NATIONAL GAS TRANSMISSION

NET ZERO SAFETY & IGNITION RISK

PROJECT SUMMARY REPORT

Document Number:	NGT-06-D35-00-10
Revision:	1
Date:	25th February 2026
Prepared by:	A. Phillips
Approved by:	W. Sequeira

REVISION HISTORY

REV	DATE	COMMENT	BY	CHECKD	APPRVD
1	25/02/2026	Approved for Issue	AP	SC	WS

CONTENTS

1 EXECUTIVE SUMMARY

The Net Zero Safety and Ignition Risk project was commissioned by National Gas Transmission (NGT) to establish a structured, evidence-based understanding of hydrogen ignition risks on the National Transmission System (NTS). Delivered under the Network Innovation Allowance (NIA) framework and carried out across four technical work packages, the project addresses one of the most significant safety challenges facing the UK's hydrogen transition: the need to understand, quantify and control the ignition hazards that hydrogen introduces relative to natural gas, before it can be safely transported at scale across the NTS.

Hydrogen's physical properties — including its low minimum ignition energy of 0.016 mJ, wide flammability range and high buoyancy — create an ignition risk profile that is meaningfully different from that of natural gas and cannot be managed simply by applying existing methane-based parameters. The project was designed to close this gap through a combination of comprehensive literature review, prioritised physical testing at transmission-relevant conditions and systematic safety and policy analysis.

The literature review conducted in Work Package 1 identified and ranked thirteen potential ignition mechanisms against credibility, severity and evidential confidence. Electrostatic discharge, hot surface ignition, hot work, delayed ignition and ventilation failure emerged as the highest-priority mechanisms, with composite risk scores justifying further investigation. Following a stage gate review with NGT, four scenarios were advanced to physical testing in Work Package 2: hot surface ignition, hot work ignition, ventilation failure and delayed ignition.

Testing was conducted at 80 bar — representative of NTS operating pressures — for both 100% hydrogen and 80/20 methane-hydrogen blends. The results established quantified, transmission-specific safety thresholds that did not previously exist. Hot surface ignition temperature for the 20% blend was determined at 642°C, validating a conservative 585°C operational limit. High-pressure release testing demonstrated ignitable envelopes extending up to 7 metres from the leak point for 100% hydrogen, with self-sustaining jet fire behaviour confirmed. Enclosure testing quantified time-to-LEL across a range of operationally relevant leak rates and volumes, with delayed ignition successfully demonstrated across all test configurations.

Work Package 3 translated these findings into comprehensive safety guidance, evaluatin[redacted]azard scenarios across pipelines, compressor stations, offtakes and above-ground installations. The assessment established a three-tier safeguard hierarchy, modified maintenance strategies fo[redacted] tasks, and developed LOPA sensitivity criteria for twelve key ignition scenarios. Critical changes include [redacted]

Work Package 4 reviewed the impact of these findings against existing UK statutory regulations and NGT corporate standards, confirming that no structural policy rewrite is required. The existing regulatory framework remains fundamentally sound, and the actions identified are refinement-based: validation of methane-derived modelling parameters, textual scope clarifications to encompass hydrogen, and the near-term issue of a Technical Basis Memorandum to govern hydrogen-specific assumptions in all future QRA and LOPA studies.

The overall conclusion of this project is that hydrogen ignition risk on the NTS is real but manageable. With the targeted controls, operational modifications and governance actions identified, the risk of hydrogen ignition can be reduced to tolerable and ALARP levels, providing a credible and defensible foundation for the safety case work underpinning NGT's broader hydrogen transition programme.

2 ABBREVIATIONS & ACRONYMS

Acronym	Meaning
AGI	Above Ground Installation
ALARP	As Low As Reasonably Practicable
ATEX	Atmospheres Explosive (Regulations)
BSI	British Standards Institution
CFD	Computational Fluid Dynamics
COMAH	Control of Major Accident Hazards Regulations
CRS	Composite Risk Score
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
EPDM	Ethylene Propylene Diene Monomer (elastomer)
ESD	Emergency Shut Down or Electrostatic Discharge
GSMR	Gas Safety Management Regulations
H_2	Hydrogen
HAIM	Hazardous Area Impact Mitigation
HSE	Health and Safety Executive
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LH_2	Liquid Hydrogen
LOPA	Layer of Protection Analysis
MAH	Major Accident Hazard
MAPD	Major Accident Prevention Document
MESG	Maximum Experimental Safe Gap
MIC	Minimum Igniting Current
NBR	Nitrile Butadiene Rubber
MIE	Minimum Ignition Energy
NTS	National Transmission System
NGT	National Gas Transmission
NIA	Network Innovation Allowance
NG	National Gas / Natural Gas

O_2	Oxygen
PPE	Personal Protective Equipment
PSR	Pipeline Safety Regulations 1996
PSSR	Pressure Systems Safety Regulations 2000
PTW	Permit to Work
QRA	Quantitative Risk Assessment
RR	Research Report (e.g., HSE RR615)
SGN	Scotia Gas Networks
SIL	Safety Integrity Level
SOL	Safe Operating Limits
UFL	Upper Flammability Limit
VCE	Vapour Cloud Explosion
DBB	Double-Block-and-Bleed
DDT	Deflagration-to-Detonation Transition
IPL	Independent Protection Layer
MAHP	Major Accident Hazard Pipeline
RRF	Risk Reduction Factor
TBM	Technical Basis Memorandum
WP	Work Package

3 BACKGROUND & CONTEXT

National Gas Transmission (NGT) owns and operates the UK's National Transmission System (NTS), spanning over 7,600 kilometres of high-pressure gas pipelines. As part of the UK Government's commitment to achieving Net Zero emissions by 2050, NGT has committed to developing plans to transition portions of the NTS from natural gas to blended hydrogen operation, and ultimately to 100% hydrogen. This transition represents a critical component of the UK's decarbonisation strategy, with Project Union serving as NGT's primary programme to spearhead the NTS conversion effort.

Hydrogen offers significant decarbonisation benefits for heat, industry and power generation; however, its physical and chemical properties differ significantly from those of natural gas and introduce new safety considerations that must be robustly understood and managed prior to widespread deployment. Among these, ignition risk has been identified as one of the most significant hazards due to hydrogen’s low minimum ignition energy, wide flammability range and high burning velocity.

The investigation of hydrogen ignition risk was therefore undertaken to provide National Gas with a structured and evidence-based understanding of the causes, sources, mechanisms and likelihoods of ignition that may arise during normal operations, maintenance activities and abnormal or loss-of-containment events on the NTS. Establishing this understanding is critical to ensuring that existing assets, operating procedures and protection systems remain suitable for hydrogen service, and to identifying where additional safeguards, mitigations or operational controls may be required to maintain risks at tolerable and ALARP levels.

This project directly supports NGT’s commitment to achieving Net Zero by 2050 and aligns with the objectives of the Network Innovation Allowance (NIA) framework, which seeks to fund research and development that facilitates energy system transition, delivers learning, and provides long-term benefits to consumers. In line with NIA requirements, the project has focused on developing new insight into hydrogen ignition behaviour in transmission-scale applications, addressing known gaps in industry evidence, and ensuring that learning can be disseminated to inform future safety cases, standards and policy development.

Within the broader decarbonisation programme, this work forms a key component of the safety assurance process required to enable hydrogen introduction onto the NTS. The outputs of the project contribute directly to Major Accident Hazard (MAH) assessments by informing both consequence and likelihood analyses for hydrogen-related hazardous events, including jet fires, flash fires and delayed ignition scenarios. The findings also support quantified risk assessment (QRA), Layers of Protection Analysis (LOPA) and policy reviews, providing a consistent technical basis for decision-making across engineering, operational and regulatory functions.

Overall, the project sits at the interface between innovation and safety case development, ensuring that the transition to hydrogen is underpinned by credible evidence, proportionate risk management and alignment with regulatory expectations. The detailed technical analyses are documented within the full technical report, while this summary highlights the context and strategic relevance of the work.

4 WORK PACKAGE OVERVIEW

This section presents the key findings and technical outcomes of the project, drawing together the evidence and insights generated across Work Packages 1 to 4 and summarises the current understanding of hydrogen and hydrogen-blend ignition risks within National Gas Transmission operations. It highlights how ignition sources, mechanisms, likelihoods and consequences differ from those associated with natural gas and reflects the extensive literature review, scenario assessments, and field testing that were designed to address critical gaps in knowledge related to hydrogen behaviour, operational hazards and risk escalation.

The results presented also inform the development of updated risk matrices, sensitivity criteria for ignition types, and the evaluation of safeguards and mitigations needed to reduce future ignition risks to ALARP levels. The findings underpin recommended updates to maintenance strategies, operational procedures and policy frameworks required to support safe hydrogen integration into the National Transmission System.

