H2 Site Safety Systems

Conceptual Study - Impact of Hydrogen on Fire & Gas Detection Systems

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1.0 Executive Summary

1.1 Purpose

This study assesses the impact of introducing hydrogen into the National Gas Transmission system, focusing on two representative facilities: Kirriemuir Compressor Station and Bacton Gas Terminal.
The aim is to evaluate how 5% and 20% hydrogen–methane blends would alter the performance, adequacy, and reliability of existing Fire and Gas (F&G) detection and suppression systems, including:

- Quantitative Risk Assessment (QRA) impacts
- Computational Fluid Dynamics (CFD) results for gas dispersion within compressor enclosures
- Suitability of existing gas and flame detector technologies
- Effects on consequence modelling, ignition probability, and risk profiles

The assessment integrates findings from DNV QRA/FRA models, EI15 hydrogen blend guidance, DNV RP-G108, and HSE RR1121 data.

1.2 Conclusions

Hydrogen fundamentally changes the risk characteristics of natural-gas facilities.
At 5% H_2 blends, the effect on risk and consequence behaviour is minimal and could potentially be accommodated by existing systems with minor parameter updates.
At 20 % H_2, several material and detection issues become significant:

Risk Profile:

- For open plant areas, the introduction of hydrogen reduces overall flammable-cloud size. Although the lower flammable limit decreases slightly (from ~4.4 vol% CH_4 to ~3.1-3.5 vol% for an 80/20 CH_4/H_2 blend), the mixture becomes lighter and more buoyant, dispersing and lofting rapidly. Consequently, LFL and ½ LFL footprints shrink by approximately 5-20%, depending on release geometry and meteorology.
- Within enclosed or semi-confined spaces, free buoyant dispersion is restricted. Hydrogen can accumulate at high level, forming stratified layers with a wider flammable range and higher reactivity. In these volumes the flammable region and ignition probability both increase, raising local explosion overpressure risk.
- Overall, the societal-risk contribution from large outdoor releases is slightly reduced, while individual-risk contributions from internal releases rise modestly, leaving the combined site risk broadly stable within the Tolerable if ALARP band.

Leak and Ignition Behaviour:

- Hydrogen permeates more readily through seals and joints, increasing internal leak frequencies by ~×1.5-3 depending on component type.
- Minimum Ignition Energy drops by an order of magnitude, doubling to tripling ignition probabilities for

internal leaks.

Detection Performance:

- Existing IR gas detectors cannot detect hydrogen; in a mixed plume methane may alarm first but detailed mapping would be required to confirm this.
- CFD simulations demonstrate that with normal ventilation, methane dominates detection response; with failed ventilation, hydrogen can accumulate undetected near the ceiling.
- IR-only systems are inadequate above ~10% H_2 blends in enclosed spaces.

Flame Detection:

- Hydrogen flames emit weakly in IR but strongly in UV.
- For 80/20 blends, flames remain largely IR-visible; however, confined or roof-void areas may require UV or UV/IR detectors for full coverage.

Materials & Equipment:

- Ageing steels, elastomers, seals, and compressor dry-gas seals not designed for hydrogen may suffer embrittlement or leakage.
- Hazardous-area electrical equipment should conservatively be treated as Group IIC unless blend-specific MESG/MIC data are available.

Overall Risk Trend:

- Kirriemuir: marginal increase in explosion risk within Compressor Acoustic Buildings (CAB); minimal change to offsite risk contours.
- Bacton: slight reduction in overall societal risk due to shorter jet/flash-fire ranges; confined-space explosion risk locally higher.
- Both sites remain within the "Tolerable if ALARP" regulatory band, contingent upon mitigation upgrades. However, this should be confirmed with more detailed study work and analysis.

1.3 Recommendations

Fire & Gas Detection Upgrades

- Retain IR detectors for methane; add hydrogen-capable aspirated or catalytic/electrochemical point detectors at ceiling and ventilation-dead-zone locations.
- Configure hydrogen alarm set-points at 10 % LEL (H_2) for alarm-only, integrated via low-flow-monitored aspiration systems.
- Maintain IR3 detectors for open-plant flames; add targeted UV/UV-IR detectors in confined or roof-void areas where hydrogen-rich pockets could ignite.
- Consider ultrasonic leak detectors (UGLDs) near high-pressure manifolds to improve early leak detection independent of gas composition.

QRA and FRA Updates

- Re-run AGI Safe/FROST consequence models using revised gas properties (LFL~3.3 %, flame speed ~1.5–2 m/s).
- Update ignition probability splits (internal leaks ×2–3, external ×1.5).
- Re-validate explosion models for confined areas; adjust ME class +1 for 20 % H_2.
- Confirm control-building and muster-area criteria remain compliant, revise escalation matrices accordingly.

System Design and Integrity

- Verify enclosure ventilation rates and perform airflow checks to prevent hydrogen stratification.
- Re-evaluate materials and seals for hydrogen compatibility (especially small-bore tubing and elastomers).
- Treat all blend systems as Group IIC under DSEAR/ATEX until proven otherwise.
- Maintain existing fire-water capacity but review nozzle coverage and hose flexibility for potentially different jet orientations.

Operational Controls and Training

- Update Cause & Effect logic to integrate hydrogen alarms and cross-zone voting (e.g. 1ooN H_2 trip inside, 2ooN outdoors).
- Enhance maintenance and bump-test frequencies for catalytic or electrochemical sensors.
- Reinforce emergency response procedures addressing invisible flames, faster ignition, and possible re-ignition after ventilation loss.

Implementation Priorities

- Phase 1 (Immediate): QRA parameter updates, hydrogen detector trials in representative CABs, verification of ventilation adequacy.
- Phase 2 (Short-Term): Procurement and installation of H_2 detection upgrades at Kirriemuir.
- Phase 3 (Medium-Term): Apply lessons to terminal-class sites such as Bacton and similar NGT assets.

1.4 Overall Summary

Consequences attributed to a 5 % hydrogen blend can potentially be safely managed within current system tolerances. The introduction of additional aspirating detection systems will alert the site to potential build-up of H2 releases in areas of stagnant airflow.

20% H_2 blend is not recommended without extensive further engineering. This requires detailed consequence modelling, explosion risk assessment in confined spaces, and confirmation of ignition/energy splits. A realistic cost and schedule cannot be provided at this stage due to significant unknowns and potential need for plant-wide F&G upgrades.

Preferred option: to minimise both capital cost and operational disruption while adequately managing the residual hydrogen risk.

Low blend (<~10% H_2)

Consequence behaviour remains broadly methane-like in open areas and there is no justification for full plant F&G upgrade.

Pure H_2 flames are not considered credible for low blends and H_2-specific flame detection would not be required.

IR detectors cannot see hydrogen and targeted H_2-capable detection would only be required in enclosed/low-ventilation areas where H_2 can accumulate (primarily in CABs).

Aspirated H_2 detection systems are recommended for these locations to capture both low-level seepage and entrained releases below methane detector thresholds.

2.0 Introduction

2.1 Project Description

Fire and Gas (F&G) systems are used on the National Transmission System (NTS) to mitigate and manage the risks posed by the enclosure of live gas assets within buildings – typically these enclosed spaces are Compressor Acoustic Buildings (CAB), which contain the compression units and systems used to create bulk flows of gas around the UK. They are also used at the UK's gas terminals. Risks are posed by the accumulation of gas within enclosed and outdoor spaces, leading to the possibility of fire and explosion. National Gas Transmission (NGT) are undertaking this project to understand the compatibility of these important systems with a change in gas mix and therefore the behaviour and risk profile of gas transported.

A F&G system on the NTS typically contains fire detection (flame detectors, smoke sensors) fire suppression (a water mist and/or a CO2 flushing system,) gas detectors (sensing of air flammability,) and an element of gas suppression (forced ventilation.) NGT previously undertook a project looking at Fire & Gas Detection and Suppression for Hydrogen Compression stations which suggested how a F&G system should be designed for a 100% hydrogen CAB. NGT would now like to build on this work to fully understand the reusability of existing systems for 5% and 20% hydrogen, to identify the point at which changes may need to be made to these systems to accommodate hydrogen blends.

As well as assessing two CABs - one legacy and one modern - this project will consider the F&G detection and suppression systems at Bacton Gas Terminal. Bacton is likely to have a more complex F&G system and is chosen both as a representative example of a UK gas terminal; and as the Network Entry Point (NEP) for the UK's two gas interconnectors it will possibly experience hydrogen blends before other parts of the NTS. As Wood are undertaking an upgrade of the Kirriemuir site, this will be used as an example of both a legacy site (Pre-upgrade) and a modern site (Post upgrade) to satisfy the required scope.

2.2 Document Purpose

This technical report reviews the impact of introducing hydrogen to the natural gas streams for both the Kirriemuir Compressor Station and the Bacton Gas terminal. The proposal is to review the impact on the existing Fire and Gas detection systems for these sites when a 5% and 20% hydrogen/methane blend is introduced.

To assess the impact on the F&G detection systems for these sites, the current site risks are reviewed to establish how Hydrogen blends may change the site risk profiles.

The assessment uses information from a selection of site documentation and considers the following;

- Computational Fluid Dynamics
- Quantitative Risk Assessment

- Detector selection
- System Integration
- F&G system evaluation

The assessment reviews each site individually and concludes with a statement for recommendations for further work and potential changes to the current F&G detection system and high level cost estimates for updated detection units.

2.3 Abbreviations

Abbreviation	Description
AIT	Auto-Ignition Temperature
ALARP	As Low As Reasonably PractiCABle
CAB	Compressor Acoustic Building
CCR	Centralised Control Room
C&E	Cause & Effect
CFD	Computational Fluid Dynamics
COMAH	Control of Major Accident Hazards
DDT	Deflagration-to-Detonation Transition
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
EA	Environment Agency
ELD	Engineering Line Diagram
EPL	Equipment Protection Levels
F&G	Fire and Gas
FRA	Fire Risk Assessment
GT	Gas Turbine
HSE	Health and Safety Executive

Abbreviation	Description
IGEM	Institute of Gas Engineers & Managers
LEL	Lower Explosive Limit
LFL	Lower Flammable limit
ME	Multi-Energy
MESG	Maximum Experimental Safe Gap
MIC	Minimum Igniting Current
MIE	Minimum Ignition Energy
NGT	National Gas Transmission
PED	Pressure Equipment Directive
PLL	Potential Loss of Life
POL	Probability of Ignition
QRA	Quantitative Risk Assessment
UGLD	Ultrasonic Gas Leak Detection
VCE	Vapour Cloud Explosion
WP	Work Pack

2.4 Definitions

Within this document, the following definition shall apply:

Definition	Meaning
Accident	These are the actual realisation of a hazard.
Hazard	This is a physical situation that have the potential to cause harm.
Risk	This is the product of likelihood and consequence. More scientifically, it is defined as the probability of a specific adverse event occurring in a specific period or in a specified circumstance.
Safety	This is the inverse of risk. The higher the risk from an installation, the lower is its safety.

