to flare (subject to noise assessment).
- **Section 9- Major Planned Venting**: Recompression should be used for all major venting operations. This project did not assess the disposal of the residual low-pressure gas left behind by recompression. This is estimated to be approx. 4 barg. It is unlikely that hazards will be as significant at 4 Barg but it ultimately depends on velocities etc. A small utility flare similar to the one used in the demonstration may be sufficient, potentially with a higher tip. Regardless, demonstrating ALARP with noise-based sterile zones and near-field overpressure will be required.

There are a number of operating procedures and policies that will need further revision. These have been listed in the table below with suggest amendments or revisions based on the evidence provided within this report.

Table 8-1 : Policies & Standards Affected

Policy number and title	Interaction points and suggested changes
T/PM/HAZ/12: Hazardous Area Classification of Cold Type Vent Stacks Typically Fitted on Below Ground Installations	• Scope and definitions would change. • Document utilises vent stack physics based on natural gas, would have to be revisited and thus vent design for hydrogen, sideways /downwards gas trajectory avoided. • Hazardous areas zones recalculated, for the same gas volume flowrate zones will be larger, redraw flowcharts. • Remedial work limits re assessed.
T/PM/HAZ/19 - Emergency Shutdown and Venting on NTS Facilities	• Gas basis updates, recalculating vent flows, dispersion and ignition consequences. • Revalidation vent stack geometry assumptions, hazardous area dimensions and sterile areas • Verify valve and seal applicability, nitrogen injection behaviours in new gas flow. • Governance to control use for different gas systems
T/PM/HAZ/2 – Manual Venting Operations on Installations Prior to maintenance	• Scope and related documents must include either exceptions or modifications for hydrogen and blends. • Ensure management of change procedures are implemented and followed to ensure sufficient mechanical and process engineering has been completed for non-flanged fittings. • Additional training requirements required for operation with hydrogen to ensure everyone is aware of the new risks. • Section 6, equipment specific considerations, here a "suitable vent pipe" will be different in hydrogen operation and its design must be revisited. • Section 6 , the bracing requirements will also need to be revisited as hydrogen flows generally have considerably larger gas velocity and will cause larger reaction forces which will require greater bracing. • Hazardous Area specific considerations reconsidered. Flowcharts revisited.

Policy number and title	Interaction points and suggested changes
T/PM/HAZ/10 – Hazardous Area Classification	• Typically referenced documents must cover hydrogen operation. • Zone classification shapes will be different with hydrogen compared to natural gas. • Sections 7.3–7.5 assume ventilation adequacy based on natural gas behaviour. Hydrogen's higher diffusivity and lower ignition energy mean ventilation effectiveness and detector placement should be reassessed. • Hazardous area classification team must include an individual with hydrogen theory, operation and standards experience. • Section 7.7 relies on procedural control for manual venting. Additional controls may be required for hydrogen to address ignition sensitivity, exclusion zones, and temporary equipment suitability. • Third party contractor must have validated hydrogen experience when reviewing hazardous areas. • Site Hazardous Area Classification Review Survey would need to be updated. • Dispersion models need to be validated for hydrogen. • A formal revalidation of hazardous extents, colour coding, and vent assumptions should be required as part of hydrogen conversion.
T/PR/MAINT/6024 – Gas Venting System covers maintenance of gas venting systems including N2 snuffing at compressor stations & terminals.	• This procedure enforces a proven competence in maintenance of gas venting systems; this must be upheld with hydrogen operations. • Permits will have to be updated for new risk categories.
T/SP/ENV/30 - Specification for Sustainability and Net Zero for Gas Transmission Projects	• No fundamental changes required.
T/PM/TR/17 - Isolation of Above 2 Bar Plant and Equipment	• No fundamental changes to the foundations are required, provided referenced technical standards are followed, safety assessments are completed appropriately, and designs for retrofit or new assets have been validated for hydrogen service. The document can therefore be used with minor wording amendments only.
T_PM/TR/30 - Commissioning and Decommissioning of Above 7 Bar Pipelines and AGIs	• Similarly to above as long as hydrogen service is addressed in project specific risk assessments, FPSAs and during MOC process document can be used. • Purge calculation revisited for hydrogen • Equipment and materials verified for hydrogen service.
IGEM/SR/25 Edition 2 – Hazardous area classification for hydrogen installations	• Standard is built round natural gas, therefore, supplementary standard should be created for hydrogen blend and 100%

Policy number and title	Interaction points and suggested changes
	hydrogen operation. • Gas specification for standard to apply for will need to be widened to encompass hydrogen, these include caloric value and molecular wight. • General procedures are gas agnostic so can be used for future operation. • Hole sizes for leakages will need to be revisited due to hydrogen considerably smaller molecule size. • Hazardous areas around leak points will increase as hydrogen gas will disperse faster. • Vent pipe terminations redesigned to prevent any downwards flow. • Dispersion calculations revisited. • All zoning distances will change.
EN 60079-10 ATEX Standard and classification of Areas with Presence of Gas	• The document is designed to be used across all flammable gases, with gas properties defined at the application level. • No fundamental changes are required for hydrogen operation.

