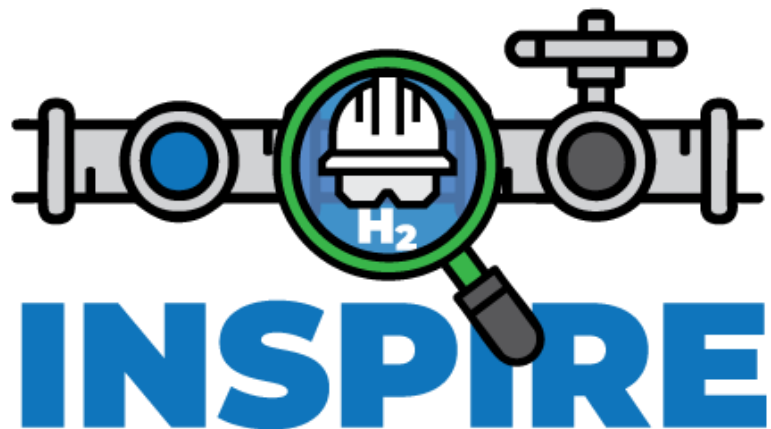




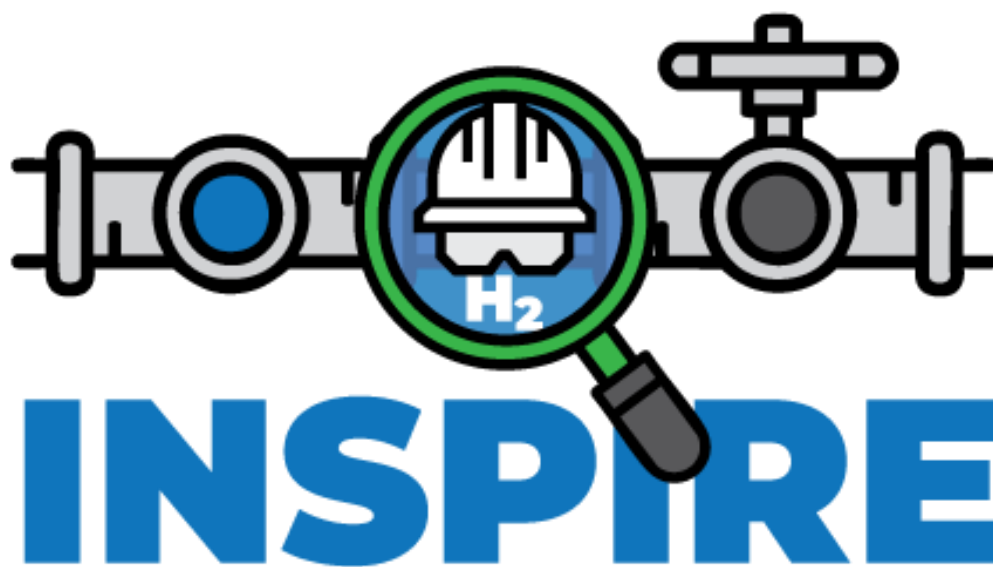
Case Studies to Support Augmented Reality Training in Hydrogen Pipeline Welding Inspection

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1. Introduction

The INSPIRE project aims to support the development of specialised competences for welding inspection in hydrogen (H₂) pipeline applications, combining updated training content with innovative learning approaches based on Augmented Reality (AR).

As part of WP4, a set of case studies was developed to translate the knowledge and competences addressed by the INSPIRE Competence Units into realistic welding inspection scenarios. The case studies place learners in situations requiring them to analyse information, identify hydrogen-specific risks, interpret inspection evidence and make justified decisions within the context of H₂ pipeline applications.

To ensure consistency across the resources developed by the partnership, a common case study template was established and applied. The case studies address different aspects of hydrogen pipeline welding inspection and follow a harmonised structure covering the scenario context, learning objectives and competence links, information provided to the learner, inspection workflow and decision points, relevant risks and acceptance considerations, assessment elements and guidance for trainers. They also identify potential AR interaction points, providing a basis for their subsequent adaptation into immersive and interactive learning experiences.

Together, the case studies provide scenario-based training resources that complement the INSPIRE Competence Units and support the application of theoretical knowledge to practical inspection situations. Their structure is intended to facilitate use by VET providers and trainers while supporting the integration of Augmented Reality into welding inspection training.