3.0 Kirriemuir Compressor Station - Engineering Discussion

3.1 Kirriemuir Hazard Identification and Assessment

3.1.1 QRA Gap Analysis

A review of the Kirriemuir Fire Risk Assessment and Quantitative Risk Assessment [1], completed by DNV GL in July 2017, was completed to identify hazards that have the potential to present with the new site fluid composition.

3.1.2 Analysis for 20% Hydrogen Blend in Natural Gas Stream

3.1.2.1 General Effects Of 20% Hydrogen Blend

Below is a summary breakdown of the general effects and changes to gas characteristics with a 20% volume blend included in the natural gas stream.

Parameter	Natural Gas	Hydrogen Blend (20%)	Effect
Molecular weight	17g/mol	~13.24g/mol	Higher rise, faster dispersion
Lower Flammability Limit (LFL)	4.4 vol%	lower overall LFL (3-3.5%)	Larger flammable cloud footprint
Flame speed	Moderate	much faster	Increased potential for flash fire & jet fire severity
Ignition energy	Moderate	very low	Higher probability of ignition
Heat of combustion	50 MJ/kg	lower per unit volume	Lower thermal radiation, but jet fires still severe due to velocity
Diffusion coefficient	Moderate	high	More rapid dispersion into the air
Explosion sensitivity (confinement dependent)	Moderate	higher	Increased overpressure risk, especially in confined areas like compressor CABs

Table 1 – General Effects Summary of 20% Hydrogen Blend

3.1.2.2 Specific Impacts On QRA / FRA Findings

A) Individual and Societal Risk

- Larger LFL cloud footprint - larger individual risk contours ($1x10^{-6}$ to $1x10^{-4}$) may move outward.
    - Farm areas and sawmill local to site, could experience a slightly increased individual risk.
- Control building and other occupied buildings:
    - Thermal radiation from jet fires might be similar or slightly reduced as hydrogen flames are low soot and radiate less per unit heat release than methane. Also, as hydrogen is more buoyant, the blended jet is lighter and once the initial momentum region decays, the flame/plume lifts upwards faster reducing the view factors from the flame to ground-level receptors such as the control building and therefore reducing the received heat flux.
    - Within the congested CAB, H2 addition increases the mixture reactivity (higher burning velocity, lower quench distance, wider flammability), which raises deflagration severity and peak overpressure for a given cloud size.
- Societal F-N curve:
    - Could shift upward slightly, potentially moving close to the ALARP line depending on assumptions.

B) Equipment Specific Impacts

- Scrubbers: Increased risk of explosive scenarios if hydrogen accumulates in confined spaces.
- Pressure Reduction Unit: Higher ignitability and faster flame speed, higher overpressure risk.
- CABs (A,B&E):
    - Jet fire radiation could become more directional due to lower mass flow but faster jets.
    - Explosion risks in CABs may increase significantly - particular attention required for:
        - Fuel gas filters.
        - CAB enclosures.
        - Ventilation adequacy.
- Recirculation pipework:
    - Hydrogen's diffusivity and embrittlement potential should be considered - potential need for reassessment of failure frequencies.
- Fuel Gas Filter Units:
    - Higher ignition probability may increase contributions to individual risk and to occupied building thermal load.

C) Escalation & Fire Water Provision

- Jet fires may become more intense and more directional, but with lower total radiant heat.

- The fire water demand calculation (based on 20 mm release) may change - possibly a reduced volume needed for thermal radiation protection, but larger areas needing protection due to faster flame spread.
- Need to re-check thermal radiation and overpressure matrices with revised hydrogen data.

D) Non-Process Hazards

- Hydrogen increases ignition potential for any existing non-process hydrocarbon inventories (diesel, lube oil, etc.).
- Need to consider interaction between hydrogen flames and non-process hazards (transformers, diesel, batteries).

3.1.2.3 Key Areas Of FRA/QRA That Will Need Further Analysis And Assessment

Section	Impact
5.1.1 Risk to People	Individual & societal risk would likely increase slightly, driven by greater cloud size and explosion risk.
5.1.2 Risk to Asset	Control Building could move closer to needing structural protection (due to increased overpressure).
Temporary Building Zones	Inner/middle zones may need to expand due to larger flammable gas footprint.
Escalation Matrices	Would need updating - more targets may fall within new jet fire and explosion zones.
Fire Water Provision	Water rates might be revised downward for thermal cooling, but provision for firefighting may need more flexibility due to increased event likelihood.

Table 2 Key Areas of FRA/QRA for further Assessment/Analysis

3.1.2.4 FRA/QRA Model Parameters That Will Require Update

Due to the changes in composition with the introduction of a 20% hydrogen blend, a number of previous QRA models will no longer remain valid and will require an update.

Parameter	Natural Gas	20% H_2 Blend	Action Required
Molecular weight	17 g/mol	13-14 g/mol	Update for dispersion modelling.
LFL	4.4 vol%	3.1-3.5 vol%	Update LFL contours in AGI Safe.
UFL	15 vol%	24-28 vol%	Update in explosion models.

Parameter	Natural Gas	20% H_2 Blend	Action Required
Ignition energy	0.3 mJ	~0.02 mJ [1]	Increase ignition probability, especially outdoors.
Laminar flame speed	0.4 m/s	1.5-2.0 m/s	Re-run explosion scenarios with higher flame speed.
Jet fire visibility	Moderate	Lower (optically thin)	Use hydrogen-adapted jet fire models - radiation still damaging but more directional.
Heat of combustion (MJ/m^3)	35-38	25-30	Adjust thermal radiation predictions accordingly.
Diffusion coefficient	Moderate	High	Increase dispersion rate; clouds will rise and move faster.

Table 3 FRA/QRA model parameters that require updating

[1] 0.02mJ is a conservative value taken for all H_2 blends as stratified pockets of leaking gas can become H_2 biased, pulling the MIE down to the 100% H_2 value.

3.1.2.5 Specific Equipment Risk Areas For Focus

There are a number of specific items of equipment onsite that will be directly affected by the change in fluid composition. These items will require detailed focus to quantify the changes in risk profiles.

Scrubbers A/B/C/D - Increased jet velocities from lower density H_2 can affect droplet separation efficiency. Internal components (e.g. mesh pads, demisters) must be checked for H_2 compatibility and flow behaviour. Risk of liquid carryover into compressors may increase if separation efficiency drops. There is a possible increase in internal explosion risk. A verification of venting and inerting should be completed.

Pressure Reduction Unit - There is a higher explosion risk associated with the 20% blend due to faster flame speeds if gas is ignited. There may also be a risk of JT cooling behaviour changes and hydrate build up. Flame arrestors, venting adequacy and filter & heater performance will all need to be investigated fully.

Water Bath Heater - Hydrogen blend changes Joule-Thomson cooling behaviour and may reduce temperature drop after pressure letdown. Heater duty may require recalculation. Check heater shell and seals for hydrogen compatibility in case of leaks.

CABs A,B&E - High risk area. H_2 permeation through seals and tubing increases internal leak frequency. H_2 has higher ignition probability, faster flame speed, and lower ignition energy. Explosion overpressures in confined CAB volumes will increase. Requires reassessment of ATEX zones, gas detection, ventilation, and structural integrity.

Recirculation Pipework (C&D) - Material fatigue and crack initiation risks increase due to H_2 embrittlement, especially at welds and elbows. Small bore connections prone to leaks. Jet velocity and dispersion behaviour of leaks differs from NG.

Fuel Gas Filter Units - Fuel gas with 20% H_2 has different combustion properties and can cause flame instability in downstream engines/turbines. Filter seals and vessels must be checked for H_2 compatibility due to internal pressures. Increased leak detection for this equipment is required.

Feeder Pipelines - H_2 embrittlement risks for carbon steel pipelines increase, especially at welds and heat-affected zones. Leak dispersion and explosion behaviour changes. Requires fracture toughness and crack growth assessment. ATEX and consequence distances may increase due to change in dispersion characteristics.

3.1.2.6 QRA Model Specific Recommendations

Dispersion Modelling:

Re-run with:

- Lower LFL.
- Higher diffusion coefficient.
- Lower molecular weight - faster rise, less "pooling" than NG.

Jet Fire Modelling:

- Use hydrogen-specific jet fire correlation (optically thin, high-velocity, more penetrating but lower thermal flux).
- Update flame length and impingement analysis.

Explosion Modelling:

Re-calculate overpressures:

- Flame speed increases, higher Deflagration to Detonation Transition (DDT) risk in confined areas (CABs).
- 20% H_2 blend can generate up to 50% higher overpressures in confined geometries.
- Re-assess temporary building blast zones.

Ignition Probabilities:

- Outdoor pipework, increase ignition probability modestly (factor 1.5-2x typical NG).
- Indoor/confined - increase significantly (factor 2–4x).

Fire Water Provision Impact:

- Jet fires: Radiation may slightly reduce; cooling demand might reduce somewhat.
- Explosion: Increased risk, fire service tactical approach needs review.

Recommendation: Keep existing fire water provision but:

- Review directionality of jets - may need more flexible hose streams.

- Confirm with local fire service that hydrogen risks have been communicated.

Emergency planning / escape routes:

Consider faster flame propagation and update evacuation assumptions if necessary.

Hazardous Area Classification

- In confined/congested volumes the addition of H_2 increases deflagration severity potential (higher laminar flame speed, lower quench distance).
- For 20% H_2, consider one step higher reactivity class in your congestion/ME/CFD sensitivity cases.
- Outdoors in open areas, explosion risk remains dominated by congestion/obstacles; still, treat 20% H_2 as higher-reactivity fuel for explosion modelling sensitivity.

Under DSEAR, the blend fluid classification will not change and still be classed as a flammable gas. Under the Pressure Equipment Directive (PED) the gas composition does not change the fluid group, and this will remain as a Group 1 hazardous fluid. However, what can change due to the blend composition will be the ATEX/IEC gas subgroup assumed for equipment selection.

- Equipment gas group (Group II, subgroup):
  - Methane - IIA
  - Hydrogen - IIC (most onerous)
  - Blends (5% or 20% H_2): unless you have tested MESG/MIC data for the specific blend per IEC 60079-20-1, the conservative (and commonly required) assumption is to treat as IIC for electrical/ignition-capable equipment. (If you want to justify IIB/IIA, you'd need defensible test data or a manufacturer's documented suitability.)
- Temperature class:
  - CH_4 AIT ~537°C, H_2 AIT ~500–585°C. Both are T1 domain, so T-class doesn't change with the blend.
- Zones/EPLs (Ga/Gb/Gc):
  - Zone assignment/EPL derives from grade of release and ventilation, not the subgroup. The blend itself doesn't force a new zone, though your PoI and flammable range sensitivity may nudge risk results and detector philosophy.
- Static/control measures:
  - H_2 content lowers MIE of the atmosphere; under DSEAR this strengthens the case for bonding/earthing and anti-static controls, but it doesn't create a new "fluid rating."