8.2 Flaring

SR/23 does not cover flaring or hydrogen; however, several concepts remain relevant when flaring hydrogen, including: the definition of controlled and sterile areas, consideration of personnel escape criteria, and operational controls for planned gas disposal. For hydrogen flaring, SR/23 should be supplemented with hydrogen-specific guidance.

Hydrogen flaring installations must comply with DSEAR and ATEX requirements for hazardous area classification, ignition source control, and equipment certification. Attention should be given to flame detection, pilot reliability, and protection of nearby equipment and personnel.

The following hydrogen-specific issues should be explicitly addressed:

- **Thermal Radiation**: Hydrogen flames exhibit lower emissivity than natural gas, and measured radiation levels are typically lower for equivalent mass flow rates. As a result, thermal radiation is unlikely to be the limiting design criterion for hydrogen flares, although it should still be assessed using established methods.
- **Noise**: Hydrogen flaring can generate high noise levels due to high exit velocities and jet turbulence. Noise has been shown to be the primary driver for exclusion zones and must therefore be explicitly assessed and mitigated through flare sizing, flow control, and, where necessary, acoustic treatment.
- **Ignition and Flame Visibility:** Hydrogen flames are pale and may be difficult to detect visually. Reliable pilot systems, ignition monitoring, and flame detection are therefore essential to ensure safe and controlled operation.
- **Siting and Urban Constraints:** In urban or space-constrained locations, the tall flare stacks required to manage noise, and radiation may be impractical due to planning, visual, or societal constraints. Enclosed flares are a good solution if space allows. In such cases, flaring should be considered alongside alternative disposal options, such as recompression or controlled venting with additional mitigation.

The OGA Flaring and Venting Guidance (2021) guidance establishes a clear principle that flaring and venting must be reduced to the lowest possible level under the circumstances, consistent with what is technically and economically justified for safe and efficient commissioning and operations. This principle is directly applicable to hydrogen and hydrogen-blend systems and aligns with the findings of this study, which show that routine venting of high mass flows of hydrogen-rich gas is often impractical due to noise and ignition risks, and that flaring is the most viable option where recompression is not feasible.

In support of the UK's net-zero commitments, Offshore Energies UK (OEUK) has published decarbonisation targets that have been incorporated into the OGA's flaring and venting performance tracking. Although these targets were developed primarily for hydrocarbon operations, their intent extends naturally to hydrogen systems: flaring and venting should be exceptional, time-limited, and demonstrably unavoidable. For hydrogen-rich systems, this reinforces the need for a hierarchical approach to gas disposal:

- Avoid flaring and venting through recompression wherever practicable,
- Use flaring only where safety or operational constraints prevent recompression, and
- Ensure flaring is temporary, controlled, and minimised

Since NGT does not have internal flaring standards, below are a list of flaring standards for consideration. It is recommended that these documents form a coherent suite of interlinked standards, allowing the framework to scale with hydrogen deployment, support regulatory engagement, and provide clarity for design, operations, and safety case approval.

Standard Area	Proposed Internal Standard	Purpose / Scope
Flaring Philosophy	Hydrogen Flaring Philosophy Standard	➢ Defines when flaring is required, preferred, or prohibited for 5%, 20%, and 100% hydrogen, ➢ Establishes the disposal hierarchy (recompression → flaring → venting), ➢ Differentiates between temporary, emergency, and permanent flaring.
Flare Design	Hydrogen Flare System Design Standard	➢ Sets engineering requirements for hydrogen flares, including tip sizing, exit velocity/Mach limits, stack height, materials compatibility, flare type (open, ground, enclosed), ➢ Requirements for temporary or portable flares.
Thermal Radiation	Thermal Radiation Assessment Standard for Hydrogen Flares	➢ Establishes hydrogen-specific radiation limits. ➢ Recognise low emissivity of hydrogen flames, ➢ Confirms applicability or conservatism of natural-gas-based radiation criteria.
Ignition & Detection	Ignition, Pilot and Flame Detection Standard	➢ Defines requirements for pilot systems, ignition reliability, flame detection technologies (UV/IR, dual systems), ➢ Flame-out response, ➢ Minimum ignition availability during hydrogen flaring.
Environmental Management	Environmental and Emissions Standard for Hydrogen Flaring	➢ Integrates environmental considerations into flaring decisions, including CO_2 impacts for blends, NO_x considerations, ➢ EA permitting principles, ➢ Flaring minimisation, and record-keeping requirements.