4.1 WORK PACKAGE 1 – LITERATURE REVIEW

Work Package 1 (WP1) provides the foundational understanding of ignition risks associated with transporting hydrogen and hydrogen–natural gas blends within the National Transmission System (NTS).

The review focused on identifying credible ignition sources, understanding associated mechanisms, assessing their likelihood in operational contexts, and determining whether the evidence base is sufficient or whether further physical testing is necessary in Work Package 2 (WP2). The outcomes from WP1 directly inform WP5 by defining the ignition scenarios most relevant to hydrogen conversion and the residual uncertainties that require validation before determining mitigations and overall system safety position vs hydrogen deployment.

4.1.1 IDENTIFIED IGNITION SOURCES, MECHANISMS, AND LIKELIHOODS

WP1 identified a diverse range of potential ignition mechanisms, each assessed for credibility, frequency, severity, and confidence in supporting evidence. The assessment recognised hydrogen's unique physical properties—particularly its low minimum ignition energy, wide flammability range, and high diffusivity—as key factors influencing ignition behaviour across operational scenarios.

Electrostatic Discharge (ESD) emerged as one of the most credible ignition sources, particularly during maintenance, venting, handling of non-conductive equipment, and activities that create charge accumulation. Evidence from operational and experimental sources consistently demonstrates the feasibility of ESD-initiated ignition, resulting in this mechanism being ranked as high-relevance with a well-supported likelihood.

Hot Surface Ignition is another significant mechanism. Hydrogen can ignite on contact with surfaces at temperatures approaching its auto-ignition temperature, and WP1 highlighted the potential for elevated component temperatures in compressor housings, turbines, and enclosed equipment. The presence of high-temperature surfaces, combined with hydrogen's propensity to form ignitable mixtures rapidly, supports this as a high-priority ignition pathway.

Delayed Ignition, resulting from the accumulation of hydrogen clouds in poorly ventilated or confined spaces, was also identified as a credible and operationally relevant mechanism. Historical incident patterns confirm that leaks can disperse and accumulate before encountering a delayed ignition source, generating overpressures and escalating consequences.

Hot Work and Purging Ignition were found to be among the most frequently recurring ignition causes in industrial environments. Failures in purging sequences, inadequate confirmation of purge endpoints, and lapses in hot-work controls lead to clear ignition potential, particularly during maintenance and commissioning activities.

Mechanisms such as Auto-Ignition during high-pressure releases, Electrical Arcing from equipment faults, and Ventilation Failure leading to cloud formation were ranked as medium to high relevance. While the technical basis for these mechanisms is strong, the empirical evidence base is less extensive, creating uncertainties that warrant deeper analysis or targeted validation.

Several mechanisms, including mechanical impact, lightning, permeation into insulation, hydrogen embrittlement as an ignition cause, and thermal runaway of neighbouring equipment, were classified as low-likelihood or not sufficiently supported by real-world incident data. These were considered non-credible as primary ignition sources within NTS-relevant conditions and were deprioritised for further investigation.

Note that Thermal Runaway, SIMOPs, Hydrogen Embrittlement and Permeation Into Insulation were removed from scope post-WP1 as literature searching and client discussion proved them to be irrelevant or subsets of other ignition scenarios. This is covered by Project Query NG-PQ-001 (“Ignition Scenarios”).

4.1.2 SCENARIO ANALYSIS HIGHLIGHTS

WP1 produced an ignition scenario register and risk matrix, combining likelihood, severity, and exposure information to prioritise ignition mechanisms across asset types such as pipelines, compressor stations, above-ground installations, venting systems, and confined-space environments.

The analysis identified a set of high-priority scenarios that possess both a strong evidential basis and clear operational relevance for hydrogen transmission:

- ESD during blowdown, venting, or maintenance
- Hot surface ignition within or near compressor units and enclosed housings
- Delayed ignition of accumulated gas clouds
- Hot-work ignition during maintenance activities
- Purging-related ignition during commissioning or shutdown sequences

These scenarios were consistently ranked at the upper end of the composite scoring framework due to recurring evidence, clear mechanistic pathways, and alignment with known hydrogen behaviour.

A second group of medium-priority scenarios includes auto-ignition during high-pressure releases, turbine re-ignition during restart cycles, and ignition from electrical faults. These mechanisms are plausible and technically justified but characterised by incomplete or model-dependent evidence. As such, they require additional evaluation to establish whether they represent material risks within NTS operations.

The scenario analysis also confirmed that several mechanisms fall into a low-priority or “non-credible” category, with limited or no evidence linking them to real-world ignition events. This includes mechanical impact ignition, lightning-driven ignition, permeation-derived ignition, and embrittlement-related failures. These scenarios were not recommended for further testing as part of WP2.

Finally, WP1 noted that while incident databases contain many hydrogen-related events overall, keyword-based searches capture only a small proportion of these, indicating wider variability and uncertainty in deriving ignition likelihoods from historical data. This reinforces the need for targeted validation in specific areas identified by the scenario matrix.

4.1.3 POST WORK PACKAGE REVIEW

Following the completion of WP1, the composite risk scores (CRS) of the identified ignition scenarios were:

- Electrostatic Discharge = 100
- Hot Work Ignition = 96
- Hot Surface Ignition = 96
- Delayed Ignition = 60
- Purging Ignition = 57.6
- Ventilation Failure = 57.6
- SIMOPS = 57.6
- Hydrogen Jet Flame Flashback = 54
- Thermal Runaway = 54
- Auto-Ignition = 50.4

All other ignition scenarios fell below the threshold of CRS = 40 and were categorised as “No GO” in terms of field testing.

Only Electrostatic Discharge criteria met the criteria of CRS = 100 or more for field testing, with all others (CRS between 40 and 100) falling into the “REVIEW” category.

This was reviewed with National Gas and following a number of review cycles, four ignition scenarios were finalised as moving forward to Work Package 2:

- Hot Work Ignition
- Hot Surface Ignition
- Delayed Ignition
- Ventilation Failure

The Composite Risk Scores reported above are relative risk-ranking metrics derived from credibility, severity, confidence and exposure factors. Absolute ignition event frequencies for each mechanism are determined by combining equipment-specific leak frequency data (sourced from FRED and OREDA, as described in the WP2 Equipment Failure Rates section below) with conditional ignition probability values derived from the LOPA sensitivity criteria developed in WP3. This combined frequency-consequence framework provides the initiating event input data for QRA and LOPA studies under T/SP/G36 and T/SP/HAZ30. The full per-mechanism frequency derivations, equipment categorisation, and sensitivity analysis outputs are documented in the Final Technical Report (NGT-06-D35-00-11).

4.2 WORK PACKAGE 2 – TESTING

Work Package 1 identified critical evidence gaps requiring physical validation across three high-risk ignition scenarios. Testing addressed specific transmission-scale operational conditions where existing hydrogen safety literature provided insufficient data for risk assessment of the National Transmission System.

4.2.1 HOT SURFACE IGNITION TESTING

Testing determined the ignition temperature for an 80% methane / 20% hydrogen blend in a stainless-steel apparatus following EN ISO/IEC 80079-20-1:2020-09 methodology. The investigation systematically increased surface temperatures from 80°C to establish ignition thresholds.

Key Findings:
- Provisional hot surface ignition temperature identified at 650°C with initial testing
- Refined ignition temperature determination established 642°C as the lower ignition threshold for the 80/20 blend
- Testing revealed consistent ignition behaviour above 644°C
- Surface temperature below 642°C showed no ignition across multiple purge time variations

4.2.2 HOT WORK IGNITION TESTING

High-pressure leakage testing investigated flammable atmosphere dispersion and ignition potential around defined leak points. Testing utilized an 80-bar pressure vessel with pneumatically controlled releases through 5mm and 10mm leak orifices for both 100% hydrogen and 80/20 methane/hydrogen blend.

a. LFL Distribution Findings

- 10mm leak with 80/20 blend: flammable atmosphere (>25% LEL) extended 13-14 meters along release axis at 1m height
- Gas cloud dispersion showed significant variation with distance from centreline, with concentrations decreasing rapidly beyond 0.75m lateral displacement
- Vertical stratification observed, with highest concentrations between 1-1.5m height above leak point
- 5mm leak demonstrated proportionally reduced hazard zones compared to 10mm leak

b. Ignition Distance Results

- 10mm leak, 100% H_2: ignition achieved at distances up to 7m from leak point at 2m height
- 10mm leak, 80/20 blend: ignition achieved at distances up to 6m from leak point
- 5mm leak, 80/20 blend: reduced ignition distances, successful ignition at 3.5m maximum distance
- Ignition probability decreased substantially with increased lateral distance from release axis

c. Jet Fire Characterization

- Immediate ignition of high-pressure releases resulted in sustained jet fires
- Thermal imaging captured jet fire dimensions and heat radiation patterns for both gas compositions
- Testing confirmed jet fire establishment for all leak sizes investigated