2. Case Study 01 – Safety for H₂ Working

2.1 Case Study Identification

Case Study ID: INSPIRE-CS-H2-01

Title: Hydrogen-Specific Safety Management During Welding of a High-Pressure Hydrogen Pipeline

Related Competence Unit (CU): CU-H2-01A – H₂ Material Integrity and Safety

EQF Level: 5 / 6

Estimated Learner Time: 60–75 minutes

2.2 Context & Scenario Description

A new high-pressure hydrogen transmission pipeline is under construction to connect a hydrogen production facility to an industrial end user. The pipeline is designed to transport pure gaseous hydrogen at operating pressures exceeding 80 bar.

The pipeline material is a high-strength low-alloy (HSLA) steel, qualified for hydrogen service. Girth welds are performed on-site using approved welding procedures. Welding activities are carried out inside a partially confined trench, approximately 2.5 m deep, with limited natural ventilation.

The construction contractor has extensive experience in natural gas pipeline projects, but limited prior exposure to hydrogen infrastructure. Hydrogen-specific safety training for site personnel has not yet been formally documented.

2.3 Learning Objectives & Competence Links

After completing this case study, the learner will be able to:

- LO1: Identify hydrogen-specific safety hazards during pipeline welding operations
- LO2: Evaluate whether site safety measures are adequate for hydrogen service
- LO3: Justify inspection decisions based on hydrogen safety principles



Competence areas addressed:

- ☐ Safety & H₂ working practices
- ☐ Welding inspection
- ☐ Hydrogen degradation mechanisms
- ☐ Inspection decision-making & responsibility

2.4 Inputs Provided to the Learner

Documentation

- ☐ Welding Procedure Specification (WPS)
- ☐ Inspection & Test Plan (ITP)
- ☐ Job Safety Analysis (JSA) – generic “flammable gas” version
- ☐ Site emergency response plan (non-hydrogen-specific)

Inspection & Site Data

- ☐ Trench depth and geometry
- ☐ Ventilation equipment description
- ☐ Gas detector specifications (methane-calibrated)
- ☐ PPE list used by welding crew

Visual Material

- ☐ Site photographs of welding inside trench
- ☐ Diagram of trench configuration
- ☐ Gas detector display images

2.5 Step-by-Step Inspection Workflow

Step 1 – Pre-Inspection Review

- ☐ JSA content and hazard identification
- ☐ Gas detection and ventilation provisions
- ☐ Emergency response documentation



Decision Point 1:

- ☐ Accept
- ☐ Request clarification
- ☐ Stop work

Step 2 – On-Site Observation

The inspector observes that:

- Welding is ongoing inside a 2.5 m deep trench
- Ventilation fans operate intermittently
- Gas detectors are calibrated for methane (CH₄)
- No hydrogen-specific emergency signage is displayed
- Workers lack anti-static grounding equipment
- No continuous atmospheric monitoring records exist

Decision Point 2:

Expected inspector action: Identify hydrogen-specific safety gaps and raise safety concern

Step 3 – Technical & Safety Evaluation

The inspector evaluates hydrogen-specific risks:

- Hydrogen's low ignition energy combined with active welding arc
- Risk of gas accumulation in confined trench
- Inadequacy of methane-calibrated detectors for hydrogen
- Absence of hydrogen-specific JSA and emergency procedures

Decision Point 3:

- ☐ Accept weld
- ☐ Reject weld
- ☐ Require corrective action | Stop work until corrective actions are implemented

Step 4 – Final Decision & Reporting

The inspector:

- Issues a stop-work instruction
- Documents hydrogen-related safety non-conformities



- Requires corrective actions before welding resumes
- Records decision in inspection and safety reports

2.6 Defects, Risks & Acceptance Criteria

Identified Defects / Risks

- Hydrogen accumulation in confined space
- Ignition due to welding arc or static discharge
- Delayed detection of hydrogen leaks
- Personnel exposure due to lack of awareness

Standards & Acceptance Criteria

- Hydrogen safety principles from international H₂ guidelines
- Confined space and flammable gas safety requirements
- Project safety specifications and HSE rules

(Acceptance criteria: welding shall not proceed unless hydrogen-specific safety controls are in place)

2.7 AR Interaction Points (Conceptual – Future Use)

Potential AR elements:

- Visualisation of hydrogen gas accumulation in trench
- Gas detector alarm simulation
- Highlighting missing grounding equipment
- Real-time feedback on inspector decisions

2.8 Case Study Learning Assessment

The following activities are intended to support formative assessment within the case study and do not replace the formal assessment requirements established for the INSPIRE Competence Units.