3.1.3 QRA Key Equipment / Locations to Focus for H_2/NG 20% Blend

Extracted from QRA report's equipment list (Section 5.1.1 - 5.1.2 & PLL table):

Equipment / Location	Reference / Tag (from report)	Reason for Reassessment
[redacted]		

Table 4 QRA Key Equipment / Locations to Focus

These are the highest priority areas where existing QRA assumptions and findings will likely change.

3.1.4 CAB Units - Most Likely Leak Points due to NG-20% H_2 Blend

Zone / Component	Typical Leak Mechanism	Relative Risk (NG – H_2 blend impact)
Suction pipework & isolation valves (inc. covered pit)	Valve stem leaks, flange leaks, threaded fittings, gasket failures	High suction side has high mass flow; H_2 embrittlement risk on older valves.

Zone / Component	Typical Leak Mechanism	Relative Risk (NG – H_2 blend impact)
Discharge pipework & isolation valves (inc. covered pit)	As above, plus high vibration-induced flange/gasket failure	High discharge side is high pressure & temp, jet risk.
CAB Recirculation Pipework (Above ground + pit sections)	Connection flanges, fatigue at welds, seal degradation	Medium-High known contributors in QRA. H_2 increases embrittlement risk.
Fuel Gas Filters & Associated Pipework (CAB Filter units)	Filter housing seals, O-rings, flanges	Medium hydrogen makes O-ring compatibility critical.
Fuel Gas Meters & Associated Pipework	Gaskets, flanges, housing seals	Medium small leaks, but H_2 disperses rapidly risk of rich cloud in CAB.
Compressor Casing Seals / Dry Gas Seals	Seal wear, seal gas system faults	Medium-High if compressor has dry gas seals, H_2ingress more likely due to permeability.
PRV Vents / Relief Devices on CAB Piping	Weeping or spurious opening	Low-Medium depends on maintenance history. Hydrogen permeation risk must be checked.
Instrumentation connections (pressure transmitters, temp sensors, flow transmitters)	Small bore tubing leaks, ferrule loosening, valve stem packing	High frequency of small leaks – hydrogen makes these more significant due to low ignition energy.
CAB penetration points (HVAC ducts, CABling entries)	Integrity breach or poorly sealed conduits	Not a leak source but allows gas accumulation inside CAB from other sources. Critical to review with H_2
Complicated jointed assemblies	Piping support fatigue leading to joint cracking	Depends on age of CAB – older CABs may have higher fatigue risk.

Table 5 CAB Units Likely Leak Point

3.1.4.1 Internal Leak Frequencies - CABs (Kirriemuir QRA)

CAB	Location / Source	Failure Frequency (per year)	Comment
CAB A	Inlet Pressure — Internal Leaks	5.14×10^{-4}	High priority source.
CAB A	Outlet Pressure — Internal Leaks	4.47×10^{-4}	High priority source.
CAB A	Fuel Gas Pressure — Internal Leaks	3.77×10^{-4}	Very relevant for H_2 blending.
CAB B	Inlet Pressure — Internal Leaks	5.14×10^{-4}	High priority source.

CAB	Location / Source	Failure Frequency (per year)	Comment
CAB B	Outlet Pressure — Internal Leaks	4.47 x 10^{-4}	High priority source.
CAB B	Fuel Gas Pressure — Internal Leaks	3.77 x 10^{-4}	Very relevant for H_2 blending.
CAB E	Inlet Pressure — Internal Leaks	5.14 x 10^{-4}	High priority source.
CAB E	Outlet Pressure — Internal Leaks	4.47 x 10^{-4}	High priority source.

Table 6 CAB Units Internal Leak Frequencies

These internal leaks represent exactly the type of leak that would likely occur at:

- Small bore tubing.
- Instrument connections.
- Flanged joints.
- Valve stem seals.
- Compressor casing seals / dry gas seals.
- Fuel gas supply connections.

Frequencies are relatively high - on the order of 10^{-4} per year, which is consistent with DNV/AGI Safe practice when no detailed parts count is used.

Hydrogen effect: These rates would need to be *adjusted upwards* when moving to H_2/NG blend, due to:

- Increased permeability through seals.
- Increased leak tendency on threaded/ferrule joints.
- Increased ignition probability.

3.1.4.2 Scaling Factor for Internal Leak Frequencies - H_2/NG Blend

Source references:

- DNV RP-G108 "Hydrogen in Existing Natural Gas Networks" [2]
- EI15 4th Ed. "Area Classification for NG/H_2 installations" [3]
- EU HySafe project reports [6]

Based on these studies, here is the practical guidance:

Leak Source Type	Scaling Factor for Internal Leak Frequency when moving to 20% H_2 blend
Small bore tubing, instrumentation, valves, seals	x 1.5 to 2.0
Flanges, bolted joints	x 1.2 to 1.5
O-rings, elastomer seals, compressor casing seals	x 2.0 to 3.0 (highly material-dependent)

Table 7 Scaling Factor for Internal Leak Frequencies

Rationale:

- Increased H_2 permeation - more leaks through seals/O-rings.
- Faster diffusivity - leaks become "visible" earlier / more significant.
- Embrittlement risk in older components - small bore failures more likely over time.

Implementation:

Since the QRA used:

- Internal leaks for CABs – 5.14 x10^{-4} /yr (inlet)
- Internal leaks for CABs – 4.47 x10^{-4} /yr (outlet)
- Fuel gas internal - 3.77 x10^{-4} / year

Suggested scaled frequencies for QRA update:

CAB Source	Suggested New Frequency (H_2/NG 20%)
Inlet Internal Leak	7.7 to 10.3 x10^{-4} /yr
Outlet Internal Leak	6.7 to 8.9 x10^{-4} /yr
Fuel Gas Internal Leak	5.7 to 7.5 x10^{-4} /yr

Table 8 Scaled Frequencies for QRA update

3.1.4.3 Ignition Probability Update - Internal Leaks (CAB)

Baseline values - AGI Safe / National Grid typical approach (NG only):

Release Type	Typical Ignition Probability
Small internal gas release in CAB (NG)	5% to 10%
Small external gas release outdoors	1% to 5%

Table 9 Ignition Probability Update

Hydrogen effect:

- H_2/NG 20% blend has 5-10x lower ignition energy.
- EI15 recommends scaling ignition probability up by x2-3 for internal releases in confined areas.
- HSE research (RR1121) suggests for 20% blend: 2x increase in observed ignition frequency in practice.

Suggested updated ignition probabilities:

Release Type	Suggested Ignition Probability (H_2/NG 20%)
Internal leak in CAB	15% to 20%
External leak outdoors	2% to 7%

Table 10 Updated Ignition Probabilities for 20% H_2 Blend

3.1.4.4 Key Point

- For the Control Building risk and F-N curve, the *single biggest sensitivity* will be the internal CAB leak ignition probability.
- Moving from 5-10% to 15-20% will significantly increase explosion contribution to individual and societal risk.

3.1.5 Conclusions & Recommendations

If National Grid upgrades to 20% H_2/NG blend:

- QRA model (AGI Safe) will need to be re-run with updated gas properties:
  - Hydrogen/Natural Gas blend flammability data.
  - Explosion overpressure data for blends.
  - Jet fire models adapted (hydrogen flames are optically thin but high velocity).
- Occupied building risk should be reassessed - particularly Control Building.
- Explosion risk in CABs will likely become more significant -ventilation adequacy and isolation strategy should be reviewed.
- Fire water system likely sufficient but should be reviewed considering potentially different fire scenarios.
- Temporary building siting will likely become more constrained.
- Risk communication - the "comparable to other National Grid sites" finding would likely no longer hold unless further mitigation is added.

3.1.5.1 Priority Ranking - What to Model / Reassess First

Based on risk contribution + H_2 sensitivity, here's a practical priority list:

[redacted]

Tier 3 Less frequent contributors but important for escalation scenarios:

- PRV vents / reliefs
- CAB penetrations (model for explosion consequence, not leak source per se).
- Complex assemblies and jointed piping sections.

In the QRA update for a 20% H_2 blend, it is recommended:

- **Explicitly model small bore / instrumentation leaks**; these are often omitted in AGI Safe models but matter hugely for H2 ignition risk.
- **Review compressor CAB ventilation rates**; verify that air changes per hour are sufficient to prevent accumulation even with small leaks.
- **Explosion modelling inside CABs**: move to higher flame speed inputs for H2 blend scenarios. Many existing NG-only models will underestimate explosion risk here.

3.1.6 Key Differences at 5% H_2 Blend

If the hydrogen blend is reduced to 5%, rather than 20%, the impact on QRA results will be substantially less but still not negligible. Below is a breakdown of what changes and what remains relevant:

Parameter	5% H_2 Blend Impact	Comparison to 20% H2 Blend
Molecular weight	Slight decrease (16.2g/mol) vs NG (17g/mol)	Negligible impact on dispersion modelling
LFL	Drops slightly (4.2–4.3%)	Minor increase in dispersion distance
Flame speed	0.45-0.55 m/s (vs 0.35m/s for NG)	Significantly lower than 1.5–2.0 m/s for 20% H2
Ignition energy	Decreases modestly	Less ignition-sensitive than 20% blend
Jet fire energy	Slightly increased radiant heat	No special hydrogen jet model required
Explosion severity	Similar to NG for most volumes	Does not trigger high-speed flame front behaviour typical of 20%+ H2
Material compatibility issues	Very low likelihood	Minimal concern unless sensitive seals used

Table 11 5% & 20% H_2 Blend Comparison

3.1.6.1 QRA Inputs - Adjustments for 5% Blend

Input Parameter	Suggested Action at 5% H_2	Notes
Gas Properties	Use adjusted mol weight 16.2, LFL 4.3%	Minimal impact; update for completeness
Leak Frequencies	No change from standard NG values	5% H_2 has negligible impact on leak tendency
Ignition Probabilities (Internal)	Increase slightly (e.g. from 5% - 6-8%)	Conservative but not critical
Ignition Probabilities (External)	Remain as-is (1-5%)	Outdoor conditions dominate dispersion
Explosion Modelling (CAB)	Use NG-based parameters	No need to model high-speed hydrogen explosions
Jet Fire Modelling	Use standard NG model	No change needed
Societal Risk (F-N Curve)	Minor impact - similar to NG profile	Lower increase in risk than 20% blend case

Table 12 QRA Adjustment for 5% H_2 Blend

3.1.6.2 Quantitative Risk Change – Summary

Risk Area	20% H_2 Blend	5% H_2 Blend
Internal ignition risk (CABs)	x2 to x3 increase	Negligible to 10% increase
Explosion overpressure in CAB	Significantly higher	Comparable to NG
Thermal radiation distances	Longer jet fire range	No significant increase
FN curve shift	Noticeable rightward shift (higher fatalities)	Minimal shift - likely within ALARP range

Table 13 5% H_2 Blend Risk Summary

3.1.6.3 Summary: What to Change in QRA at 5% H_2

- Update gas properties in Phast/SAFETI to reflect 5% H2 blend
- Keep leak frequencies the same (no adjustment for H2 embrittlement/permeation)
- Consider small increase in ignition probability for enclosed volumes (e.g. compressor CABs 5% - 8%)
- Use standard NG explosion and jet models — do not apply H2 specific flame speeds or jet fire adjustments
- No significant impact on societal risk or control building exposure expected

3.1.6.4 Conclusion

At 5% hydrogen, the system consequence analysis behaves very similarly to pure natural gas and most of the H_2 related risk amplification seen at 20% does not apply.