4.2.3 VENTILATION FAILURE TESTING

Enclosed volume testing investigated gas accumulation rates and LEL achievement timescales across three enclosure sizes ($2m^3$, $5m^3$, $10m^3$) with varying gas release rates and leak positions. Testing examined both 100% hydrogen and 80/20 blend behaviour under ventilation failure conditions.

a. Key Findings

- Gas accumulation rates demonstrated direct correlation with release flowrate and inverse relationship with enclosure volume
- Leak position significantly influenced LEL achievement time, with bottom-positioned leaks showing different accumulation patterns versus centre or top positions
- 100% hydrogen exhibited more rapid dispersion toward ceiling due to buoyancy effects compared to 80/20 blend
- Testing quantified time-to-LEL for operational scenarios ranging from 3.84 l/min to 192 l/min release rates

4.2.4 DELAYED IGNITION TESTING

Spark plug ignition sources positioned at bottom, centre, and ceiling locations within the three test volumes investigated delayed ignition behaviour under varying gas and air flowrate combinations. Testing established ignition location patterns for different ventilation and leak conditions.

a. Key Findings

- Ignition location varied systematically with gas/air flowrate ratios
- 100% hydrogen: ceiling ignition predominated at lower gas flowrates with adequate air supply

- 80/20 blend: bottom and centred ignition locations more common due to reduced buoyancy effects
- Testing identified critical gas/air flow combinations resulting in consistent ignition at specific locations
- Successful delayed ignition demonstrated across all test volumes, confirming ignition risk under ventilation failure recovery scenarios

4.2.5 EVIDENCE GAPS ADDRESSED

Physical testing provided transmission-system-relevant data addressing critical knowledge gaps:

- Quantified ignition temperature for blend composition under controlled hot surface contact conditions
- Established ignition distance envelope for high-pressure transmission scenarios (80 bar)
- Determined LFL cloud dimensions for leak sizes relevant to transmission infrastructure
- Characterized jet fire consequences for immediate ignition scenarios
- Quantified accumulation timescales and ignition patterns for enclosed equipment scenarios
- Validated delayed ignition occurrence across realistic operational conditions

Testing confirmed that blend-specific behaviour differs from pure hydrogen literature values, particularly regarding buoyancy-driven dispersion and ignition location patterns. Results demonstrated that transmission pressure conditions (80 bar) create extended hazard zones requiring specific control measures beyond those derived from lower-pressure hydrogen research.

4.2.6 EQUIPMENT FAILURE RATES AND LEAK LIKELIHOOD

Equipment failure rate data for transmission system components was assessed as a distinct SoW deliverable to underpin the likelihood analysis for hydrogen ignition risk calculations. Failure frequency data was drawn from established industry sources including FRED (Failure Rate and Event Data) and OREDA, supplemented by NGT operational history where available. Failure modes assessed included flange and fitting leaks, valve seal failures, compressor casing leaks and instrument connections, categorised by asset type and operating regime. It is noted that the current failure rate datasets are derived predominantly from methane service operational records. While these provide a defensible baseline for initiating event frequency, they carry an inherent uncertainty for hydrogen service given the differences in material compatibility, seal permeation behaviour and detection sensitivity. This uncertainty has been explicitly carried through the LOPA sensitivity criteria as a conservative modelling assumption, consistent with the residual risk treatment set out in Section 6A.5. These failure rates provided the initiating event frequencies for each ignition scenario, enabling leak likelihood to be combined with ignition probability to determine overall hazardous event frequency. The full failure rate dataset by equipment type and failure mode, the hydrogen service adjustment rationale, sensitivity analysis against methane baseline values, and all supporting frequency calculations are documented in full in Section 5 of the Final Technical Report (NGT-06-D35-00-11). Reviewers should refer to that section for the complete tabulated dataset required under the SoW failure rate deliverable.

4.3 WORK PACKAGE 3 – SAFETY IMPLICATIONS

Work Package 3 delivered comprehensive safety guidance for hydrogen conversion across the National Transmission System, establishing safeguard requirements, maintenance modifications, and risk assessment criteria. The assessment evaluated [redacted] Pipelines, Compressor Stations, Offtakes, Above Ground Installations) to identify control measures required for safe hydrogen service.

4.3.1 KEY DELIVERABLES

The assessment produced:

- Three-tier safeguard hierarchy identifying engineering controls for three high-risk scenarios (Electrostatic Discharge, Hot Surface Ignition, Hot Work Ignition), enhanced procedural controls for nine moderate-risk scenarios, and monitoring requirements for four low-risk scenarios
- Modified maintenance strategies addressi[redacted]asks across all asset types, with specific requirements for inspection intervals, defect tolerance, atmospheric controls, material compatibility, and energy isolation procedures
- Scenario-specific LOPA sensitivity criteria for twelve key ignition scenarios, providing quantitative inputs (ignition probabilities, severity ratings, SIL requirements) for integration into HAZ/30 risk assessment methodology
- Comprehensive documentation includi[redacted]ragraphs of operational guidance, mapping of [redacted]onal Gas policies to hydrogen requirements, an[redacted] [redacted]uctured guidance

4.3.2 CRITICAL FINDINGS

a. Validated Control Thresholds

WP2 experimental testing established quantitative safety thresholds integrated throughout the assessment. Hot surface ignition temperature of 642°C for 20% hydrogen blend validated the conservative 585°C operational limit (10% margin). Hot work exclusion distances of 12m for 100% hydrogen and 5m for 20% blend at 80 bar pressure confirmed the need for extended work zones beyond natural gas requirements. Delayed ignition testing demonstrated 100% ceiling-level ignition across all confined space scenarios, validating multi-tier detection strategies.

b. Asset-Specific Risk Profiles

Severity assessment revealed significant variation across asset types. Compressor stations presented highest ris[redacted]equiring LOPA for all activities and SI[redacted]strumentation. Pipeline, offtake, and AGI systems typically rate[redacted]uring maintenance (manageable wit[redacted]ontrols and robust procedures) b[redacted]

c. Material Compatibility Requirements

Assessment identified critical material changes required for hydrogen service. All conventional sealing materials (NBR, EPDM) require replacement with fluoroelastomers. High-strength fasteners (>900 MPa yield, >450 HV hardness) prohibited due to embrittlement susceptibility. All maintenance consumables – tools, lubricants, temporary materials – require hydrogen compatibility verification before use.

d. Enhanced Isolation Philosophy

Single-barrier isolation determined insufficient for hydrogen service. Modified philosophy established double-block-and-bleed as minimum standard, with triple-barrier isolation for critical maintenance. All isolation activities require nitrogen purging to <1% hydrogen, pressure decay verification (<10 mbar/hour leak rate), and continuous atmospheric monitoring during intrusive work.

e. Inspection and Monitoring Modifications

Hydrogen's lower defect tolerance necessitated 50% reduction in inspection intervals and more conservative acceptance criteria (crack depths <10% wall thickness trigger repair, versus <30% for natural gas). Advanced NDT techniques mandated, including ultrasonic testing with >10 MHz transducers and phased array methods for weld inspection. Continuous monitoring required for hydrogen concentration (10% LEL alarm), surface temperature (550°C alert, 585°C trip), and leak detection with hydrogen-specific sensitivity.

f. Deflagration

Deflagration-to-detonation transition (DDT) was assessed as a specific SoW-required consequence scenario within the WP3 safety implications analysis. DDT represents an escalation pathway from deflagration in which a propagating flame accelerates to supersonic detonation velocity, generating significantly higher overpressures than a conventional vapour cloud explosion. The assessment evaluated whether the physical conditions necessary for DDT — stoichiometric hydrogen concentration, sufficient unobstructed run-up distance (typically equivalent to 10–15 pipe diameters minimum), and geometric confinement to sustain flame acceleration — could be simultaneously present in NTS assets under credible loss-of-containment scenarios. For above-ground installations and compressor station enclosures, hydrogen's higher laminar flame speed and wider flammability range relative to methane increase its theoretical DDT susceptibility, particularly in partially confined geometries with congestion from pipework and equipment. However, the combination of conditions required was judged unlikely to be simultaneously realised across typical NTS assets: ventilation controls limit stoichiometric accumulation; existing enclosure geometries generally do not provide the run-up distances required for flame acceleration to detonation velocity; and hydrogen's strong buoyancy in open or partially vented spaces inhibits the sustained mid-level cloud formation most conducive to DDT. DDT was therefore classified as a credible but low-probability consequence pathway and was not assigned a standalone SIL requirement in the WP3 LOPA sensitivity criteria. The quantified detonation probability bound, the geometric analysis underpinning the DDT exclusion for standard NTS asset configurations, and the full consequence modelling outputs demonstrating that detonation overpressure does not govern the design basis for any assessed scenario are documented in Section 7 of the Final Technical Report (NGT-06-D35-00-11). This position is conditional on continued compliance with the ventilation requirements, inspection intervals and gas detection thresholds identified in WP3. A formal DDT sensitivity review for enclosed compressor station geometries — where confinement and congestion levels are highest — is documented as a required action in the Final Technical Report and is recommended as part of the QRA parameter validation exercise.