Assessment Items

- MCQs on hydrogen properties and safety
- Scenario-based decision-making question
- Short written justification of stop-work decision



Expected Answers

- Methane-calibrated detectors are not suitable for hydrogen
- Intermittent ventilation is insufficient in confined hydrogen welding
- Inspector has authority to stop work on safety grounds

Scoring Criteria

- Correct identification of hydrogen risks
- Safety-first decision logic
- Proper justification based on hydrogen behaviour

2.9 Instructor Notes (Internal Use Only)

- Common error: treating hydrogen like natural gas
- Emphasise invisible flame and ignition sensitivity
- Reinforce inspector's safety authority

2.10 Case Study Summary

This case study highlights that hydrogen is not "just another gas." Welding inspectors must apply enhanced safety awareness, recognise hydrogen-specific hazards, and confidently exercise stop-work authority when conditions are unsafe.



3. Case Study 02 – Industrial Standards for H₂ Pipelines

3.1 Case Study Identification

Case Study ID: INSPIRE-CS-H2-02

Title: Application of Industrial Standards for Welding and Inspection of Hydrogen Pipelines

Related Competence Unit (CU): CU-H2-02B – Inspection & Testing for Hydrogen Pipelines

EQF Level: 5 / 6

Estimated Learner Time: 60–75 minutes

3.2 Context & Scenario Description

A long-distance onshore hydrogen transmission pipeline is under construction as part of a national hydrogen infrastructure project. The pipeline is intended to transport pure hydrogen gas at high pressure and will be integrated into a future hydrogen network.

The contractor responsible for construction has extensive experience in natural gas pipeline projects. Welding and inspection activities are performed according to well-established pipeline standards that have historically been used for natural gas service.

During a routine documentation review, the Welding Inspector observes that the project specifications and inspection documentation reference general pipeline welding standards only, with no explicit reference to hydrogen-specific standards or requirements.

The contractor states that: These standards are internationally recognised and have been used successfully for decades in pipeline projects.

3.3 Learning Objectives & Competence Links

After completing this case study, the learner will be able to:

LO1: Identify standards applicable to hydrogen pipeline welding and inspection

LO2: Distinguish between natural gas and hydrogen requirements in standards

LO3: Evaluate whether acceptance criteria are suitable for hydrogen service

LO4: Clarify responsibilities for standards compliance in hydrogen projects



Competence areas addressed:

Standards interpretation

- ☒ Welding inspection
- ☒ Hydrogen awareness
- ☒ Inspection decision-making

3.4 Inputs Provided to the Learner

Documentation

- ☐ Project technical specification
- ☐ Welding Procedure Specification (WPS)
- ☐ Inspection & Test Plan (ITP)
- ☐ List of referenced standards (general pipeline standards only)

Inspection & Site Data

- ☐ Pipeline design pressure and service description
- ☐ Material grade and wall thickness
- ☐ Welding processes and heat input ranges

Visual Material

- ☐ Extracts of standards referenced in project documentation
- ☐ Pipeline layout diagram

3.5 Step-by-Step Inspection Workflow

Step 1 – Pre-Inspection Documentation Review

The inspector reviews:

- Project specification and scope of service
- Referenced welding and inspection standards
- Acceptance criteria for weld quality and hardness



The inspector notes that:

- Standards commonly used for natural gas pipelines are referenced
- No hydrogen-specific guidance or limitations are included

Decision Point 1:

- ☐ Accept documentation as-is
- ☐ Request clarification on hydrogen applicability
- ☐ Stop work

Step 2 – Standards Applicability Assessment

The inspector evaluates whether the referenced standards:

- Explicitly permit hydrogen service
- Address hydrogen-related risks (e.g. embrittlement, hardness limits)
- Include guidance on inspection methods suitable for hydrogen pipelines

The contractor argues that: Hydrogen is also a gas, so the same acceptance criteria apply.

Decision Point 2:

Expected inspector action: Challenge the applicability of standards and request hydrogen-specific justification

Step 3 – Technical Evaluation of Acceptance Criteria

The inspector reviews:

- Weld defect acceptance limits
- Hardness limits in weld metal and HAZ
- NDT method suitability

The inspector identifies that:

- Acceptance criteria are based on natural gas service
- Hydrogen-related degradation mechanisms are not addressed
- No reference is made to hydrogen-specific annexes or complementary standards



Decision Point 3:

- ☐ Accept acceptance criteria
- ☐ Reject with additional controls
- ☐ Reject documentation until hydrogen-appropriate standards are applied

Step 4 – Final Decision & Reporting

The inspector:

- Issues a formal comment / non-conformance on documentation
- Requires identification and application of hydrogen-relevant standards
- Requests update of WPS, ITP, and acceptance criteria
- Documents decision in inspection report