This means the current QRA can remain largely valid with only minor updates to gas properties and the inclusion of a note on ignition sensitivity.

3.2 Kirriemuir Gas Compressor Enclosure CFD Hydrogen Gas Detection Study

For the new gas composition cases (5% & 20% Hydrogen blends), CFD analysis was completed to assess the impact this change would have on detecting a gas release within a gas compressor enclosure. The current system and equipment have not been specified for hydrogen blend duty, and it cannot be confirmed at this stage, that the new composition can be contained.

As a result, hydrogen is assumed to leak from seals and flanges, carrying methane with it, which could potentially lead to the buildup of a hazardous atmosphere within the turbine CAB enclosure.

The CFD study was carried out considering two separate cases. Case 1 considered the gas compressor & ventilation system running and case 2 considered the compressor shutdown and ventilation system not operational. In case 2 the worst case of no air movement within the CAB was considered.

3.2.1 CFD Case 1 – Compressor and Ventilation System Operational

The leakage rate for each of the CFD model runs is based on a 0.1mm equivalent hole at 30 flange locations in the area. It was assumed that the gas leaking would have the same composition as the gas present within the local piping system.

This area has been selected due to lack of congestion within the area to demonstrate the movement and separation of the gas composition.

The two gas types (as blended) have been plotted with the gas cloud at 10% LFL CH4 (***BLUE***) and H_2 (***RED***) for both cases 5% and 20% H_2

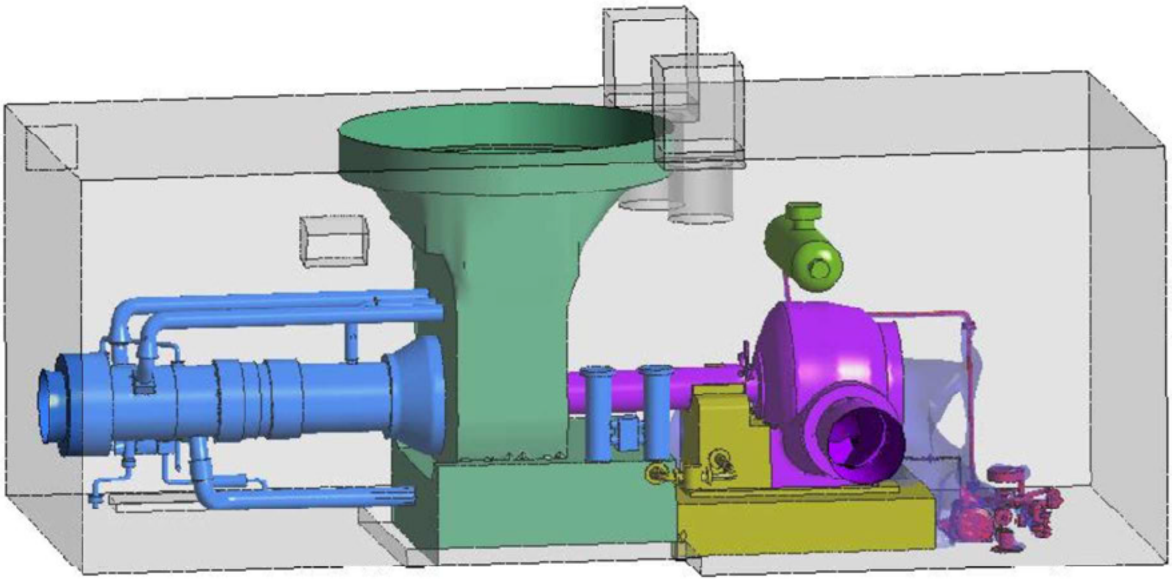

Figure 1 – CAB Unit with H_2 @**5%** and Ventilation System Operational (Whole Unit View)

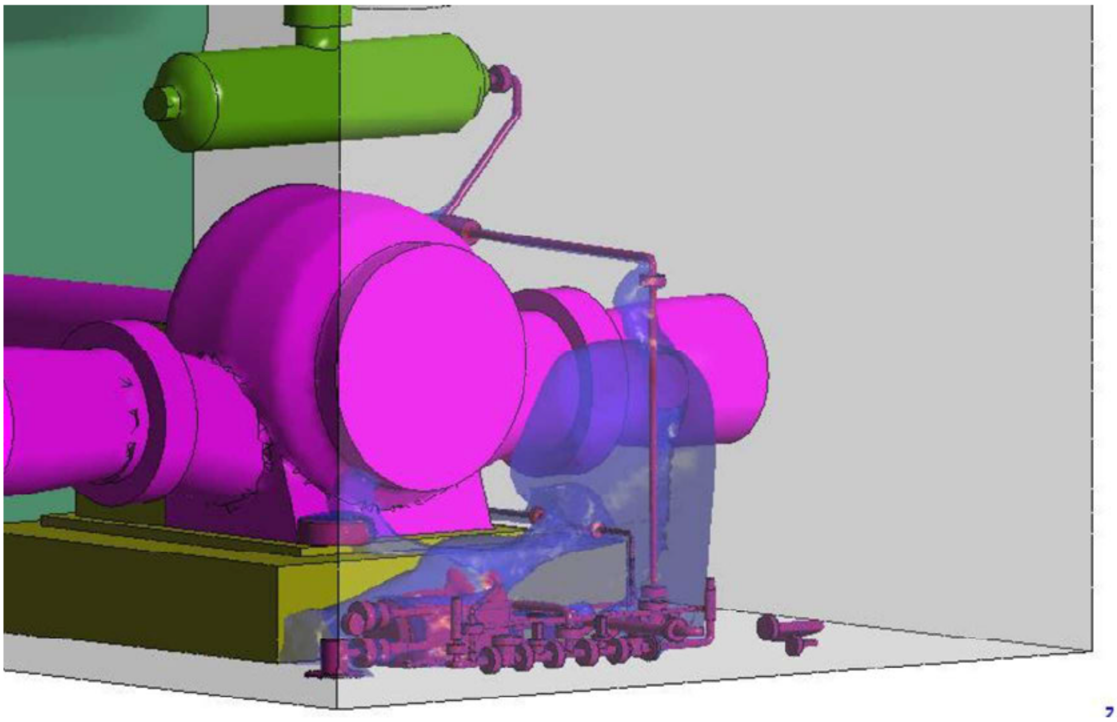

Figure 2 – CAB Unit with H_2 @**5%** and Ventilation System Operational (Local Area View)

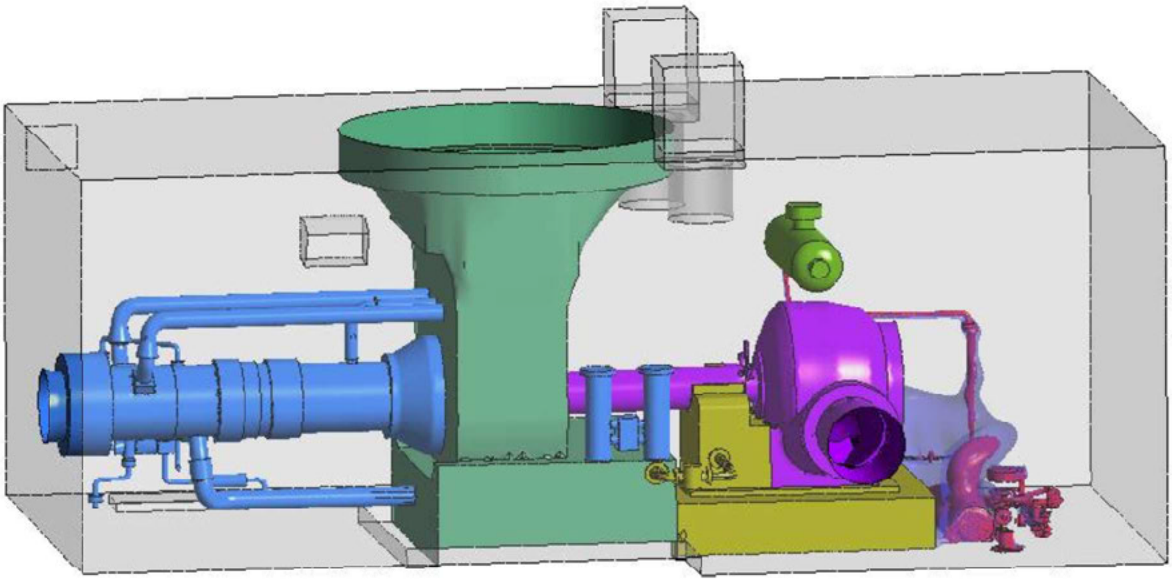

Figure 3 – CAB Unit with H_2 @**20%** and Ventilation System Operational (Whole Unit View)