4.3.3 IMPLEMENTATION IMPACT

The assessment identified comprehensive policy updates required across National Gas's operational framework. Affected areas include asset management procedures, maintenance practices, permit-to-work systems, emergency response protocols, hazardous area classifications, and material specifications. The integration of WP2 experimental validation with WP1 literature findings eliminated reliance on extrapolation and provided defensible, evidence-based criteria for safety-critical decisions. The LOPA sensitivity criteria developed enable consistent, technically robust risk assessments as hydrogen is introduced across the transmission network, with clear prioritization of scenarios requiring enhanced controls versus those adequately addressed by existing practices.

4.3.4 POLICY DEVELOPMENT FOUNDATION

The structured guidance delivered in twelve appendices provided the technical foundation for Work Package 4 policy recommendations. The assessment mapped specific control measures to National Gas policy documents, identified gaps requiring new procedures, and established performance criteria for hydrogen-specific equipment and systems. This systematic approach enabled efficient translation of technical findings into operational requirements, supporting the development of a comprehensive hydrogen safety framework aligned with regulatory obligations and industry best practices.

4.4 WORK PACKAGE 4 – POLICY IMPACT

Work Package 4 (WP4) formed the final technical assessment layer of the Net Zero Safety & Ignition Risk programme. Its purpose was to determine whether the empirical ignition data established in WP2 and the technical safety implications developed in WP3 required corresponding changes to the regulatory compliance position or corporate policy framework that governs National Gas Transmission's (NGT) operations on the National Transmission System (NTS).

WP4 was a policy-level adequacy review. It did not reinterpret the experimental science generated in WP2, nor did it re-design the consequence modelling frameworks assessed in WP3. Instead, it evaluated whether hydrogen-specific ignition behaviour invalidated assumptions embedded in current policy, required explicit clarification within policy language, or necessitated formal parameter validation to maintain regulatory defensibility.

The review encompassed UK statutory regulations — including DSEAR, COMAH, ATEX Directive 2014/34/EU, PSR 1996, PSSR 2000 and GSMR — alongside external technical standards such as BS EN 60079-10-1 (hazardous area classification) and EN ISO 21789:2022 (turbine fuel systems), and a suite of NGT corporate standards covering QRA, LOPA, hazard assessment, major accident prevention, and installation management.

The central conclusion of WP4 was that no structural policy rewrite was required. The impact of hydrogen introduction was refinement-based: existing frameworks remained fundamentally sound, and the actions identified related to explicit scope clarification, validation of modelling parameters historically derived from methane datasets, and alignment of integrity governance with the hydrogen transition programme.

4.4.1 KEY TECHNICAL FINDINGS AND POLICY IMPLICATIONS

WP4 evaluated five principal technical areas. The findings and their policy implications are summarised below.

a. Temperature Classification

WP2 testing established hydrogen hot surface ignition temperature at approximately 558°C and the 80/20 methane–hydrogen blend at approximately 623°C. Both values sat comfortably above the 450°C threshold defining Temperature Class T1 under IEC 60079-0. WP3 confirmed that hydrogen blending at up to 20 mol% did not reduce this parameter below methane levels. No reduction in T-class was therefore required, and equipment classification under DSEAR and ATEX remained unchanged. The policy recommendation was limited to ensuring that corporate standards explicitly confirmed the T1 classification basis applied to hydrogen and blend scenarios, removing any risk of interpretive ambiguity in future compliance assessments.

b. Explosion Group Classification

The explosion group classification of a gas governs flameproof enclosure design, flame arrester selection and equipment protection levels. WP3 review of internationally recognised literature confirmed that MESG (Maximum Experimental Safe Gap) classification remained IIA for blends up to approximately 25 mol% hydrogen. However, MIC (Minimum Ignition Current) ratios decreased with increasing hydrogen content, which may have justified IIB classification where ignition energy limitation was the governing protection mechanism. Pure hydrogen was classified as Explosion Group IIC under ISO/IEC 80079-20-1, and WP2 findings did not alter this. No blanket reclassification was required for blends at or below 20%, but corporate policy should clearly specify whether equipment selection references MESG or MIC methodology, particularly within T/SP/G36 and T/SP/HAZ30.

c. High-Pressure Release and Major Accident Scenarios

WP2 80 bar testing demonstrated that pure hydrogen produced a larger ignitable envelope than the 80/20 blend under equivalent conditions, with axial ignition distances of up to approximately 12–13 m for a 10 mm orifice release, and self-sustaining jet flame behaviour. Blend flames were not self-sustaining under the same conditions. WP3 confirmed that hydrogen jets were momentum-dominated, that similarity-law scaling remained applicable for conservative modelling, and that hydrogen jet flame persistence increased the potential duration of thermal radiation exposure. The hazardous area classification philosophy and the underlying modelling methodology remained structurally valid. However, the quantitative inputs to QRA and pipeline hazard assessment tools — including jet length parameters, radiation fractions and ignition probability values — required formal validation for hydrogen service within T/SP/G36, T/SP/HAZ16 and T/SP/HAZ30.

d. Ventilation and Ignition Control

WP2 enclosure testing demonstrated rapid time-to-LEL sensitivity dependent on leak rate, ventilation performance and enclosure geometry. WP3 identified two hydrogen-specific effects requiring particular attention: the production of stronger vertical concentration gradients due to hydrogen's low molecular weight, and the potential for localised adiabatic compression ignition during rapid high-pressure discharge. BS EN 60079-10-1 methodology remained applicable but warranted conservative interpretation for hydrogen, particularly in relation to Zone of Negligible Extent (NE) classification, high-level accumulation behaviour, and high-pressure jet dispersion assumptions. Corporate standards T/SP/G37, T/SP/HAZ25 and T/SP/G36 were identified as requiring updates to explicitly recognise hydrogen dispersion characteristics and enclosure accumulation behaviour.

e. Risk Assessment and Ignition Probability

The risk assessment framework embedded in corporate standards was developed with reference to methane ignition behaviour. WP2 confirmed that hydrogen produced a geometrically different ignitable envelope, a lower minimum ignition energy, and differing jet flame persistence characteristics. WP3 concluded that ignition probability assumptions and Risk Reduction Factors (RRFs) derived from methane datasets were not directly transferable to hydrogen service without formal validation. The overall risk assessment structure remained appropriate; however, ignition probability inputs within T/SP/HAZ30, QRA parameters within T/SP/G36, and pipeline rupture modelling assumptions within T/SP/HAZ16 all required formal hydrogen-specific validation before being applied to hydrogen or high-proportion blend scenarios.

4.4.2 REQUIRED POLICY ADAPTATIONS

WP4 identified the required policy adaptations across three levels, based on the nature and urgency of each change.

Level	Description	Affected Standards	Action Type
Level 1 – Clarification	Standards that are technically robust but implicitly framed around methane service. Amendments are interpretive: scope	[redacted]	Textual amendment via normal governance cycle

Level	Description	Affected Standards	Action Type
	statements, modelling assumption documentation and hazard identification prompts.		
Level 2 – Parameter Validation	Standards relying on quantitative inputs directly influencing Individual Risk, Societal Risk and ALARP demonstration. Hydrogen-specific validation of numerical parameters is required.	[redacted]	Technical Basis Memorandum + formal validation study
Level 3 – Integrity & Transition	Longer-term governance considerations extending beyond ignition modelling: material degradation, composition control and regulatory interface management.	[redacted]	Align with Hydrogen Transition Programme stage gates

Table 1 – Policy Adaptation Summary

External standards BS EN 60079-10-1 and EN ISO 21789:2022 remained structurally applicable to hydrogen service. Targeted clarifications were recommended for conservative interpretation in relation to hydrogen ignition sensitivity, dispersion behaviour and explosion protection design. These cannot be amended unilaterally by NGT; the draft clarification text developed in WP4 was intended to support future engagement with BSI/ISO technical committees or serve as internal interpretative guidance pending standards update.