Standard Area	Proposed Internal Standard	Purpose / Scope
Operations & Procedures	Hydrogen Flaring Operations and Control Standard	➤ Defines procedural controls for flaring, including but not limited to permitting, weather checks, personnel access control, PPE requirements, emergency response ➤ Training/competency expectations.
Temporary Flaring	Temporary and Portable Hydrogen Flare Standard	➤ Sets requirements for short-duration and project-specific flaring, covering siting, exclusion zones, monitoring, duration limits, and safeguards for hydrogen service.
Integration with Recompression	Hydrogen Disposal Decision Standard (Recompression, vs Flare)	➤ Provides decision logic linking recompression capability with flaring justification; ➤ Ensures flaring is secondary to recompression where practicable ➤ Demonstrates ALARP and environmental justification.

8.2.1 [redacted] Utilsied flare

For the demonstration work conducted through this report the [redacted] 4" utility flare design information has been provided below for references. These are confidential and proprietary so cannot be shared or used for design purposes. It is important to note that no design review of this information has been undertaken as this was out of scope. However, it was determined suitable for the range of demonstration cases to be tested.

[redacted]

Figure 8-1 : [redacted] Flare Tab

The red lines in Figure 8-1 indicate the top of the tab be flush with the flare tip exit and the tab is welded to the inside of the flare tip pipe. The flame tab is 3/4" wide (depth into the page). Also, the pilot should be positioned above the flame tab.

[redacted]

Figure 8-2 : 4" Utility Flare Design

9.0 Environmental Benefits and Impacts.

This assessment has been undertaken in the context of the UK's statutory Net Zero commitment and NGT/SGN's role in enabling the safe and environmentally responsible transition to hydrogen-rich transmission systems. Achieving Net Zero requires not only the reduction of greenhouse gas emissions, but also the deployment of hydrogen in a manner that maintains safety, public confidence, and environmental acceptability.

Venting of hydrogen or hydrogen-rich gas has the lowest direct carbon impact in isolation, as hydrogen itself does not produce CO_2 when released to atmosphere. However, hydrogen is now recognised to contribute indirectly to global warming through its influence on atmospheric chemistry, by reducing concentrations of hydroxyl radicals (OH) that control the breakdown of methane. Reduced OH availability leads to an extended methane atmospheric lifetime, increased background methane concentrations, and secondary impacts on tropospheric ozone and stratospheric water vapour. As such, hydrogen releases are increasingly regarded as environmentally significant despite the absence of direct CO_2 emissions.

Environment Agency guidance recognises that environmental impact is not limited to greenhouse gas emissions alone, and includes wider considerations such as noise, public nuisance, safety, and the potential for uncontrolled ignition events. These wider impacts are particularly relevant for hydrogen-rich systems, where even short-duration releases may have disproportionate environmental and safety consequences.

The findings of this study demonstrate that hydrogen venting, particularly for ≥20% hydrogen, is associated with significant non-CO_2 impacts, including high noise emissions extending well beyond typical site boundaries, increased ignition risk due to high jet velocities, and potential delayed-ignition overpressure events. These effects can create acute environmental disturbance and safety risk for both site personnel and the surrounding environment, even where the duration of venting is short. When combined with hydrogen's recognised indirect contribution to climate forcing, repeated or large-scale venting events represent a non-trivial environmental burden that is inconsistent with Net Zero objectives.

Flaring converts hydrogen or hydrogen–natural-gas blends into controlled combustion products. For hydrogen flaring, this results primarily in water vapour, while for blended gases CO_2 emissions arise from the methane fraction. Consistent with Environment Agency policy, flaring is therefore considered preferable to uncontrolled venting from a safety and environmental control perspective as it fixes the ignition location, avoids the formation of large unignited gas clouds, and reduces the likelihood of abnormal ignition events. However, flaring remains an intentional disposal of energy and, for hydrogen–natural-gas blends, a direct source of greenhouse gas emissions. It should therefore be treated as non-routine, minimised in duration, and applied only were justified on a technical, safety, and environmental basis.

Recompression, as demonstrated in the Recompression Project, aligns most strongly with Environment Agency objectives by avoiding atmospheric release altogether and returning gas to the network. From an environmental perspective, recompression represents the lowest-impact disposal option, notwithstanding the energy consumption associated with compression. By preventing hydrogen release, recompression avoids both direct energy loss and the indirect climate effects associated with hydrogen emissions. Where recompression is not available or practicable, flaring should be considered the preferred alternative disposal mechanism in preference to uncontrolled venting, on the basis of safety, environmental control, and regulatory compliance. For large or repeat disposal events, the avoided gas loss and emissions significantly outweigh the additional compression energy, particularly for hydrogen-rich systems.

Demonstration results presented in this study confirm that hydrogen flaring produces lower thermal radiation than natural gas and provides a predictable and controllable hazard outcome. However, flaring represents loss of gas. As such, flaring should be treated as a secondary disposal option and applied only where recompression is not practicable, consistent with environmental permitting and net-zero principles.