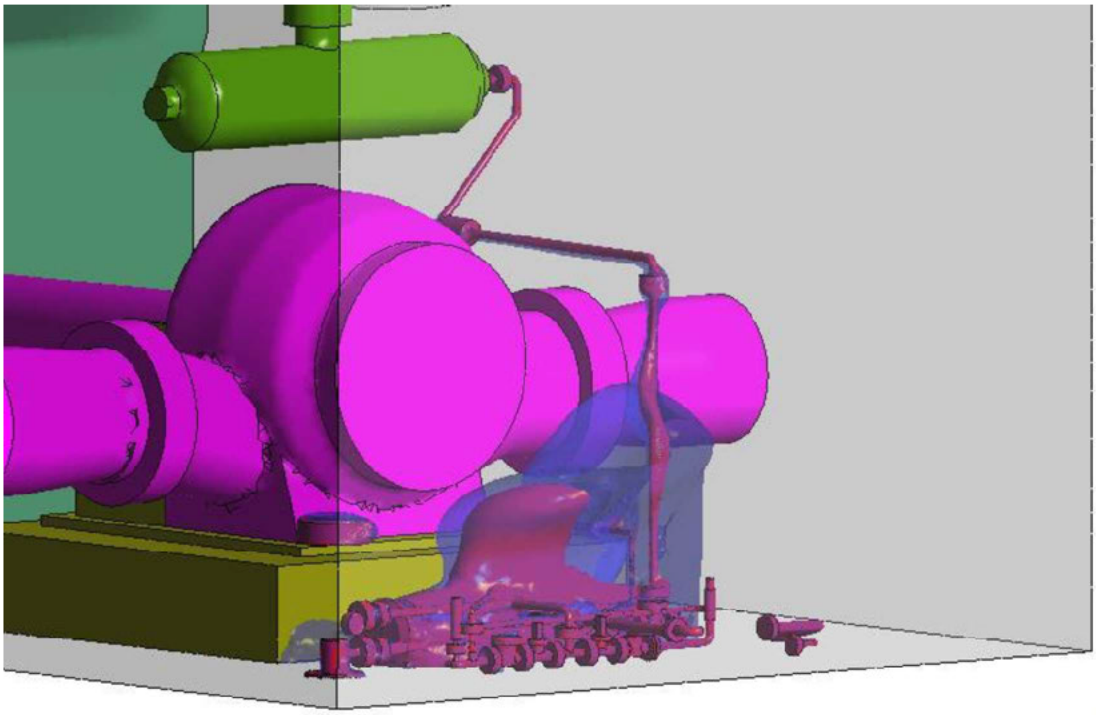

Figure 4 – CAB Unit with H_2 @**20%** and Ventilation System Operational (Local Area View)

The CFD results for both blends show;

- With the ventilation system operating, there is enough momentum in this area to prevent accumulation of gas at detectable concentrations. The released combined gas cloud is well "ventilated" and disperses quickly.
- There is not enough residence time for the H_2 to separate from the CH_4, hence in this instance, the methane will be always detected first.

3.2.2 CFD Case 2 – Compressor and Ventilation System Not Operational

In this CFD model scenario, the same area and release volumes are considered. Again, the two gas types forming the blend have been plotted with the gas cloud at 10% LFL CH4 (***BLUE***) and H_2 (***RED***), in this model only 20% H_2 has been plotted.

The CFD plots show the concentration of each of the 2 gas types at 10% LFL. In all instances, the volume of hydrogen within the blend affects the concentration at LFL.

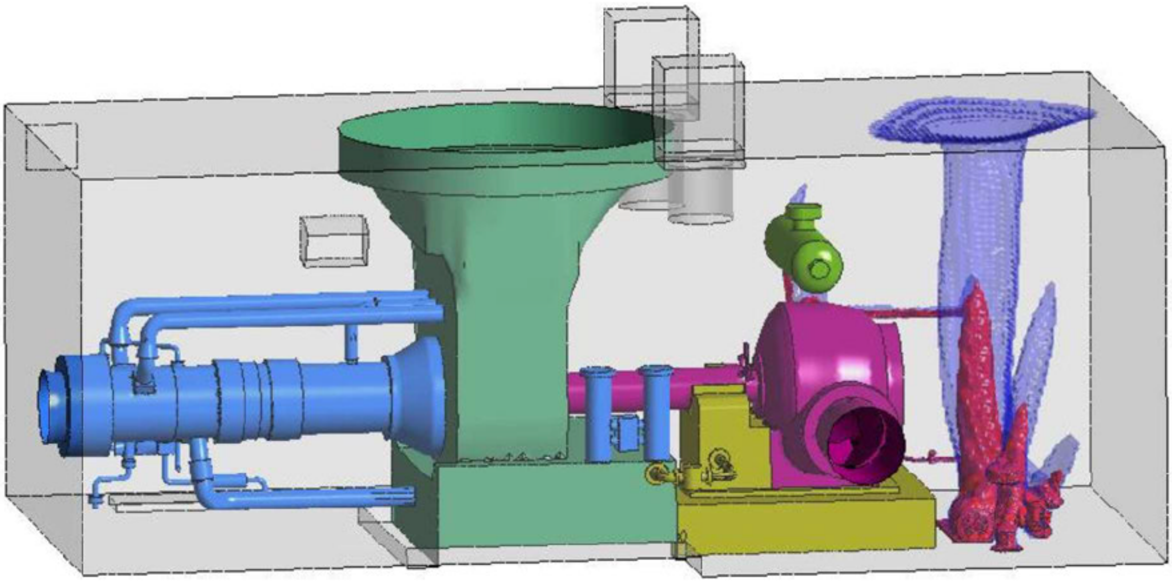

Figure 5 – CAB Unit with H_2 @**20%** and Ventilation System Not Operational – Release time **60 Seconds**

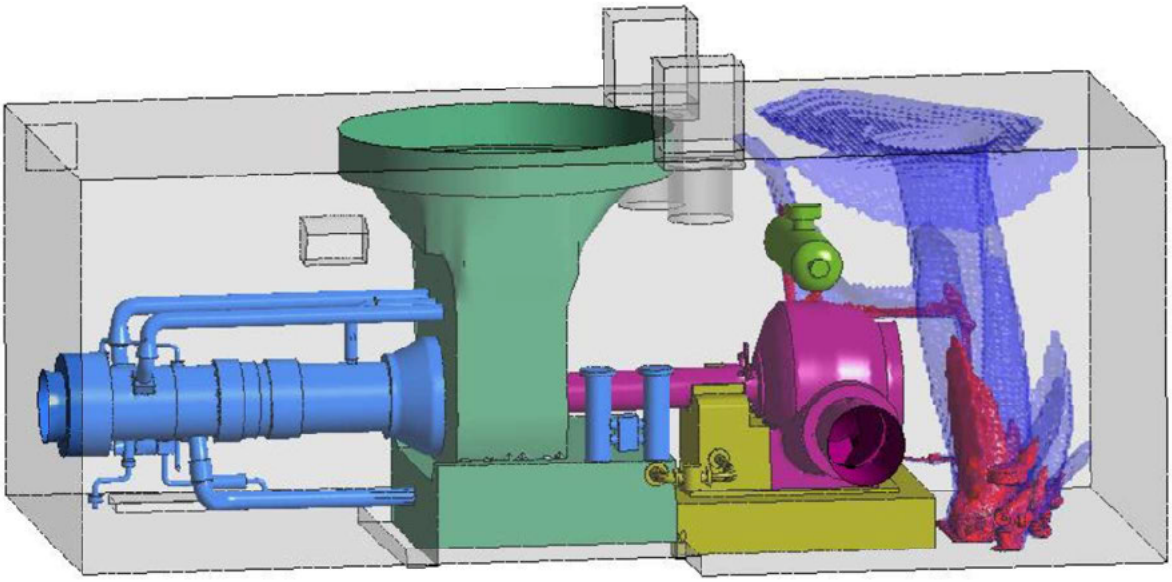

Figure 6 – CAB Unit with H_2 @**20%** and Ventilation System Not Operational – Release time **120 Seconds**

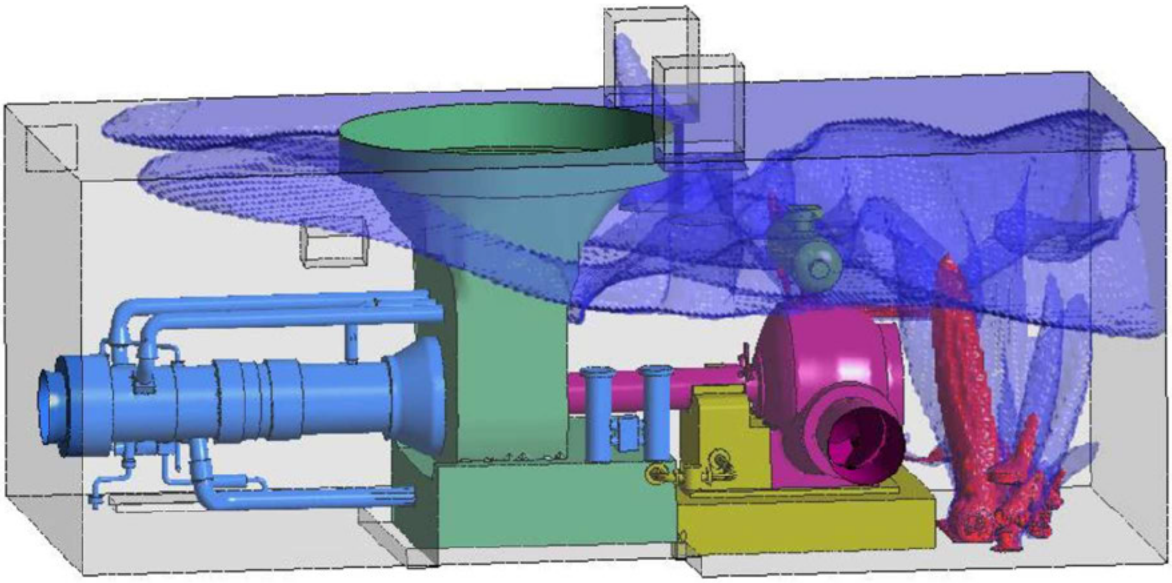

Figure 7 – CAB Unit with H_2 @**20%** and Ventilation System Not Operational – Release time **300 Seconds**

The results show that it does not take long for significant quantities of gas to accumulate in dangerous quantities within the CAB Unit. They also showed that the gas segregation is slower than expected, there was not enough time for the volume of H_2 to separate from the CH_4 in sufficient quantities to spread further and to be detected by area F&G detection. It means that the CH_4 will be always detected first and no pocket of isolated H_2 could be seen, for the time scale simulated.

The reasons for the lack of separation in this instance is due to a number of factors;

- **Jet momentum - buoyancy (early phase).** Leak jets can be ~10-100 m/s at the orifice; the characteristic buoyant rise speed for a light-gas plume in an enclosure is on the order of ~0.1-0.5 m/s. In the first minutes, turbulent entrainment from momentum dominates, so both streams are carried and mixed together before buoyancy can stratify them.
- **Both gases are lighter than air.** CH_4 (MW≈16) and a CH_4/H_2 blend (e.g., 80/20 - MW≈13.2) are both buoyant vs air (MW≈29). Stratification mainly occurs relative to air, not cleanly between two already-light gases. The density contrast between CH_4 and H_2 is small compared to their contrast with air, so you don't get a neat "H_2 layer" separating on minute timescales.
- **Segregation is slow; mixing is fast.** Molecular diffusion that would separate H_2 from CH_4 has a timescale of $t \sim L^2/D$. With $L10^{-5}$–10^{-4} m^2/s, this occurs over hours, not seconds-minutes. Meanwhile, turbulent mixing inside the CAB with recirculation, happens in seconds.