3.6 Defects, Risks & Acceptance Criteria

Identified Risks

- ☐ Use of inappropriate acceptance criteria for hydrogen service
- ☐ Increased risk of hydrogen embrittlement
- ☐ Undetected planar defects critical for hydrogen pipelines
- ☐ Long-term integrity risk due to standards misapplication

Applicable Standards

- ☐ ISO / EN pipeline welding standards (hydrogen applicability check required)
- ☐ ASME / API standards with hydrogen-related provisions
- ☐ Hydrogen-specific guidelines and technical reports

(Acceptance criteria: standards must be verified as suitable for hydrogen service — not assumed)

3.7 AR Interaction Points (Conceptual – Future Use)

Potential AR elements:

- Interactive standard selection menu
- Highlighting clauses relevant to hydrogen service
- Comparison between natural gas and hydrogen acceptance criteria
- Immediate feedback on correct/incorrect standard choice



3.8 Case Study Learning Assessment

The following activities are intended to support formative assessment within the case study and do not replace the formal assessment requirements established for the INSPIRE Competence Units.

Assessment Items

- MCQs on standards applicability for hydrogen pipelines
- Scenario-based question: accept or reject documentation
- Short written justification of inspector's decision

Expected Answers

- Not all pipeline standards are automatically applicable to hydrogen
- Hydrogen service requires stricter control of defects and hardness
- Responsibility for compliance lies with contractor and operator, verified by inspector

Scoring Criteria

- Correct identification of applicable standards
- Understanding of hydrogen-specific requirements
- Logical and standards-based decision-making

3.9 Instructor Notes (Internal Use Only)

- Common misconception: "international standard = hydrogen-compatible"
- Emphasize inspector's duty to verify applicability, not assume compliance
- Encourage discussion on shared responsibility (contractor-operator-inspector)

3.10 Case Study Summary

This case study demonstrates that using internationally recognised standards is not sufficient unless their applicability to hydrogen service is clearly established.

Welding inspectors play a key role in ensuring that standards, acceptance criteria, and inspection methods are appropriate for hydrogen pipelines, protecting long-term safety and integrity.



4. Case Study 03 – Defects of H₂ Pipeline Welds

4.1 Case Study Identification

Case Study ID: INSPIRE-CS-H2-03

Title: Identification and Assessment of Hydrogen-Critical Defects in Pipeline Girth Welds

Related Competence Unit (CU): CU-H2-02B – Inspection & Testing for Hydrogen Pipelines

EQF Level: 5 / 6

Estimated Learner Time: 75–90 minutes

4.2. Context & Scenario Description

A newly constructed high-pressure hydrogen transmission pipeline has completed welding and initial non-destructive testing. The pipeline is intended for pure hydrogen service and will operate at pressures above 70 bar.

The pipeline is manufactured from high-strength pipeline steel, and girth welds were executed on-site using mechanised GMAW with qualified welding procedures. Visual inspection (VT) and Radiographic Testing (RT) were performed during construction, and all welds were reported as acceptable according to the referenced pipeline standards.

Several months after commissioning preparation, during pre-service integrity verification, additional ultrasonic testing (UT) identifies indications in the heat-affected zone (HAZ) of selected girth welds.

4.3. Learning Objectives & Competence Links

After completing this case study, the learner will be able to:

- LO1: Identify weld defects that are critical for hydrogen service
- LO2: Distinguish fabrication defects from hydrogen-induced damage
- LO3: Evaluate NDT method suitability for hydrogen pipelines
- LO4: Apply hydrogen-appropriate acceptance criteria and inspection judgment



Competence areas addressed:

Standards interpretation

- ☒ Welding inspection
- ☒ Hydrogen degradation mechanisms
- ☒ NDT selection and interpretation
- ☒ Inspection decision-making

4.4. Inputs Provided to the Learner

Documentation

- ☐ Welding Procedure Specification (WPS)
- ☐ Procedure Qualification Record (PQR)
- ☐ Inspection & Test Plan (ITP)
- ☐ RT reports and acceptance records
- ☐ Applicable pipeline welding standard)

Inspection & Site Data

- ☐ UT / PAUT reports indicating planar indications
- ☐ Weld maps showing defect locations
- ☐ Hardness survey results (selected welds)
- ☐ Welding heat input and preheat data

Visual Material

- ☐ UT/PAUT scan images
- ☐ Weld macro photographs
- ☐ Schematic of defect location (WM / HAZ)



4.5 Step-by-Step Inspection Workflow

Step 1 – Review of Previous Inspection Results

The inspector reviews:

- RT acceptance reports
- Original VT findings
- Acceptance criteria applied during construction

The inspector notes that:

- RT showed no volumetric defects
- No additional UT or PAUT was specified initially