9.1 NO_x Emissions Considerations

From an environmental perspective, NO_x emissions associated with hydrogen and hydrogen-blend operations are primarily relevant to intentional combustion scenarios, rather than venting. Unignited venting of hydrogen or hydrogen-natural gas blends does not generate NO_x, and any unintended ignition following venting would only result in transient NO_x formation during the brief combustion event, leading to negligible overall emissions.

The principal NO_x consideration therefore arises from flaring. It is well established that NO_x formation increases with flame temperature, and that hydrogen addition to natural gas raises combustion temperatures relative to natural gas alone. On this basis, hydrogen flares can be expected to produce higher NO_x emissions per unit of energy released when compared with conventional natural-gas flaring. Indicative data provided by [redacted] suggested that a hydrogen flare may generate NOx at a rate as high as 0.025 kg/ MWh. For a 1kg/s hydrogen flaring 0.1 mg/s of NOx could be produced. This would be the upper limit as the flare temperature will increase with time, thus during the first few seconds of flaring the NOx production would be considerably less. This is three times higher than natural gas for the same gas flowrate.

Consistent with broader decarbonisation and flaring-reduction principles, including those promoted by the Environment Agency, these findings reinforce the importance of avoiding routine flaring wherever reasonably practicable. Recompression, where feasible, entirely avoids NO_x formation while also preventing loss of gas and associated emissions. Where recompression is not practicable, flaring provides a controlled and predictable disposal route but should remain secondary, time-limited, and clearly justified, with NO_x emissions considered as part of the overall environmental and ALARP assessment.

10.0 Cost Benefit analysis

The purpose of this cost benefit analysis is to outline some high-level CAPEX estimates for the various design changes required for different venting scenarios. This estimate is an AACE Class 5 cost estimate as conceptual costs are as detailed as will be investigated here. OPEX is excluded due to insufficient operational definition and is assumed to be comparable across options at this stage, unless material differences are identified.

10.1 CAPEX

As this is a high-level cost estimating task the lang factor multiplier will be used to estimate total capital investment which includes the engineering and instillation costs of a piece of equipment. Furthermore, the lang factor will overestimate small plant retrofits as the costing multiplier includes major plant expansions with new piping and control.

Table 10-1 : Cost Estimate, benefit score, modification list

[redacted]

Table 10-1 present the unit cost and the total capital investments to install and commission the various solutions that have been suggest throughout this report to help mitigate the hazards generated by the addition of hydrogen into natural gas streams. For items 1 – 11 a material benefit cannot be determined as these process equipment changes are driven by improved safety and reputational basis. However, a high-level assessment can be made on the flare stack.

10.2 Decision Boundary and Assumptions

The question which the CBA aims to address: "*Is it economically and technically justified to install a flare system for safe disposal of hydrocarbon/hydrogen releases under defined operational and emergency scenarios over the asset life?*"

This section presents a comprehensive CBA for flare installation. The analysis incorporates:

- Current venting volumes and associated greenhouse gas emissions
- Regulatory framework under RIIO-2 and RIIO-3 mechanisms
- Capital and operating cost estimates for mobile recompression fleet
- Net present value analysis over 15-year asset life
- Sensitivity to hydrogen blending using iso-energetic methodology
- Strategic recommendations for phased deployment

RIIO Price Control Mechanism

NGT operates under Ofgem's Revenue = Incentives + Innovation + Outputs (RIIO) price control framework. The current RIIO-2 period (2021-2026) established incentive mechanisms to encourage emissions reduction, including rewards for avoided methane venting.

[redacted]

[redacted] 3 introduces a dedicated financial incentive for pipeline recompression (Greenhouse Gas Emissions (Pipeline) ODI-F), targeting at least 90% gas recompression during planned pipeline maintenance, with incentive exposure of +/- £3.5m and rewards/penalties based on the government's central carbon price methodology. However, this incentive applies specifically to planned pipeline maintenance activities and does not directly cover the operational venting scenarios addressed in this business case (pig traps, ball valves, and filter maintenance).

10.2.1.1 Venting Cost Evolution and RIIO-3 Expectations

This business case adopts the UK Government Green Book methodology for valuing greenhouse gas emissions. The Department for Energy Security and Net Zero (DESNZ) publishes annually updated carbon values for policy appraisal, which reflect the social cost of carbon and the UK's Net Zero trajectory.

For methane emissions in 2026/27, the Green Book central carbon value of £278 per tonne CO_2e, combined with methane's global warming potential (GWP) of 28, yields an effective venting cost of £7,800 per tonne CH_4. This value escalates at approximately 1.5% per year in real terms through 2040, reflecting increasing stringency of climate policy. This business case applies the £7,800/tonne venting cost to evaluate the economic merit of flare system investment for operational venting scenarios.