If the leakage were to occur by selective permeation through a seal that has not been qualified for hydrogen service, the effluent at the seal will be Hydrogen-enriched (potentially near-pure H_2), even when the process gas is a H_2/CH_4 blend. This is a diffusion-limited micro-seep, so the mass flow is very low (typically orders of magnitude below a mechanical leak/jet). It does not imply bulk separation of the room atmosphere.

The current CAB unit detection would also suffer "Detection bias". If the gas detection uses IR hydrocarbon channels, they will "see" CH_4 but not H_2. So, in a mixed plume, the CH_4 part will alarm first even when H_2 is present.

3.3 Gas Detectors For Detection of Hydrogen Gas

3.3.1 IR Gas Detection

The new IR gas detectors that will be installed within the CAB enclosures under the Kirriemuir F&G Upgrade will be IR point gas detectors. These types of devices are unable to detect hydrogen as IR detectors work on the principal of measuring the gas that passes through the IR source and how the IR source has been absorbed by the gas molecules.

Hydrogen gas has no IR absorption signature and as such IR detection cannot detect a Hydrogen gas release.

Industry best practices are to use catalytic point gas detectors for detection of Hydrogen. These measure the heat generated when flammable gas burns on a heated bead, producing a signal proportional to the gas concentration as a percentage of its LEL.

3.4 Gas CAB – Hydrogen Detection and CFD Study Findings

3.4.1 Enclosure Ventilation System Operating

With the gas compressor ventilation system running, the airflow within the CAB prevents a hazardous atmosphere from forming with the gas seals leaking. Therefore, the proposed new gas detection system being installed within the CAB i.e. IR point gas detectors calibrated for Methane under the Kirriemuir F&G Upgrade is still appropriate as Methane will still be the larger fraction of the leaked gas.

3.4.2 Enclosure Ventilation System Not Operating

When the ventilation system is not operating, the CFD study indicates that it takes approximately five minutes for hydrogen concentration in the CAB to reach 20% LEL, the highest hydrogen alarm setpoint recommended by the HSE.

The study also indicated that methane will be present in greater quantities and will be detected first, triggering alarms before hydrogen. Therefore, the proposed new gas detection system being installed within the CAB enclosure i.e., IR point gas detectors calibrated for methane under the Kirriemuir F&G Upgrade remains appropriate, as Methane will still be the larger fraction of the leaked gas.

However, given that hydrogen will also be present within the CAB, and that the CFD modelling considers only specific scenarios, and with hydrogens highly explosive properties with flammable limits of 4% -75% and being by volume air and much more sensitive to ignition it is recommended as a safeguard and to account for any potential future changes in gas composition at the Kirriemuir plant that a hydrogen aspirated gas detection system should also be installed.

As stated previously - in all instances and blend compositions, if hydrogen is introduced to a system that has not been designed for hydrogen service, it will, in all likelihood, escape from that system. For the lower blends (1% – 10%), the consequence effects and characteristics of methane will dominate, and it could be considered that existing F&G detection may be adequate. However, this does not consider areas where low pressure seepage may accumulate to concentrations that pose additional risk.

Beyond this blend ratio (10%+), the consequence effects of hydrogen will have a direct impact on all mitigation and control systems, and existing detection cannot be relied on to respond to loss of containment events.

In most high-pressure outdoor leaks, the methane in the blend will still trigger the IR heads quickly. However, in enclosed or low ventilation areas, H_2 pockets can accumulate at high level without enough methane to alarm IR instruments.

It is recommended that if a hydrogen blend is introduced, a method of detecting all releases (no matter the size) should be employed.

In this arrangement:

- The aspiration unit would be located outside the enclosure, with the gas detector housed inside it.
- Sample tubing is routed into the CAB, positioned near credible leak sources and at ceiling height, to detect hydrogen accumulation when the ventilation system is switched off.
- Having the hydrogen gas detector in this set up and not within the CAB itself protects the catalytic detector's sinter disk (flame arrestor) from blockage such like in CABs if oil or dirt gets attached to it, which prevents gas from entering the sensor bead and is also considered an unrevealed fault under IEC 61508 / IEC 60079.
- The aspiration system will include a low-flow alarm that signals back to the F&G system, ensuring any malfunction is detected.

3.4.3 Hydrogen Gas Detector Set Points

Given the Kirriemuir gas mixture of 20% H_2 and 80% CH_4, the hydrogen detector setpoint should be configured at 10% LEL (H_2) for alarm-only purposes. Alarm only recommendation is due to the gas compressor would not be operating, and NGT would implement appropriate measures to safely vent the gas atmosphere within the CAB on hydrogen gas alarm.

Figure 8 – Typical Aspiration System

4.0 Bacton Gas Terminal – Engineering Discussion

4.1 Hazard Identification & Assessment

4.1.1 Basis of Assessment

This section reviews the potential impacts of changing the process fluid at the Bacton Gas Terminal from natural gas to a natural gas/hydrogen blend consisting of 80% methane and 20% hydrogen by volume.

As discussed in previous sections of this report, a 5% hydrogen blend has negligible impact on the consequence behaviours of the released gas stream. Therefore, the assessment for Bacton Gas Terminal will focus primarily on the 20% blend case.

The assessment is based on the Bacton Gas Terminal QRA 2023 Update (Report No.10388091-4, Rev 1), with natural gas as the baseline case. The focus is on safety and risk implications, with emphasis on consequence behaviour, ignition, and Fire & Gas detection performance.

4.1.2 Baseline Assumptions in the 2023 QRA

The 2023 QRA considered 28 scenarios spanning inlets, feeders, GYPL, BBL, vents, PRU6/7 and diesel.

Consequence modelling was undertaken using DNV FROST with CORCE outflow and hazard types considered included;

- Jet-fire radiation,
- Flash-fire,
- Explosion/Overpressure.

Flash-fire limits were defined in terms of the lower flammable limit (LFL) and half LFL footprints. Explosion modelling was limited, as the site was considered largely open plant with few congested areas capable of producing vapour cloud explosions.

The maximum hazard distances reported for major releases were on the order of 736-964m for LFL, 1184-1502m for half LFL, and jet-fire radiation distances between approximately 498-870m for 1% lethality and 516-812m for piloted ignition.

4.1.3 Properties of the 80/20 Natural Gas–Hydrogen Blend

As discussed in the previous sections of this report, the introduction of 20% hydrogen into natural gas changes the physical and flammable properties of the fuel.

The molecular weight is reduced, increasing buoyancy and sonic velocity. The lower flammable limit decreases slightly to around 4.7-4.8% by volume, while the upper flammable limit increases, widening the flammability range.

Minimum ignition energy (MIE) is reduced, and laminar flame speed increases, both of which make immediate ignition more likely. Jet-fires become less sooty, with lower emissive power and shorter radiative hazard ranges.

Dispersion characteristics are altered, with stronger buoyancy reducing ground-level flammable clouds outdoors.

4.2 Consequence Impacts

4.2.1 Consequence Analysis

4.2.1.1 Jet/Flash-fire

Radiation distances are expected to reduce by approximately 5%-10% (typical) and up to 15% in favourable cases, compared to the baseline. This is due to lower mass flow at fixed volumetric control and lower flame radiative fraction for H_2 rich flames.

Flash-fire and jet-fire consequences: Adding 20% H_2 reduces molecular weight and increases buoyancy, so ground-level gas clouds are smaller. Jet flames are also less radiant. Both effects reduce the distances to flash-fire and thermal lethality. These reductions mainly benefit long-range consequences that drive offsite individual risk contours and societal risk in the F-N curve.

Flash-fire distances defined by LFL and half LFL footprints are expected to reduce by approx. 5%-20% outdoors. Explosion potential on open plant remains broadly unchanged, as congestion assumptions are not affected. However, in confined or congested pockets such as PRU kiosks or feeder enclosures, the increased reactivity of the blend could produce higher overpressures than reported in the baseline.

4.2.1.2 Explosions/Overpressure

Explosion potential does rise in confined spaces, but the site is mostly open plant. Only a few scenarios (PRU kiosks and small congested feeder areas) are sensitive to this, and their contribution to total PLL is limited compared with the major pipeline rupture cases.

Hydrogens higher reactivity lowers the MIE and widens the flammable range. Ignition probability is expected to shift, with a higher likelihood of immediate ignition outdoors, while delayed ignition outdoors is less likely. Within enclosures, however, the buoyant hydrogen fraction may accumulate near roofs, increasing the likelihood of delayed ignition within confined volumes.

4.2.1.3 Ignition probability

Hydrogen is easier to ignite, so the proportion of immediate ignitions increases slightly. This means fewer delayed-ignition scenarios develop, but more jet-fires occur close to the source. While this slightly raises the probability of local fires, these events already dominate the baseline QRA and tend to affect onsite rather than offsite risk.

The reduction in long-range flash-fire lethality distances pulls the societal risk curve downwards because fewer people can be affected offsite. The increase in ignition probability shifts some outcomes towards early jet-fires but does not add significant new risk drivers. Explosion severity in confined pockets is a localised issue but does not materially change site-level results.

When the two effects are considered together, the decrease in consequence range outweighs the small increase in ignition likelihood. The net effect is that the risk profile remains in the same regulatory band: "Tolerable if ALARP." Compliance conclusions therefore remain unchanged, but additional ALARP demonstrations such as upgrades to Fire and Gas detection are still recommended.

4.2.1.4 Ignition Probability Adjustment Basis for QRA modelling

- Hydrogen MIE ~0.02mJ (approx.1/15 of methane); blends reduce MIE and increase laminar flame speed.
- Immediate ignition (II): apply multiplier x1.1 (5% H_2) and x1.2 (20% H_2).
- Delayed ignition (DI)(indoors): apply multiplier x0.9–1.0; Indoors x1.1 (use engineering judgement per geometry and ventilation).
- Indoors/Confined: consider +1 ME class at 20% H_2, subject to geometry.
- Outdoors: retain baseline 'no VCE' assumption; higher lofting reduces ground-level cloud persistence.

4.2.2 Risk Implications

For open plant areas, reduced jet-fire and flash-fire hazard distances should reduce the contribution to individual and societal risk, leading to a modest overall reduction in site risk levels.

For enclosed or congested areas, particularly PRU kiosks and small congested feeder regions where vapour cloud explosions were previously identified, the increased reactivity of the hydrogen blend may increase localised risk.

The overall societal risk profile is therefore expected to decrease modestly, with specific confined region scenarios requiring closer attention to ensure risks remain ALARP.