A full Regulatory Compliance Mapping, tracing each WP2/WP3 technical finding to the applicable statutory or standards requirement and corporate policy impact, was provided in Appendix 11.1 of the WP4 report. This mapping confirmed that no hydrogen-related finding resulted in an unmitigated regulatory compliance gap.

4.4.3 HIGH-LEVEL RECOMMENDATIONS

WP4 conclusions supported a structured programme of actions, prioritised by their direct influence on process safety risk calculations and regulatory defensibility.

a. Immediate Priority Actions

The most significant near-term action identified was the preparation and issue of a Technical Basis Memorandum (TBM) formally documenting hydrogen-specific ignition modelling assumptions derived from WP2 and WP3. This TBM should address ignition probability basis, high-pressure jet dispersion parameters, radiation fraction assumptions and enclosure accumulation considerations. Until formal standards revision is completed, this document should be referenced in all QRA, LOPA and hazard assessment studies involving hydrogen service.

In parallel, a modelling parameter validation exercise was recommended for T/SP/G36 (QRA), T/SP/HAZ30 (LOPA), T/SP/HAZ16 (pipeline risk modelling) and AGI risk tools. Sensitivity analyses should confirm whether existing methane-based inputs will remain conservative when applied to hydrogen scenarios or whether calibrated adjustment is warranted. This work directly supported continued ALARP defensibility and was identified as the highest-priority technical action arising from the programme.

Textual clarification updates to explicitly include hydrogen and blends within policy scope statements, clarify the explosion group classification basis (MESG vs MIC), and recognise hydrogen buoyancy and delayed ignition behaviour are to be progressed through the normal standards governance cycle. Draft amendment wording developed in WP4 Appendices 11.2 and 11.3 provide a ready basis for this work.

b. Medium-Term Actions

[redacted] be [redacted] and [redacted] releases.

Developments in BS EN 60079-10-1 and EN ISO 21789:2022 are to be monitored and, where hydrogen-related updates are under consideration, NGT is recommended to engage with the relevant BSI and ISO technical committees. The technical evidence base developed across WP2, WP3 and WP4 provide a sound foundation for such engagement.

c. Longer-Term Governance

Structured regulatory engagement is recommended to be maintained with HSE and relevant regulators regarding GSMR evolution for hydrogen blends, PSR and PSSR expectations for hydrogen conversion programmes, and alignment of MAPD and safety case content with hydrogen hazard characteristics. Following initial hydrogen operational phases, a formal post-deployment evidence review is to confirm the continued validity of ignition modelling assumptions and determine whether parameters require calibration based on operational experience. This review should be formally embedded as a stage-gate requirement within the Hydrogen Transition Programme governance framework.

5 IGNITION LIKELIHOOD AND RISK PROFILE IMPACT

Hydrogen exhibits lower minimum ignition energy (0.016 mJ) and wider flammability limits compared with methane; however, no new initiating event categories have been identified. The initiating events remain consistent with those defined in T/SP/HAZ30: loss of containment, mechanical damage, operational error, and maintenance activities.

The absolute ignition probability for hydrogen is higher than for methane under equivalent release conditions, driven by its lower minimum ignition energy and wider flammability range. However, when conservative modelling inputs are applied, no step-change in overall societal risk classification has been identified. Ignition probability assumptions and associated Risk Reduction Factors (RRFs) have been reviewed for applicability under hydrogen service, and parameter validation is required before routine application in QRA and LOPA studies. Composite Risk Scores developed in WP1 and refined through WP3 confirmed that the three highest-priority mechanisms — Electrostatic Discharge, Hot Surface Ignition, and Hot Work Ignition — each justified GO classification, with ignition probability inputs of 1.0 assigned for LOPA purposes. Detailed ignition probability derivations, RRF validation assessments, and LOPA sensitivity outputs are provided in the Final Technical Report (NGT-06-D35-00-11).

6 MAJOR ACCIDENT HAZARD (MAH) ASSESSMENT SUMMARY

6.1 MAH CONTEXT UNDER PSR AND MAPD FRAMEWORK

In accordance with T/PM/PSR7 (Major Accident Prevention Document) and the Pipeline Safety Regulations 1996 (PSR), this project assessed whether the introduction of hydrogen (≤20% blend and 100% hydrogen scenarios) alters: the identification of Major Accident Hazards (MAHs); the nature or severity of credible MAH consequences; the frequency of initiating events leading to MAH outcomes; and the adequacy of existing prevention and mitigation measures.

The assessment was undertaken consistent with the Quantified Risk Assessment (QRA) methodology defined in T/SP/G36 and the initiating event and protection layer logic defined in T/SP/HAZ30.

6.2 MAH CONSEQUENCE CATEGORIES (QRA-ALIGNED)

The MAH consequence types assessed remain those already defined within NTS QRA and MAPD frameworks: Jet Fire (high-pressure release ignition); Flash Fire (unconfined cloud ignition); Vapour Cloud Explosion (confined/congested ignition); and Escalation due to sustained flame impingement. These are the same MAH outcome categories currently modelled within T/SP/G36-based QRAs for Major Accident Hazard Pipelines (MAHPs) and Above Ground Installations (AGIs).

Table 5A-1 – Hydrogen Impact on MAH Consequence Categories (QRA Basis)

MAH Consequence Type	Methane Baseline (T/SP/G36)	≤20% Hydrogen Blend	100% Hydrogen	Change to MAH Category?
Jet Fire	High-pressure momentum-dominated release	Slightly increased ignitable envelope	Increased ignitable envelope; sustained flame persistence	No
Flash Fire	Transient cloud ignition	Comparable behaviour	Faster flame speed; wider flammability limits	No
Vapour Cloud Explosion	Confinement-dependent	No structural change	Increased reactivity under congestion	No
Escalation Duration	Radiation-driven separation basis	Comparable	Potential increase in sustained flame duration	No

Conclusion (MAPD Position): Hydrogen does not introduce new MAH categories under PSR. Consequence mechanisms remain unchanged in type, but modelling parameters require validation under hydrogen service.

6.3 FREQUENCY AND INITIATING EVENT CONSIDERATIONS (HAZ30-ALIGNED)

Consistent with T/SP/HAZ30, hydrogen does not introduce new initiating event types. Initiating events remain: loss of containment; mechanical damage; operational error; and maintenance intrusion. Hydrogen modifies ignition sensitivity but does not alter initiating event frequency. Where hydrogen increases ignition sensitivity, ignition probability assumptions used within event trees require validation, and Risk Reduction Factors (RRFs) associated with ignition prevention layers must be confirmed as applicable under hydrogen conditions. No step-change in initiating event frequency has been identified.

6.4 BLEND (≤20%) VS 100% HYDROGEN – QRA AND CLASSIFICATION BASIS

Table 5A-2 distinguishes between near-term blend introduction and full hydrogen conversion scenarios, covering explosion group classification, temperature class, QRA consequence modelling, ignition probability, and introduction of new MAH types. For blends up to 20%, existing explosion group and temperature class assumptions remain valid. For 100% hydrogen, Explosion Group IIC classification must be recognised and conservative modelling parameters applied. In both scenarios, no new MAH category is introduced. Hazardous area classification methodology under IEC 60079 and QRA methodology under T/SP/G36 remain structurally valid.

Table 5A-2 – Comparative Implications: ≤20% Blend vs 100% Hydrogen

Aspect	≤20% Hydrogen Blend	100% Hydrogen
Explosion Group (IEC 60079 Basis)	IIA infrastructure assumptions remain valid	IIC classification required
Temperature Class (ISO 80079)	T1 remains valid	T1 remains valid
QRA Consequence Modelling	Methane-based structure valid; parameters validated	Conservative hydrogen-specific parameters required
Ignition Probability (HAZ30)	RRF validation required	RRF validation required
Introduction of New MAH	No	No
Jet Flame Persistence	Comparable to methane; self-sustaining flame not confirmed at	Increased persistence; self-sustaining jet flame confirmed at

Aspect	≤20% Hydrogen Blend	100% Hydrogen
	80 bar for 10 mm orifice blend releases	80 bar — extended thermal radiation duration; QRA radiation fraction parameter validation required
Ignitable Envelope (80 bar, 10 mm orifice)	Axial ignition to 6 m from leak point; methane-based QRA jet length parameters applicable with validation	Axial ignition to 7 m from leak point; extended envelope relative to blend; hydrogen-specific jet length parameters required for T/SP/G36 and T/SP/HAZ16

6.5 SOCIETAL AND INDIVIDUAL RISK POSITION (T/SP/G36)

Consistent with T/SP/G36, individual risk contours remain governed by jet fire radiation modelling, and societal risk FN-curves remain driven by event frequency and consequence extent. Hydrogen introduction modifies flame persistence and ignitable envelope extent (particularly for 100% hydrogen) but does not produce a step-change in calculated societal risk category when conservative parameters are applied. Residual risk remains within tolerability thresholds defined under NTS QRA acceptance criteria.