10.2.1.2 Hydrogen Transition Context

The UK Government's hydrogen strategy envisions blending up to 20% hydrogen by volume into the gas distribution network by the early 2030s. The timing and extent of hydrogen introduction create strategic uncertainty for infrastructure investment decisions. Equipment investments must either be designed from the outset to handle hydrogen-natural gas blends or accept potential obsolescence if hydrogen introduction renders equipment incompatible.

Mobile recompression units specified in this business case are hydrogen-ready, capable of handling gas blends up to 100% hydrogen without modification. This specification provides resilience against hydrogen transition uncertainty while incurring modest capital cost premium (~10%) over methane-only equipment.

10.3 Current Venting Profile

To undertake this assessment the Felindre site was taken as an example case. The compressor and pig trap venting were defined for this site during the Hydrogen Recompression project. Based on these volumes the ball valve cavities and filters & scrubber venting volumes were inferred. As this is a high-level cost estimate, further refinement is not required. The table below present a summary of these values.

Table 10-2 : Current Annual Methane Venting by Maintenance Activity

[redacted]

[redacted]s CH_4 per year represent a potential target for flare system abatement. Pipeline venting is not considered here as recompression here is well established. The assessment will be undertaken assuming a 100% NG system. In the current regulatory environment, there is no cost for venting hydrogen, and this estimation must be revisited once this is better understood. In reference to this CBA hydrogen will not be considered in the calculations but the conclusions will be influenced by the potential future roll out of hydrogen. The first scenario to be assed is the base case.

10.4 CBA Scenarios

T[redacted]

Table 10-3 : Future Annual Economics at £7,800/tonne CH_4 Venting Cost

[redacted]

their venting incentive threshold, however, the plant only exceeds its venting limits by an additional 10 % (5.44 tonnes).

[redacted]

[redacted]

The results for each analysis have been presented below.

Table 10-4 : 15 Year NPV CBA Results

[redacted]

[redacted]

11.0 Conclusions

11.1 Venting

- Across all venting scenarios tested, noise exposure consistently exceeded personnel safety thresholds defined in SR/23 and by other safety standards. Delayed-ignition venting generates significantly more severe acoustic impacts, with transient A-weighted noise levels of ~120–127 dB(A) and linear levels exceeding 140 dB, extending well beyond 60 m for high-hydrogen cases.
- Pig traps and DBB vents are typically located in congested, personnel-accessible areas. The measured noise levels demonstrate that local venting of ≥20% hydrogen is not practicable, even with restricted access and 5% will require silencer. while 5% hydrogen does not represent a significant hazard increase over methane but highlights that existing local vent arrangements are already sub-optimal, with silencers or remote venting required to achieve acceptable noise and operational conditions.
- For venting scenarios, thermal radiation was significantly low (0.16–0.99 kW/m^2) and only relevant in the immediate vicinity following delayed ignition.
- Measured peak overpressures during delayed ignition reached approximately 4.5 kPa at 5 m for high-flow 100% hydrogen cases. While overpressures beyond 5–10 m remained below structural-damage thresholds, TNT/TNO ME modelling and extrapolation indicate that overpressures can exceed 6 kPa within 1–3 m of the vent for 20% and 100% hydrogen cases, particularly for larger vent diameters and higher flow rates.
- For the TNO ME overpressure estimation class 3 provided the most accurate predications when compared to experimental free field overpressure recordings. Class 7 on the other hand overestimated overpressure while Class 1 significantly underestimate overpressure.
- To predict overpressures close to the vent stack curve fitting with a power law provided the most accurate overpressure estimations as individual power law relationships can be made for individual testing scenarios.
- Increasing hydrogen content results in higher noise levels, larger flammable gas clouds, greater flame speeds, and increased overpressure severity. 5% hydrogen blends behave similarly to natural gas, with limited overpressure and manageable hazards, whereas 20% and 100% hydrogen cases represent a step change in risk, particularly for local venting.
- Although overpressure decays rapidly with distance, near-field loads from hydrogen venting may challenge equipment integrity and support design, particularly for larger vents and hydrogen-rich releases.
- Although gas cloud dispersion could not be directly measured, CFD predictions of jet behaviour, gas cloud volume, and ignition severity were validated against measured noise, thermal radiation, and overpressure data. The strong correlation between predicted supersonic flow and measured acoustic levels provides confidence in using CFD to assess untested scenarios and operational cases.
- For hydrogen concentrations of 20% and above in all scenarios, local venting leads to large noise based sterile zones and elevated overpressure risk near the vent.
- Lower wind speeds result in reduced dispersion, larger gas clouds, and higher overpressures. Comparisons with previous [redacted] testing show that reduced wind conditions can increase overpressures by 40–60%, highlighting the need to consider worst case meteorology in design and operations.
- [redacted]
- [redacted]

11.2 Flaring

- While flaring generally produces lower noise than venting, measured noise levels at 15 m ranging from approximately 82–118 dB(A) and attenuating progressively with distance.
- Measured thermal radiation from hydrogen flaring ranged between 0.75 and 2.63 kW/m^2 at 15 m, remaining well below typical thresholds. Since measured thermal radiation from hydrogen flaring was lower than or comparable to natural gas and remained well below limiting criteria, confirming that thermal radiation is not the controlling hazard.