- Individual Risk (IR): Competing effects - slightly shorter fire footprints vs modestly higher ignition fractions provide a net IR direction of stable to slight reduction; dominant contributors (inlet ruptures) for individual risk remain unchanged.
- Societal Risk (F-N): Expected to remain within 'Tolerable if ALARP'region. Reduced long-range flash-fire lethality offsets a small increase in ignition probability. No plausible change to compliance conclusions.

4.3 Fire and Gas Detection System Impacts

4.3.1 Gas Detection

Gas detection systems currently designed around infrared methane detection will under-report hazard levels because hydrogen does not absorb in the infrared band. While the methane fraction of the mixture will still be detected, the hydrogen contribution will be missed.

To address this, dual-technology detectors are required. Infrared methane detectors should be retained, with catalytic bead, thermal conductivity, or electrochemical hydrogen detectors added to provide hydrogen coverage.

Detection setpoints should continue to be based on percent lower flammable limit of the mixture. (e.g., AL1 10%LEL, AL2 20%LEL inside; outdoors AL1 20%LEL, AL2 40%LEL). If instruments are methane-calibrated, apply vendor compensation for blends or change sensors. Placement of detectors should emphasise roof or high-level locations where buoyant hydrogen is likely to accumulate.

4.3.2 Flame detection

Flame detection also needs to be re-assessed. Hydrogen flames emit weakly in the infrared and strongly in the UV spectrum. Standard triple-IR detectors may be slow or insensitive for hydrogen flames. UV or UV/IR flame detectors with hydrogen sensitivity could be deployed in areas where high-pressure hydrogen releases are credible.

UV detectors are less commonly used in UK O&G and therefore lack a history of proven in use in this type of plant operation.

4.3.2.1 Flame Characteristics

Methane flames:

- Sooty, (Methane is a low-soot fuel not a no-soot fuel. In a pre-mixed context, it is essentially soot free as there is limited pyrolysis. In turbulent diffusion flames some soot can form - in Jet fire release scenarios, the inner flame zones are fuel rich at very high temperature and residence times causing methane molecules to crack - soot formation increases with pressure and residence time)
- emit strongly in IR.
- Standard triple-IR detectors respond well.

Hydrogen flames:

- Nearly invisible to IR because of low emissivity.
- they emit mostly in the UV.

In an 80/20 blend, for most leaks or ruptures, the visible flame would not be "pure H_2." The 80% CH_4 content ensures IR radiation is still dominant. Only in very small releases, or where H_2 preferentially leaks/escapes from a separation or membrane, might you get a more hydrogen-rich jet with reduced IR content.

4.3.2.2 Practical likelihood of "hydrogen-only" flames

In the Bacton Gas Terminal case, with a uniform blend in bulk pipelines and PRU skids, the escaping mixture will remain close to 80/20. That means the jet flame will still have a strong IR component and will be detectable by IR3 detectors.

"Hydrogen-only" flames would be rare, mostly if there was a small breakout from an enclosure where hydrogen could stratify and then ignite with little methane present. Even then, the flame might transition quickly into burning the blended stream.

4.3.2.3 Benefit of UV detection

Where it helps: In confined volumes or enclosures where H_2 could accumulate aloft, displacing methane. A delayed ignition in this type of pocket could yield a flame with much lower IR output. UV detection offers a safeguard in these niches.

Where it adds little: Open-plant jet-fires. With 80% methane, the flame signature remains IR-rich and IR detectors will function normally. Installing UV across the whole plant would add cost and spurious-trip risk (UV is sensitive to welding arcs, sunlight reflections, etc.) without clear justification.

4.3.2.4 Detector Placement

Airflow governs detectability more than buoyancy alone. In buildings with high roofs, heat sources and summer solar loading can create thermal stratification layers that trap warm, clean air aloft and keep a lighter-than-air leak from ever reaching roof-mounted heads. We need to treat "detectors at roof height" as one layer of coverage, not the only layer. In practice that means placing additional heads at intermediate elevations and near credible leak sources (valve manifolds, PRU internals, analyser panels), and validating coverage with on-site airflow checks rather than relying on generic buoyancy assumptions.

For detector mapping and placement, it must be assumed that ignition can precede detection. It is important to state explicitly that installing point detectors in a room does not guarantee detection before the gas reaches an ignition source. This is not a defect of the system but a limitation of physics and airflow; it underscores the need for elimination of sources, zoning compliance, ventilation management, and realistic expectations in the ERP.

4.3.3 Detector Summary

For the 80/20 blend, IR point detectors remain the backbone for hydrocarbon gas because the flame and gas signatures are still methane dominant. A modern IR head with a typical T90 around one second will generally outpace catalytic bead heads whose response slows with aging, contamination, and low flow. Retaining IR in HVAC ducts is not recommended as a primary strategy; flow is variable, transit times are long, and catalytic detectors in ducts are especially poor performers. If there is a need to monitor ventilation ducts, use purpose-built duct sampling cells with IR optics and a flow assist, and treat them as a secondary layer to room coverage rather than a substitute.

Hydrogen is invisible to IR gas detectors, so IR alone will under-read a hydrogen-rich cloud. In an 80/20 release you still get strong IR response from the methane fraction, which makes IR a good first-line technology in open plant and general rooms. Where stratification or enclosure geometry could create hydrogen-biased pockets (PRU kiosks, roof voids, analyser shelters), addition of hydrogen-capable technology (thermal-conductivity or electrochemical) at high-risk positions should be considered. Keeping catalytic bead to a minimum because of poisoning risk and slower response; if used for H_2 resilience, we need to specify poison-resistant elements and tighter bump-test intervals.

Detector height alone cannot be relied on. Confirmation of actual airflow with quick, low-disruption trials: smoke-stick visualisation, handheld anemometer transects, or a safe tracer puff (helium) at credible leak elevations to confirm whether plumes rise, stall, or recirculate. This would be used to learn where to adjust mounting heights and to justify any mid-height arrays that break through stratified layers.

Consideration could be given to adding ultrasonic gas leak detection in noisy, high-pressure areas. UGLDs are indifferent to wind and stratification and will alarm on the acoustic signature of a pressurised gas jet, whether it ignites or disperses. They do not replace LEL detection but materially reduce the risk that a fast jet escapes detection due to poor plume transport to a point head.

Calibration and alarming should be set on percent LEL of the mixture, but ensure the instrumentation genuinely measures both components or apply a documented correction factor. Many IR heads report %LEL as "methane equivalent"; in blend service, we need to either configure the instrument's gas library for the mixture or document a conservative conversion so the displayed %LEL corresponds to the mixture LFL used in the QRA. First-stage alarms need to kept fast (for example one-out-of-N) and trips robust (for example two-out-of-N), so we do not pay for speed with spurious shutdowns.

Airflow patterns within enclosed spaces can prevent gas from reaching detectors before it encounters ignition sources, particularly under thermally stratified conditions. Gas detection is therefore a mitigative layer and not a guarantee of pre-ignition warning. Ventilation management, ignition source control, and correct zoning remain essential.

Bottom line is that IR is still the primary flame and gas technology for an 80/20 blend in open and general indoor areas because the signal is methane-led and response is rapid. UV or UV/IR flame detection and H_2-capable gas sensors are targeted tools for specific enclosed or roof-void locations where hydrogen pockets can form. This keeps the system fast, resilient, and ALARP without over-engineering.

4.3.3.1 Detector Voting Logic

Alarm voting logic should be updated to ensure hydrogen-capable detectors are incorporated while still guarding against false trips.

Voting & actions: enclosed spaces - move to 1ooN gas-trip for H_2 or 2ooN with time filtering; outdoors retain 2oo3 or 2ooN voting. Cross-zone logic to avoid single-point false trips; link to ESD and HVAC shutdown

4.3.3.2 Detection Mapping (Current vs Proposed)

Area	**Baseline (typical)**	**Proposed for H_2 blends**
Process corridors / inlets / feeders	Open-path IR HC across corridors; point IR near valves	Retain HC IR; add H_2 point detectors high under any canopy/eaves; AL1 20%LEL, AL2 40%LEL (blend-scale).
Control building / offices / MCCs	Limited HC detection; HVAC not interlocked	Add H_2 point detectors at high level in vestibules, plant rooms, cable basements; interlock HVAC on AL1; 1ooN for H_2 trip in small rooms.

PRU6/PRU7 skids	Local HC point detection	Add H_2 point detection above piping; verify outdoor coverage; consider local ESD on 2ooN with time filter.
Pig-trap areas / shelters	HC point only near ground	Add H_2 point detection at high level (gantries, roofs); cross-zone with HC IR; review ventilation.
HVAC intakes & rooflines	Not instrumented for gas	Add H_2 point at intakes/roof parapets; trip/recirc on AL1; shutdown on AL2.

Table 14 Detection Mapping (Current V Proposed)

4.4 Muster Areas & Escalation

What drives muster area impairment in the baseline (100%NG) is Jet-fire thermal radiation from high-pressure NG releases (inlet/feeder ruptures and certain pig-trap scenarios). These set the limiting heat-flux exceedances at the existing muster points; flash-fire and open-plant VCE are secondary for muster impairment.

Day-to-day muster suitability is typically checked against relatively low thermal flux (e.g., ~1.5-2 $kW \cdot m^{-2}$) for survivable egress/sheltering, while emergency planning overlays consider higher contours (e.g., ~6-12.5 $kW \cdot m^{-2}$ bands) and "1% lethality" as outer anchors. In the baseline, one or both muster points sit near the edge of the relevant radiation contours from a small set of high-energy jet scenarios; that's why the conclusion is "marginally above criterion."

How 5–20% H_2 changes from the baseline;

- Jet-fire radiation distances (primary for muster):
  - Heat release rate: With H_2 in the blend, mixture MW and density drop. For otherwise unchanged operating envelopes, the mass discharge rate and flame radiative output per unit jet length tend to decrease slightly.
  - Radiative fraction: H_2 richer flames have lower soot, lower radiative fraction, and shorter radiation contours at a given HRR.
  - Screening effect: Expect ~0-5% shorter 1% lethality and piloted-ignition distances at 5% H_2, and ~5-10% shorter at 20% H_2.
  - Implication for muster: If a muster point is only just inside a baseline radiation contour, a 5–10% shrink might move it just outside for individual scenarios, but the frequency of exceedance won't necessarily fall below the category threshold because of ignition behaviour.
- Ignition behaviour (affects event frequencies):
  - Immediate ignition increases: H_2 lowers MIE and widens the flammability range. Immediate

Ignition (II) probability increases (screening multipliers: ×1.1 at 5% H_2; ×1.2 at 20% H_2). Delayed ignition (DI) also slightly increases (×1.05 / ×1.1).