6.6 MAH SUMMARY CONCLUSION (MAPD STATEMENT)

Under T/PM/PSR7 and PSR requirements: no new Major Accident Hazards are introduced by hydrogen; existing prevention and mitigation measures remain structurally valid; parameter validation is required for ignition probability and jet modelling; and with identified safeguard refinements, MAH risk remains tolerable and capable of being reduced to ALARP. These conclusions directly inform the COMAH Safety Case and MAPD content for the hydrogen transition programme: the absence of new MAH categories confirms that the existing Safety Case structure remains appropriate, while the identified parameter validation requirements define the technical actions required to maintain MAPD defensibility as hydrogen introduction progresses. Detailed QRA modelling and event tree derivations are provided in the Final Technical Report (NGT-06-D35-00-11).

7 IMPACT ASSESSMENT

This project has generated substantial new learning across four areas critical to National Gas Transmission's hydrogen transition programme, each carrying direct implications for how safety is managed, governed and operationalised on the National Transmission System.

7.1 NGT SAFETY MANAGEMENT

The project fundamentally advances NGT's ability to manage hydrogen ignition risk on a quantitative, evidence-based footing. Prior to this work, risk assessments for hydrogen scenarios relied on methane-derived parameters that have now been shown to be insufficient for direct transfer to hydrogen service. Physical testing at transmission-relevant pressures (80 bar) established validated ignition thresholds — including a hot surface ignition temperature of 642°C for 20% hydrogen blends and ignition distances of up to 7 metres from high-pressure releases — that eliminate the need for conservative extrapolation and provide defensible inputs to QRA and LOPA studies. The development of LOPA sensitivity criteria for twelve key ignition scenarios, with quantified ignition probabilities and SIL requirements, gives NGT a consistent technical basis for Major Accident Hazard assessments as hydrogen introduction progresses. Critically, the project has also confirmed that asset-specific risk profiles vary significantly: compressor stations present the highest severity (S4–S5), requiring SIL 2–3 controls, while pipelines and AGIs are generally manageable at SIL 1 under robust procedural regimes during normal unattended operation.

Ignition Scenario	CRS	Class	Worst-Case Ignition Type	Ignition Probability (LOPA Input)	Typical SIL
Electrostatic Discharge (ESD)	100	**GO**	Delayed (VCE potential)	1.0	SIL 2–3
Hot Surface Ignition	96	**GO**	Immediate (jet fire)	1.0 if T ≥ 585°C 0.5–1.0 if 200°C ≤ T < 585°C	SIL 1–2
Hot Work Ignition	96	**GO**	Delayed (confined-space VCE)	1.0	SIL 2–3
Delayed Ignition (Cloud)	60	**REVIEW**	Delayed with VCE	1.0 (default) Reduced if detection < 50% accumulation time	SIL 2
Purging Ignition	57.6	**REVIEW**	Delayed during purge	1.0 (without continuous monitoring)	SIL 1–2
Ventilation Failure	57.6	**REVIEW**	Delayed post-vent failure	1.0 (without gas detection response)	SIL 2

Ignition Scenario	CRS	Class	Worst-Case Ignition Type	Ignition Probability (LOPA Input)	Typical SIL
Jet Flame Flashback	54	**REVIEW**	Immediate + flashback to source	1.0 (immediate) 0.5 (flashback, >50 barg, >100 m/s)	Design-based (arrestors)
Auto-Ignition (non-surface)	50.4	**REVIEW**	Spontaneous (no external source)	0.1 (open) 0.3 (confined)	Design-based
Electrical Fault / Arcing	45	**REVIEW**	Immediate from arc	0.01 (Ex-certified) 1.0 (non-compliant equipment)	Design-based
Re-Ignition Post-Shutdown (Turbines)	43.2	**REVIEW**	Delayed re-ignition during restart	0.5 (without SIL 2 flame detection)	SIL 2
Mechanical Impact Ignition	36	**NO-GO**	Immediate (if occurs)	Screen out (routine ops) 0.01–0.05 (excavation/maintenance)	N/A
Lightning / Atmospheric Discharge	24	**NO-GO**	Immediate	Screen out 0.01 (during storms, standard lightning protection)	N/A

Table 2: Ignition Probability Summary – 12 Key Hydrogen Ignition Scenarios (LOPA Sensitivity Criteria)

7.2 POLICY AND STANDARDS UPDATES

The policy review confirmed that no wholesale rewrite of existing regulatory frameworks is required; however, targeted and material updates are necessary to maintain regulatory defensibility for hydrogen service [redacted]

Engagement with BSI and ISO technical committees is also recommended to support future updates to BS EN 60079-10-1 and EN ISO 21789:2022.

7.3 OPERATIONAL PRACTICE: MAINTENANCE, ISOLATION AND SITE LAYOUT

The project has identified extensive modifications required [redacted] aintenance tasks across all asset types, representing a [redacted] The central shift in isolation philosophy — [redacted]

7.4 HYDROGEN READINESS OF ASSETS

The assessment evaluat [redacted] enarios across pipelines, compressor stations, offtakes and above-ground installations, providing a structured picture of where existing assets are suitable for hydrogen service with procedural controls, and where engineering upgrades are required. [redacted] These findings provide NGT with a clear, prioritised roadmap for asset conversion planning, directly supporting the engineering and safety case development work underpinning Project Union.

8 ALARP DEMONSTRATION SUMMARY

8.1 ALARP CONTEXT (PSR AND QRA BASIS)

Under T/SP/G36, risk must be demonstrated to be Broadly Acceptable, or Tolerable if ALARP. Under T/SP/HAZ30, ALARP is demonstrated by: identification of initiating events; identification of Independent Protection Layers (IPLs); confirmation that Risk Reduction Factors (RRFs) are sufficient and valid; and demonstration that additional measures would be grossly disproportionate. This project assessed hydrogen ignition risk within this framework.

8.2 INDEPENDENT PROTECTION LAYERS (HAZ30-ALIGNED)

The following IPL refinements were identified as required for hydrogen service. Table 6A-1 summarises the additional safeguards assessed against their methane baseline, the hydrogen-specific enhancement required, and their functional role within the HAZ30 protection layer framework.

Table 6A-1 – Hydrogen-Specific Prevention and Mitigation Measures

IPL / Safeguard	Methane Baseline	Hydrogen Enhancement	Function (HAZ30 Basis)
Isolation	Task-dependent DBB	DBB minimum for intrusive work	Prevent ignition during maintenance
Hot Work Controls	Methane-based exclusion	Extended exclusion distance	Reduce ignition probability
Inspection Intervals	Standard asset frequency	50% reduction for hydrogen-sensitive components	Reduce initiating event frequency
Gas Detection	Methane-calibrated	Hydrogen-capable ceiling sensors	Early detection IPL
Electrostatic Control	Standard bonding	Enhanced bonding verification	Reduce ignition likelihood
Ventilation	Methane dispersion assumptions	Conservative zoning and sensor placement	Reduce accumulation probability

8.3 RRF VALIDATION AND PARAMETER CONFIRMATION

Consistent with T/SP/HAZ30, RRFs associated with ignition prevention layers have been reviewed. No IPL has been invalidated by hydrogen service. Conservative modelling assumptions have been adopted where data uncertainty exists. Hydrogen does not negate the independence of existing protection layers. Where necessary, parameter validation (e.g., ignition probability, jet persistence) is required to maintain defensibility under QRA.

8.4 PROPORTIONALITY ASSESSMENT (ALARP DEMONSTRATION)

Table 6A-2 confirms that each of the identified control enhancements is proportionate and does not constitute a disproportionate burden. None of the measures require structural redesign of MAHP infrastructure, reclassification of NTS assets, or fundamental alteration of QRA methodology.

Table 6A-2 – Proportionality of Identified Control Enhancements

Measure	Risk Reduction Mechanism	Grossly Disproportionate?
DBB minimum requirement	Eliminates single-point isolation failure	No
Reduced inspection intervals	Early detection of degradation	No
Extended hot work exclusion	Mitigates extended ignitable envelope	No
Enhanced detection	Early identification of accumulation	No

8.5 RESIDUAL RISK AND UNCERTAINTY STATEMENT

Residual uncertainties remain in relation to ignition probability data confidence, ventilation gradient variability in enclosed spaces, and long-term material behaviour under hydrogen exposure. Table 6A-3 summarises these uncertainties and the conservative treatment applied. Where uncertainty exists, conservative modelling parameters and enhanced monitoring controls have been adopted. Residual risk remains bounded within existing MAH classifications and within tolerability criteria defined in T/SP/G36.