- By controlling the ignition location, flaring avoids large unignited gas clouds and reduces uncertainty associated with delayed ignition, particularly for hydrogen-rich releases.
- In city-based or space-restricted locations, the tall flare stacks required to manage noise and radiation may be impractical, necessitating alternative mitigation strategies.

Table 11-1 : Flaring Scenarios Summary

FlareSim Scenarios	Did thermal radiation breach SR23 standards
Pig Trap	Yes within 5 – 10 m
DBB	Yes within 5 – 10 m
Compressor casing	No, due to sufficient stack height

This study provides a unique experimental dataset for hydrogen and hydrogen–natural gas blend venting and flaring. To the best of our knowledge, it represents the first full-scale demonstration of its kind and establishes a validated reference point for future hydrogen hazard assessments, operational guidance, and standards development. Table 11-1 highlights the importance of correctly sizing the flare stack as much higher flare requirement flowrates can be offset considerably in terms of thermal radiation by increasing the stack height.

12.0 Recommendations

The following recommendations recognise the differing operational contexts of Transmission (NGT) and Distribution (SGN) networks.

12.1 Recommendations for Transmission Network

- All hydrogen venting activities shall include provision of appropriate hearing protection for personnel. For hydrogen blends below 20%, venting may be permitted provided acoustic silencers are installed to reduce noise levels, typically achieving 15–20 dB attenuation, such that personnel exposure limits can be managed. Local venting of ≥20% hydrogen should be avoided wherever practicable. Flow control through an inline regulator could be used in some scenarios to reduce flowrate and thus noise, however, they may not be useful in other cases such seal shocking of ball valve cavities that must be vented quickly.
- Current silencer design should be assessed for hydrogen and hydrogen blend performance. Acoustic insulation is utilised in other parts of industry and can be considered as an alternative or in addition to a dedicated silencer.
- Vent configurations similar to the tested DBB arrangement incorporating two 90-degree elbows are not recommended for hydrogen concentrations above 5%, due to the high steady-state and transient forces imposed on elbows during venting and delayed ignition. Where higher hydrogen concentrations must be vented, vent pipework ID should be increased, the number of elbows reduced, and large-radius bends adopted to limit mechanical loading. Alternatively, gas release should be channelled to a collection header for venting or flaring.
- Although 5% hydrogen venting does not materially increase hazard compared with methane, this study shows that some existing local vent designs (e.g pig trap vent) are already sub-optimal, routine review and targeted improvements (e.g. silencers and/or remote venting) are therefore recommended.
- For hydrogen concentrations ≥ 20%, venting can result in very high noise levels and significant near-field overpressure following delayed ignition. Exclusion zones should therefore be clearly defined and controlled, based primarily on noise exposure or with adequate acoustic control, and additional consideration of near-field overpressure effects on personnel and equipment. SR/23 requires update to provide operations a usable guide to these exclusion zones.
- When updating SR/23, flow will become a significant factor. To reduce the complexity of the document, limiting venting flowrates via orifice plate should be considered where appropriate.
- NGT will be developing a new 100% hydrogen system. Therefore, venting and flaring of 100% hydrogen within the transmission network should be addressed using new, hydrogen-specific assets, rather than legacy natural-gas configurations. Collection headers and flare systems should be designed explicitly for hydrogen service, incorporating simplified pipework layouts, reduced Mach numbers in compliance with API 521.
- Although thermal radiation from hydrogen venting is lower than from flaring, and hydrogen flaring radiation is lower than natural-gas thresholds due to low flame emissivity, thermal radiation should still be assessed when defining exclusion zones for new transmission assets, alongside noise and overpressure.
- For new transmission assets, automated or frequent venting and flaring systems should be routed to a common collection header prior to discharge. This supports controlled operation, consistent hazard management, and more effective noise and exclusion-zone control. For existing assets, cost benefit is not likely to be positive although this may need to be addressed on a case by case basis.
- Where disposal of hydrogen/hydrogen-natural gas blend is required, flaring is generally safer than venting, as it avoids delayed-ignition overpressure risk and produces lower noise levels. Although flaring generates higher thermal radiation than venting, radiation levels remain below harm thresholds for hydrogen and should not be the limiting factor.
- For sites located within urban or densely populated areas, flaring should not be assumed to be a practicable mitigation measure without detailed site-specific assessment. Where flaring is considered, tall flare stacks may be required to sufficiently reduce thermal radiation levels at ground level, however, such configurations may be incompatible with planning, land availability, or public acceptance constraints.
- Where flaring or open venting presents an unacceptable thermal radiation or ignition risk, the use of nitrogen

purging is recommended as an additional mitigation measure. Nitrogen purging can be used to displace residual flammable gas from vent lines, equipment, or confined volumes prior to venting, thereby reducing the likelihood of ignition and limiting any resulting thermal radiation consequences.