- Competing effects: More II means more jet-fires (which drive thermal impairment) and fewer large unignited clouds (which would drive flash-fire). For muster, that offsets some of the benefit from shorter radiation distances. Net effect on thermal-impairment frequency is therefore roughly unchanged to perhaps a slight decrease; usually not enough to flip a "marginal fail" to "pass."

- Dispersion and gas ingress (secondary for muster):
  - Ground-level clouds: Greater buoyancy with H_2 provides smaller ground-hugging LFL/½LFL footprints near musters at grade. That reduces the probability of low-level gas envelope impinging directly on open-air musters.
  - Lofting and recirculation: Conversely, more lofting raises the risk of high-level gas around eaves, canopies and HVAC intakes. That mainly affects shelter-in-place spaces and enclosed muster shelters (gas ingress risk), not open-air musters.
  - Operationally: You gain a little margin against outdoor half LFL criteria at the muster points, but controls must be tightened on HVAC isolation/recirc for any indoor refuge or control building that supports mustering.
- Explosion loads at muster:
  - Open-plant VCE remains not-credible in most areas. Where congestion is local (e.g., pig-trap shelters), a +10-25% uplift in deflagration contours near the source could be justified, but those zones don't normally set muster impairment at the established muster locations. So, explosion risk at muster locations is unchanged in practice.

H_2 blending pushes physics in helpful ways for open-air gas at ground level and jet-fire radiation distances, but the slight rise in immediate ignition and the small magnitude of the radiation shrink together mean the muster area verdict doesn't change.

4.5 Bacton Gas Terminal Assessment Recommendations

The QRA model should be updated with the 80/20 blend composition and recalculated for key representative scenarios. Ignition probability splits should be modified to reflect a higher likelihood of immediate ignition (see below for breakdown of QRA updates required).

Explosion models for PRU kiosks and congested feeders should be re-run with increased reactivity parameters.

Fire and Gas detection systems should be upgraded to incorporate hydrogen-capable gas detectors and consideration should be given to flame detectors with UV sensitivity.

Ventilation adequacy and hazardous area classification should also be re-validated for enclosures. Finally, updated societal risk calculations should be performed to confirm that risks remain within the tolerable if ALARP range.

Maintain action to relocate or create alternative muster points and reinforce ERP for evacuation vs shelter-in-place triggers.

Re-casing the QRA for an 80/20 CH_4-H_2 Blend

The update the Bacton QRA from the natural-gas baseline to an 80% methane / 20% hydrogen blend should be undertaken with the following considerations.

The objective is to maintain full comparability with the 2023 report while only capturing fuel-driven changes. Meteorology, isolation times, leak size taxonomy, geometry and frequencies remain unchanged.

Fuel and modelling setup

Define a new material with 80% methane and 20% hydrogen by volume, updating the molecular weight and flammability data accordingly. The same meteorology, isolation times, and leak size categories should be retained as the baseline. Continue to use LFL and half LFL as the basis for flash-fire distances.

Scenarios to re-run

Re-run scenarios 1, 3, 5, 7, 9, 11, 13, 18, 21 and 23 to span the site. For each, output LFL and half LFL distances, piloted-ignition and 1% lethality radiation distances, and 40mbar and 200mbar overpressure radii where applicable.

Consequence model adjustments

Dispersion and flash-fire modelling should be repeated with the revised fuel properties. Jet-fire calculations should reflect hydrogen's lower emissive power, yielding shorter radiation ranges. Explosion reactivity should be increased only for the confined pockets already recognised in the baseline model.

Ignition modelling adjustments

Increase the proportion of immediate ignition outcomes for high-pressure releases. Reduce delayed ignition outdoors due to faster dispersion of buoyant hydrogen, while maintaining or slightly increasing delayed ignition potential in enclosures.

Risk calculation and reporting

Re-run the risk engine with the updated consequence files and ignition splits. Export per-scenario PLL and the F-N curve. The expected outcome is a modest reduction in societal risk due to smaller outdoor footprints, with localised increases in confined areas. The overall risk profile should remain within the Tolerable if ALARP band.

5.0 Key points of note

5.1 Materials And Equipment May Not Be Suitable

Hydrogen can cause embrittlement and leaks in steels, seals, valves, and compressors that were only ever designed for methane. Old equipment may need replacement or upgrade before hydrogen can be introduced.

5.2 Hydrogen Is Harder To Contain And Detect

Hydrogen is the smallest molecule, so it leaks more easily through joints and seals. Standard methane detectors may not "see" it, so detection systems might need new sensors.

5.3 Hydrogen Ignites More Easily

Hydrogen needs far less energy to ignite than methane. Ignition sources that were not critical for methane may become credible with hydrogen.

5.4 Hydrogen Burns Differently To Methane

Hydrogen flames are almost invisible and give off less radiant heat but can burn very fast. This changes how fires are spotted and how people and equipment are exposed

5.5 Existing Site Safety Systems May Not Provide Enough Protection Against Hydrogen Service.

Shutdown, blowdown, fire and gas detection, and ventilation systems were designed for methane hazards. They may not provide adequate protection for hydrogen, so a full re-assessment of all safeguards is required.

6.0 Recommendation – Consequence V Detection

For both Kirriemuir and Bacton, adopting a 20% H_2 blend would require targeted engineering to confirm consequences, ignition splits, and Fire & Gas detection implications before committing to implementation. Consequence behaviour and explosion sensitivity in confined pockets, and the scope/placement of H_2 capable gas detection, all need more detailed modelling and layout review to produce a robust cost and schedule. It is not possible to provide a realistic cost that the management of this degree of change to the site would incur, without further detailed analysis.

Therefore, the Wood recommended approach for both cost and impact to site operation, would be to progress the low blend (<~10%) option though engineering design.

At low blends (<~10% H_2), consequence behaviour in open plant remains methane-like and does not, on its own, justify a plant-wide F&G upgrade. However, because IR gas detectors do not measure hydrogen, we recommend targeted H_2 capable detection in enclosed/roof-void/low-ventilation locations where H_2 can stratify; selection between point and aspirating H_2 detection is based on geometry and ventilation, not blend percentage. At these low blends, pure H_2 flames are not deemed credible and therefore H_2 specific flame detection would not be recommended.

The risk of low blend H_2 entering an enclosed space externally is not considered credible as low level concentrations would have been dispersed in open air.

Therefore, with both sites, the areas where low blend H_2 could potentially accumulate would be in areas that gas pipework passes into enclosed areas. This realistically only occurs in the CAB's and these would be the nominated areas for the introduction of aspirating systems.

In these areas, aspirating detection systems should be used. This provides a method of increasing the likelihood of detecting all releases of H_2. This may be entrained releases that are not at sufficient concentrations to alert current methane detection devices or low seepage leaks of pure H_2. Over time both cases may create sufficient concentrations of H_2 that would generate a harmful or hazardous scenario.

6.1 Costs associated with these recommendations

6.1.1 Kirriemuir Fire and Gas System Hydrogen Upgrade

Kirriemuir Fire and Gas System is currently under upgrade with system commissioning scheduled to complete in [redacted] Upgrade of the new [redacted] system to provide aspirated Hydrogen detection with Unit A and B CAB's and Unit E compressor building could be accomplished using available spare system capacity as the system has been Engineered to provide a minimum 20% wired spare I/O and field multicore cable capacity.

Introduction of Hydrogen detection would require modifications to existing Cause and Effect logic and SCADA and telemetry system modifications, supply of detectors and associated management activities.

Wood Consulting in-house estimating tool CSV-FOR-110031 has been used to provide an estimate for the provision of 3 aspirated Hydrogen detection systems (1 for each of the CAB's at Kirriemuir). The tool provides man-hour norms and allows input of Supplier quotation values and is used to generate work scope estimated costs.

The tool was populated with anticipated activities and deliverables to Engineer, Supply, Install and Commission aspirated Hydrogen detectors for Units A, B and E (3 total) and provided an indicative cost o[redacted]ncluding all G35 and safety management processes.

It should be noted that costs associated with access scaffolding within units A and B to provide access for installation of detection tubing are excluded. Recent experience at Kirriemuir suggest that this cost would form a significant proportion of the installation budget.

6.1.2 Bacton Fire and Gas System Hydrogen Upgrade

The existing Bacton Fire and Gas system uses Tyco/How MR3 modular fire detection system combined with Sieger 5700 modular gas detection racks which are fully populated with limited spare capacity. Both systems were developed in the late 1990s/early 2000s, and first Issue loop drawings dated 2005/2006 indicate that the system is at least 20 years old.

Whilst system components can still be obtained it is generally accepted that detection device lifespan is 10-15 years with control panels expected to be serviceable for 25 years the system is approaching the end of its serviceable life.

[redacted]

Given the age of the existing system, plant upgrade to enable introduction of Hydrogen blends is likely to require a full Fire and Gas system upgrade to modernise and align the system with the NG preferred asset Fire and Gas system solution. Provision of a cost for replacement of the existing system would include analysis of Hydrogen risk areas requiring deployment of additional Hydrogen detection technology.

Detailed cost analysis for this upgrade has not been considered given the extent of the likely modifications. However, as an indicative cost for system upgrade the Kirriemuir system hardware and Supplier Engineering costs were [redacted]ncluding all replacement field detection and system cabinets but excluding Wood Engineering, Procurement, Construction and Commissioning services.

6.1.3 Detector unit pricing

The recommended units for upgrade in the fire and gas systems to ensure H2 detection are Dräger aspirating gas detectors.

A representation of per/unit prices for H_2 detection components are as below (Point detectors are also included for reference):

Detector Unit Type	Cost per Unit (£)
[redacted]	[redacted]
[redacted]	[redacted]

Table 15 Dräger unit prices (VAT & Shipping costs are not included)

7.0 References

1. **DNV GL Fire Risk Assessment:** Fire Risk Assessment and Quantitative Risk Assessment of the Kirriemuir Compressor Station – Report No. 161605-4, Issue 1. July 2017
2. **DNV RP-G108**: "Hydrogen in Existing Natural Gas Networks", DNV Recommended Practice, 2022.
3. **EI15, 4th Edition**: "Area Classification for installations handling flammable fluids – Supplement for Hydrogen/Natural Gas blends", Energy Institute, 2023.
4. **HSE RR1121**: "Experimental studies of ignition of hydrogen / natural gas / air mixtures", Health and Safety Executive Research Report RR1121, 2018.
5. **EI19**: "Model code of safe practice Part 19: Fire precautions at petroleum refineries and bulk storage installations", Energy Institute, 2007.
6. **EU HySafe Network** (www.hysafe.org), various technical reports, 2010-2021.
7. Bacton Quantitative Risk Assessment (QRA) Update Report. Report No. 10388091-4, Rev 1. 14th September 2023.

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