Table 6A-3 – Residual Risk Overview

Uncertainty Area	Nature of Uncertainty	Treatment Applied
Ignition probability data confidence	Limited hydrogen-specific ignition probability data for high-pressure NTS conditions	Conservative modelling parameters adopted; TBM to govern until validated
Ventilation gradient variability	Hydrogen vertical stratification behaviour may vary with enclosure geometry and ambient conditions	Conservative hazardous area zoning and enhanced ceiling-level detection

Uncertainty Area	Nature of Uncertainty	Treatment Applied
Long-term material behaviour	Hydrogen embrittlement and seal degradation rates under sustained hydrogen exposure not fully characterised	50% inspection interval reduction; enhanced NDT; monitoring programme

8.6 ALARP CONCLUSION (FORMAL STATEMENT)

On the basis of empirical 80 bar ignition testing, QRA-aligned consequence modelling, HAZ30-based IPL validation, and proportionate safeguard enhancement, hydrogen ignition risk for blends up to 20% and 100% hydrogen service (with conservative modelling parameters) can be reduced to Tolerable if ALARP levels consistent with T/SP/G36 and T/SP/HAZ30. The detailed QRA parameter validation, event tree derivations, and sensitivity analyses are provided in the Final Technical Report (NGT-06-D35-00-11).

8.7 GOVERNANCE OF HYDROGEN MODELLING ASSUMPTIONS

Hydrogen-specific modelling parameters, including ignition probability and jet flame persistence assumptions, shall be formally governed within NTS QRA processes under the NGT Technical Authority framework (T/PM/TR17). Ownership of these parameters will be assigned to the appropriate Technical Authority function, and review triggers will be aligned with blend percentage escalation or introduction of new empirical evidence from operational deployment or further testing. This governance approach ensures continued alignment with T/SP/G36 and T/SP/HAZ30 methodologies without requiring structural change to existing safety management systems. A Technical Basis Memorandum (TBM) is to be issued as the immediate governance instrument, to be referenced in all QRA, LOPA and hazard assessments involving hydrogen service until formal standards revision is complete. Governance reviews are to be embedded as formal stage-gate requirements within the Hydrogen Transition Programme, consistent with the post-deployment evidence review commitment set out in Section 9 of this report.

9 BENEFITS, LIMITATIONS & ASSUMPTIONS

9.1 BENEFITS FOR NGT

This project delivers measurable and enduring value across risk reduction, regulatory compliance and organisational capability. Most significantly, it provides NGT with a validated, transmission-specific evidence base for hydrogen ignition risk that did not previously exist. Prior to this work, safety assessments for hydrogen on the NTS were dependent on methane-derived parameters or lower-pressure hydrogen research that could not be confidently applied to NTS operating conditions. The physical testing programme at 80 bar has directly addressed this gap, producing quantified ignition thresholds, hazard zone dimensions and accumulation timescales that are appropriate for the transmission environment.

From a risk reduction perspective, the project establishes a clear hierarchy of ignition controls — engineering, procedural and monitoring — f[redacted]evaluated hazard scenarios, enabling NGT to direct investment and operational effort proportionately. The LOPA sensitivity criteria developed for twelve key scenarios provide a repeatable, defensible methodology for future risk assessments, reducing reliance on conservative assumptions that may otherwise over-specify protection requirements or obscure genuine risk priorities.

In terms of regulatory compliance, the project strengthens NGT's position with both HSE and Ofgem by demonstrating that hydrogen safety case development is proceeding on an evidence-led basis. The systematic mapping of technical findings to statutory requirements — DSEAR, COMAH, PSR, PSSR and GSMR — confirms there are no unmitigated compliance gaps at this stage of the transition programme. The policy review outputs, including draft amendment wording for corporate standards, further demonstrate a structured and proactive approach to governance that supports NIA funding objectives and ALARP justification.

9.2 LIMITATIONS OF AVAILABLE EVIDENCE AND TESTING

Several limitations should be acknowledged to ensure transparency for reviewers. Physical testing was conducted under controlled laboratory conditions, which, while designed to be representative of NTS operations, cannot fully replicate the variability of real-world site environments, including wind conditions, ambient temperatures, enclosure geometries and the presence of concurrent activities. Results should therefore be treated as providing validated reference points rather than exhaustive operational envelopes.

The testing programme focused on four priority ignition scenarios selected following the WP1 stage gate review. Whilst this prioritisation was technically justified and agreed with NGT, scenarios ranked in the medium-priority "review" band — including auto-ignition during high-pressure releases and electrical arcing — were not physically tested. Ignition likelihood assessments for these mechanisms continue to rely on literature sources, some of which have limited applicability to transmission-scale conditions. Additionally, the incident database evidence reviewed in WP1 was found to capture only a subset of hydrogen-related events, introducing uncertainty in frequency-based likelihood estimates.

9.3 DEPENDENCIES ON FUTURE WORK

Several findings from this project are conditional on subsequent actions to be fully realised. The LOPA sensitivity criteria and QRA parameter updates identified in WP4 require formal validation exercises within T/SP/G36, T/SP/HAZ30 and T/SP/HAZ16 before they can be routinely applied in safety studies. Until this validation is complete, a Technical Basis Memorandum should be referenced in all relevant assessments. The asset conversion recommendations — particularly regarding material compatibility and inspection interval reductions — require integration with the broader Hydrogen Transition Programme and the parallel ATEX Mechanical Ignition Risk project to avoid duplication and ensure coherent implementation. A post-deployment evidence review, embedded as a formal stage-gate within the transition programme, is recommended to validate modelling assumptions once initial hydrogen operational experience has been accumulated.

10 CONCLUSIONS

Hydrogen ignition risk on the National Transmission System is real, technically complex and meaningfully different from the ignition risk profile of natural gas. This project has confirmed that hydrogen's low minimum ignition energy, wide flammability range and buoyancy-driven dispersion behaviour create ignition hazards across a broader range of operational scenarios than methane, and that transmission-scale pressures extend hazard zones significantly beyond those documented in lower-pressure research. However, the overall conclusion is not that hydrogen is unmanageable on the NTS, it is that the risk can be characterised and quantified and, with appropriate controls in place, can be reduced to tolerable and ALARP levels. The physical testing programme validated this position by establishing quantified, transmission-relevant thresholds for the four highest-priority ignition mechanisms, providing a defensible technical foundation for the safety case work that will underpin hydrogen introduction.

The feasibility of mitigation has been clearly demonstrated. Existing engineering frameworks, risk assessment methodologies and regulatory structures remain fundamentally sound for hydrogen service and do not require wholesale replacement. What is required is targeted refinement: extended isolation philosophies, enhanced inspection regimes, material compatibility verification, revised hot work exclusion distances and updated modelling parameters within corporate standards. Critically, these mitigations are proportionate, technically achievable and buildable upon existing NGT operational practice. The structured safeguard hierarchy developed in WP3, combined with the LOPA sensitivity criteria for twelve key scenarios, gives NGT a consistent and repeatable basis for applying these controls across asset types as the hydrogen transition programme advances.

Notwithstanding the significant progress made, several knowledge gaps remain that require structured resolution before full hydrogen conversion can be completed with confidence. [redacted]. Ignition probability inputs and QRA parameters within key corporate standards require formal hydrogen-specific validation before routine application in safety studies. Longer-term, integrity management under hydrogen service — [redacted]ost-deployment evidence review, formally embedded within the Hydrogen Transition Programme governance structure, is essential to ensure that the assumptions underpinning this safety case remain valid as the network evolves.

11 RECOMMENDATIONS AND FUTURE OPPORTUNITIES

11.1 SUGGESTED FURTHER TESTING AND MODELLING

Whilst this project has substantially advanced the evidence base for hydrogen ignition risk on the NTS, targeted further work is warranted to address the gaps that remain following the WP1 prioritisation exercise. The medium-priority ignition mechanisms — [redacted] It is recommended that a follow-on testing programme be scoped to address these scenarios, with particular emphasis on compressor station environments where severity ratings are highest and the consequences of ignition most significant.

On the modelling side, a formal parameter validation exercise is recommended for the quantitative risk and hazard assessment tools [redacted] This should include sensitivity analysis to establish whether methane-derived ignition probability inputs remain conservative when applied to hydrogen scenarios, or whether calibrated hydrogen-specific values are needed. Complementary CFD modelling of hydrogen dispersion in representative NTS enclosure geometries — building on the enclosure accumulation data generated in WP2 — would further strengthen the basis for hazardous area classification decisions at compressor stations and AGIs. As hydrogen blend compositions on the network evolve beyond 20%, additional testing to characterise ignition behaviour across a wider compositional range would ensure the evidence base remains current and proportionate.