- Existing methane-based guidance is not adequate for hydrogen service. Standards should be updated to explicitly address hydrogen-specific behaviour, including supersonic jet noise, delayed ignition overpressure, and the transition points where flaring becomes mandatory. New flaring standard are also required as NGT does not have at the moment.
- Building on this study, NGT should develop detailed operational procedures, emergency response guidance, and site-specific sterile-zone management plans for hydrogen venting and flaring activities.
- If venting cannot be avoided, substantial noise mitigation measures such as reduced venting rates, increased vent diameter, and acoustic silencers would be required to reduce noise to acceptable levels.
- When choosing a flare, thermal radiation, noise and general social impacts should not be a limiting factor for flare deployment as flare system such as ground flares or enclosed flares could be utilised to minimise their local impact.
- Where venting cannot be avoided, vent outlets should be located away from congestion, confinement, and flame-acceleration paths by avoiding proximity to pipe racks, structural steel, buildings, and equipment, preventing venting in partially enclosed areas or near solid reflective surfaces, and ensuring clear, open surroundings in the near field to minimise overpressure severity.

12.2 Recommendations for SGN

In addition to some of the recommendations listed above for NGT'S transmission networks which some of them are applicable to the distribution network, other recommendations for the SGN transmission operations

networks include:

- Given the close proximity of distribution assets to the public, hearing protection, access control, and strict exclusion zones are essential for any hydrogen venting/flaring activities. Please see below for risk mitigation methods.
- For hydrogen concentrations below 20%, venting may be considered where effective acoustic silencers are installed to reduce noise to acceptable levels and exclusion zone provided as it relates to overpressure and thermal radiation risk on a case by case basis.
- For sites located within urban or densely populated areas, flaring should not be assumed to be a practicable mitigation measure without detailed site-specific assessment. Where flaring is considered, tall flare stacks may be required to sufficiently reduce thermal radiation levels at ground level, however, such configurations may be incompatible with planning, land availability, or public acceptance constraints.
- Where venting cannot be avoided, vent outlets should be located away from congestion, confinement, and flame-acceleration paths by avoiding proximity to pipe racks, structural steel, buildings, and equipment, preventing venting in partially enclosed areas or near solid reflective surfaces, and ensuring clear, open surroundings in the near field to minimise overpressure severity.

12.3 Recommendations for Modelling

Recommendations Modelling include:

- [redacted]
- [redacted]
- [redacted]

QRA.

- [redacted]
- [redacted]
- [redacted]

12.4 Recommendation for Future Work

Recommendations for future work include:

- A demonstration campaign is recommended to better characterise the resulting overpressure and dispersion behaviour, and to support robust risk management for compressor casing venting.
- It is recommended that IGE/SR/23 be reviewed and updated to incorporate updates suggested in this report.
- IGE/SR25 will need careful updates for hydrogen, therefore it is recommended this is started right away.
- Flaring policy and standards need to be developed for hydrogen transmission and distribution networks.
- Develop an NTS wide hydrogen venting and flaring standard. This should define design requirements for hydrogen capable flare systems, including stack height, ignition systems, purge strategies, metallurgy, and sterile zones.
- Site specific feasibility assessments will be needed to determine how each installation can accommodate the required upgrades. This includes assessing land availability for flare systems and sterile zones, identifying routing options for collection headers, reviewing existing vent geometries, and ensuring that utilities such as nitrogen, propane and power can support the new systems.
- A detailed structural assessment is required for the DBB vent, as the impulsive forces on the 2-inch 90 °elbows during hydrogen venting are severe and may necessitate upsizing the pipe to 4 inches, using 45-degree elbows, and implementing controlled valve-opening procedures.
- A phased rollout strategy should be established. This should identify which sites are prioritised based on risk, hydrogen throughput, or operational criticality, and align vent redesign and flare system deployment with wider hydrogen conversion plans. The rollout should also include transitional measures for blended-hydrogen sites and specify readiness criteria for each site before commissioning flaring systems. CFD captures transient flow behaviour, jet dynamics and dispersion patterns with higher fidelity than simplified process simulation tools. It should therefore be integrated into defining flare stack height.
- It is recommended to conduct a detailed assessment of how common gas impurities (e.g., N_2, CO_2, CH_4, O_2, moisture, and trace contaminants) influence hydrogen venting and flaring performance, including their effects on flammability limits, jet behaviour, ignition and pilot stability, combustion efficiency, radiation levels, emissions, and overall hazard distances for both normal and emergency operating scenarios.