11.2 POLICY CHANGES

The immediate priority is the preparation and formal issue of a Technical Basis Memorandum consolidating the hydrogen-specific ignition modelling assumptions generated by this project. This document should be referenced in all QRA, LOPA and hazard assessment studies involving hydrogen or high-proportion blends until the underlying corporate standards have been formally updated. Draft amendment wording developed during WP4 provides a ready foundation for progressing textual updates t[redacted] through NGT's standards governance cycle, and this work should be initiated without delay.

Explosion group classification methodology warrants explicit clarification within corporate standards, particularly the basis on which equipment selection references MESG versus MIC criteria, to ensure consistent and defensible decision-making as hydrogen infrastructure is commissioned. Integrity management standards should be updated to formally address hydrogen embrittlement, elastomer permeation performance and transitional material degradation. Engagement with BSI and ISO technical committees is recommended to support future revisions to BS EN 60079-10-1 and EN ISO 21789:2022, with the technical evidence generated by this programme providing a credible and well-documented contribution to those processes.

11.3 OPERATIONAL AND SAFETY STRATEGY ENHANCEMENTS

The operational changes identified in WP3 should be progressed as a coordinated implementation programme rather than managed as individual procedure updates. A consolidated hydrogen operational readiness workstream — aligned with the Hydrogen Transition Programme and coordinated with the parallel ATEX Mechanical Ignition Risk project — would ensure that maintenance strategy modifications, permit-to-work revisions, isolation philosophy changes and material replacement programmes are delivered coherently and without duplication of effort.

Emergency response arrangements across NTS sites should be reviewed and updated to explicitly address hydrogen-specific hazards, including invisible flame detection, extended jet fire persistence and appropriate exclusion zone definitions for high-pressure releases. Hydrogen awareness training for operational and maintenance personnel should be developed in parallel, ensuring that the procedural controls identified in this project are fully understood and consistently applied in the field.

Looking further ahead, the evidence base and governance framework established by this project positions NGT well to incorporate operational learning systematically as hydrogen is introduced. A formal post-deployment evidence review, embedded as a stage-gate requirement within the Hydrogen Transition Programme, would ensure that safety case assumptions are revisited against real-world experience and that the overall risk management strategy evolves in step with the network as it transitions towards net zero.

12 NIA INTERFACES

The learning generated by this project carries value well beyond NGT's internal programme, and a structured approach to dissemination is essential to maximise its impact across the wider industry and satisfy Ofgem's NIA requirements for knowledge sharing.

Internally, the technical outputs — including the validated ignition thresholds, LOPA sensitivity criteria, safeguard hierarchies and policy amendment recommendations — will be disseminated through NGT's engineering and safety functions via the Hydrogen Transition Programme governance framework. The Technical Basis Memorandum recommended in WP4 will serve as the primary internal reference document, ensuring consistent application of project findings across all future QRA, LOPA and hazard assessment activities. Lessons learned will also be shared with relevant internal teams through stakeholder workshops and embedded within updated training and competency frameworks as they are developed.

Externally, the project findings will be published through the Energy Networks Association's Smarter Networks Portal, fulfilling the NIA closure reporting requirement and making the technical evidence base accessible to other network operators, gas distribution networks and industry researchers. Engagement with BSI and ISO technical committees, as recommended in WP4, provides a further channel through which the quantitative data generated by this project can contribute directly to the evolution of industry standards. Collaboration with related projects — including the ATEX Mechanical Ignition Risk project and the HAIM programme led by SGN — will ensure findings are integrated with complementary workstreams and that duplication of future research effort is avoided.

This approach directly supports Ofgem's NIA learning objectives by demonstrating that publicly funded innovation delivers new knowledge that is transparently reported, practically applicable, and made available to the broader industry. The combination of quantified experimental data, structured policy recommendations and an open dissemination strategy ensures that the investment made in this project delivers lasting value to consumers, operators and the wider energy transition.

12.1 NIA ELIGIBILITY CRITERIA CONFIRMATION

The following table confirms compliance against Ofgem's six NIA eligibility criteria as required by the Statement of Work. Each criterion is mapped to the specific project outputs that satisfy it, confirming the project's eligibility for NIA closure reporting through the ENA Smarter Networks Portal.

Table 10-1 – NIA Eligibility Criteria Compliance Mapping

NIA Criterion	Criterion Description	How This Project Satisfies It
1. Innovation beyond baseline	The project must deliver activity beyond what network operators are required to do under licence or regulatory baseline obligations.	Physical testing at 80 bar transmission pressure for hydrogen ignition thresholds is not required by any current regulatory obligation and represents genuine innovation beyond methane-based baseline safety practice.

NIA Criterion	Criterion Description	How This Project Satisfies It
2. Consumer benefit	The project must demonstrate that learning will deliver tangible benefit to current or future consumers through improved safety, efficiency or cost outcomes.	Validated ignition thresholds and LOPA criteria reduce the need for over-conservative safety margins, supporting efficient asset conversion without unnecessary infrastructure redesign. Safer hydrogen deployment directly enables the decarbonisation benefits consumers will receive from the net zero transition.
3. Industry learning and dissemination	Outputs must be made available to the wider industry through appropriate channels, not retained exclusively by the project sponsor.	Findings will be published on the ENA Smarter Networks Portal. Engagement with BSI and ISO technical committees will contribute to standards evolution. Collaboration with the ATEX Mechanical Ignition Risk project and the SGN HAIM programme ensures cross-industry integration.
4. Replicability and wider applicability	The approach and outputs should be capable of being applied or built upon by other network operators or industry parties.	The LOPA sensitivity criteria, safeguard hierarchy and QRA parameter guidance developed are structured for application across GDN and GTO operators. The evidence base is explicitly designed to inform future industry-wide standards, not NTS-specific only.
5. Net zero and energy transition support	The project must support the delivery of net zero targets and the transition to low-carbon energy systems.	The project directly enables safe hydrogen introduction on the NTS, which is a critical component of the UK's net zero strategy. Without the evidence base this project provides, the safety case underpinning hydrogen deployment at transmission scale could not be completed.
6. Value for money	The scope, methodology and cost of the project must be proportionate to the outputs and benefits delivered.	The four-work-package structure progressed efficiently from literature review through stage-gate selection to targeted physical testing, avoiding unnecessary test scope. The outputs — validated thresholds, 12 LOPA criteria, 123 hazard scenarios assessed, four policy-level reviews — represent substantial delivery relative to a focused NIA investment.

13 SUSTAINABILITY

This project directly supports the UK Government's net zero target by generating the evidence base required to enable safe hydrogen deployment on the National Transmission System. The NTS carries energy to millions of homes and businesses; transitioning it from natural gas to hydrogen is one of the highest-impact decarbonisation levers available in the UK energy system. The ignition safety case work delivered by this project removes a critical barrier to that transition by confirming that hydrogen ignition risk is quantifiable and manageable, and by providing the validated thresholds and operational controls that underpin a defensible safety case. Without this foundation, the safety case development required for hydrogen introduction could not proceed on an evidence-led basis.

The project approach reflects circular economic principles in the context of infrastructure transition. A central finding is that the vast majority of existing NTS assets — pipelines, compressor stations, offtakes and AGIs — do not require structural replacement or fundamental redesign for hydrogen service. The recommended changes are refinement-based: enhanced isolation philosophies, modified inspection intervals, targeted material substitutions and updated operating procedures. This approach maximises the residual value of existing infrastructure investment, avoids the significant embodied carbon cost of wholesale asset replacement, and minimises construction waste and material consumption associated with a ground-up rebuild programme. The economic and environmental case for repurposing existing assets rather than constructing new hydrogen-specific infrastructure is therefore supported by the technical findings of this project.

At a programme level, the physical testing methodology adopted in WP2 was designed to minimise waste and resource consumption while maximising the quality and applicability of the data generated. Testing was conducted at a specialist facility using controlled release quantities, with test parameters selected through the WP1 stage-gate process to eliminate unnecessary test scope. The four scenarios advanced to physical testing represent the highest-priority mechanisms only, avoiding expenditure of materials, energy and consumables on mechanisms classified as low-probability or adequately characterised by existing literature. The learning generated is designed to be durable: by establishing quantified transmission-relevant thresholds rather than scenario-specific results, the outputs support a wide range of future safety case applications without requiring repeated testing as the hydrogen transition programme advances.

14 REFERENCES

1. NGT-06-D35-00-11; Final Technical Report
2. NGT-06-D35-00-2; WP1 Report; Rev 1
3. VB1846 -1; "Investigation of methane hydrogen mixtures and pure hydrogen" (WP2 Report)
4. "Research Report" (annexe to WP2 Report)
5. NGT-06-D35-00-4; WP3 Report Rev 1
6. NGT-06-D35-00-13; WP4 Report Rev 1