13.0 References

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

14.0 Appendix

Appendix A – Hazard Measurement Limits

Table 14-1 : Overpressure Limits [6]

Peak Overpressure (kPa)	Maximum Wind Speed (mph)	Effect on Structures	Effect on the human body
6.89	38	Window glass shatters	Light injuries from fragments occur
13.79	70	Moderate damage to house (windows and doors blown out and severe damage to roofs	People injured by flying debris and glass
20.68	102	Residential structures collapse	Serious injuries are common fatalities can occur.
34.37	163	Mist buildings collapse	Injuries are universal and fatalities are widespread.

Thermal Radiation Limits

Thermal Radiation Limit	Comment
4.6 kW/m²	4.6 kW/m² is defined by API 521 as the heat flux threshold in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing. It is also defined by the International Fire Code as the threshold for exposure to employees for a maximum of 3 minutes. [8]
6.3 kW/m²	With aluminized clothing (EN1486) till 6.3kW/m² can be worked safely during incident related activities up to five minutes [9].

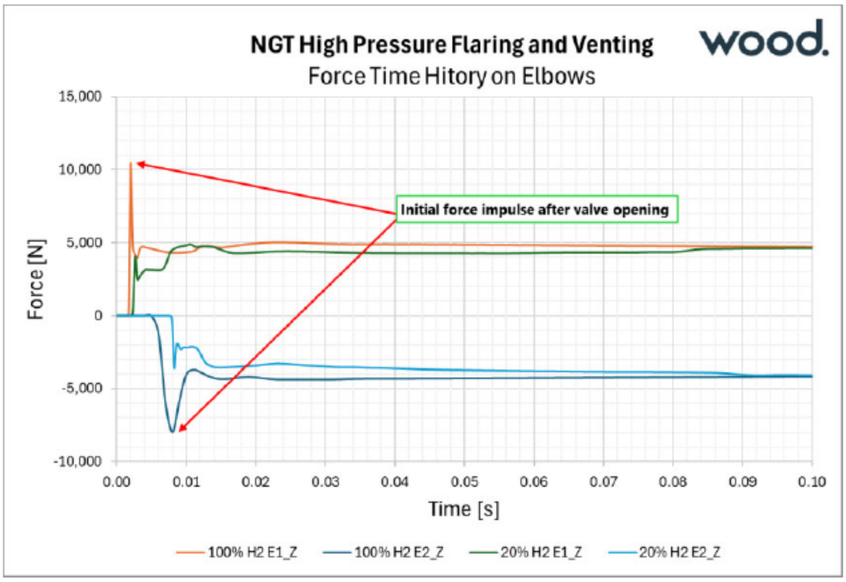
Noise Exposure Limit Chart [7]

Sound pressure level, L_{Aeq} (dB(A))	Duration of exposure: 2 min	5 min	15 min	30 min	1 h	2 h	4 h	8 h	10 h	12 h
120	1300									
110	130	330	1000	2000						
105	42	105	315	625	1250					
100	13	34	100	200	395	790	1600			
98	8	22	60	125	250	500	1000	2000		
97	7	17	50	100	200	395	790	1600	2000	
95	4	10	32	65	125	250	500	1000	1250	1500
94		8	26	50	100	200	395	790	1000	1200
93		7	20	40	80	160	315	630	790	950
92		5	16	32	65	125	250	500	625	750
91		4	12	26	50	100	200	400	500	595
90			10	20	40	80	160	315	395	475
89			8	16	32	65	125	250	315	375
88			6	12	26	50	100	200	250	300
87			5	10	20	40	80	160	200	240
86			4	8	16	32	65	125	155	190
85				6	13	26	50	100	125	150
84				5	10	20	40	80	100	120
83				4	8	16	32	65	80	95
82					6	13	26	50	65	75
81					5	10	20	40	50	60
80					4	8	16	32	40	48
79						6	13	26	32	38
78						5	10	20	26	30
75							5	10	13	15

Total exposure points (sum of points from individual exposure components)	Daily noise exposure $L_{EP,d}$ (dB(A))
320000	120
32000	110
10000	105
3200	100
2000	98
1600	97
1000	95
790	94
630	93
500	92
400	91
315	90
250	89
200	88
160	87
125	86
100	85
80	84
65	83
50	82
40	81
32	80
26	79
20	78
10	75

- Red: Above upper exposure action value ($L_{EP,d}$ 85 dB(A))
- Yellow: Above lower exposure action value ($L_{EP,d}$ 80 dB(A))
- Green: Below lower exposure action value ($L_{EP,d}$ 80 dB(A))

Appendix B Forces on Elbow within the 2 inch Double Block and Bleed Vent



[redacted]

[redacted]

[redacted]

[redacted]