Decision Point 1:

- ☐ Accept previous inspection as sufficient
- ☒ Proceed with detailed evaluation of new UT indications
- ☐ Dismiss UT results

Step 2 – Evaluation of Detected Indications

UT/PAUT reveals:

- Planar indications located in the HAZ
- Indications oriented parallel to the weld fusion line
- No clear volumetric character

The inspector considers whether:

- These defects could propagate under hydrogen exposure
- RT was capable of detecting such defects

Decision Point 2:

Expected inspector action: Treat indications as potentially hydrogen-critical

Step 3 – Hydrogen-Specific Defect Assessment

The inspector evaluates:

- Susceptibility of HAZ to hydrogen-induced cracking



- Local hardness values approaching upper allowable limits
- Welding parameters (heat input, cooling rate)

The inspector recognises that:

- Planar defects acceptable in natural gas pipelines may be unacceptable for hydrogen
- HAZ cracking poses a high integrity risk

Decision Point 3:

- ☐ Accept welds
- ☐ Accept with monitoring
- ☒ Reject welds and require corrective action

Step 4 – Final Decision & Reporting

The inspector:

- Issues a non-conformance report (NCR)
- Requires defect removal and re-welding or weld replacement
- Recommends enhanced NDT (PAUT) for remaining welds
- Updates inspection strategy for hydrogen service

4.6. Defects, Risks & Acceptance Criteria

Identified Defects

- Planar cracking in HAZ
- Potential hydrogen-assisted cold cracking
- High local hardness zones

Hydrogen-Specific Risks

- Crack initiation and propagation under hydrogen pressure
- Reduced fracture toughness in hydrogen environment
- Sudden failure without prior leakage

Acceptance Criteria Considerations

- Stricter defect tolerance for hydrogen pipelines
- Planar defects considered critical regardless of size
- Hardness limits must be strictly enforced



4.7. AR Interaction Points (Conceptual – Future Use)

Potential AR elements:

- Visualisation of HAZ cracking growth under hydrogen exposure
- Interactive UT/PAUT scan interpretation
- Comparison between RT-visible and RT-invisible defects
- Feedback on inspector decision pathways

4.8. Case Study Learning Assessment

The following activities are intended to support formative assessment within the case study and do not replace the formal assessment requirements established for the INSPIRE Competence Units.

Assessment Items

- MCQs on hydrogen-related weld defects
- Scenario-based defect acceptance decision
- Short written justification for weld rejection

Expected Answers

- RT alone is insufficient for hydrogen pipelines
- Planar HAZ defects are hydrogen-critical
- UT/PAUT provides superior detection of planar defects

Scoring Criteria

- Correct defect classification
- Understanding of hydrogen degradation mechanisms
- Appropriate application of acceptance criteria

4.9. Instructor Notes (Internal Use Only)

- Common misconception: “RT acceptance = weld integrity”
- Emphasise hydrogen’s effect on crack sensitivity
- Highlight importance of NDT method selection



4.10. Case Study Summary

This case study demonstrates that defects acceptable in conventional pipelines may be unacceptable in hydrogen service.

Hydrogen pipelines require enhanced inspection methods, stricter acceptance criteria, and inspector judgment focused on long-term integrity, not only construction acceptance.



5. Case Study 04 – Accidents of H₂ Pipelines

5.1 Case Study Identification

Case Study ID: INSPIRE-CS-H2-04

Title: Investigation of a Hydrogen Pipeline Accident Related to Weld Integrity and Inspection Decisions

Related Competence Unit (CU):

- CU-H2-01A – H₂ Material Integrity and Safety
- CU-H2-02B – Inspection & Testing for Hydrogen Pipelines

EQF Level: 5 / 6

Estimated Learner Time: 75–90 minutes

5.2. Context & Scenario Description

A high-pressure onshore hydrogen pipeline has been commissioned to transport pure hydrogen from a production facility to an industrial consumer. The pipeline has been in operation for less than one year.

During normal operation, a sudden hydrogen release occurs in a remote section of the pipeline route, followed by ignition and jet flame formation. Emergency shutdown systems activate successfully, and no fatalities occur, but the incident results in significant material damage and temporary shutdown of the hydrogen supply.

A formal accident investigation is initiated. The Welding Inspector is asked to support the investigation by reviewing welding, inspection, and acceptance records for the affected pipeline section.

5.3. Learning Objectives & Competence Links

After completing this case study, the learner will be able to:

- LO1: Analyse hydrogen pipeline accidents and identify contributing factors
- LO2: Assess the role of welding defects and inspection decisions in accident causation
- LO3: Apply root-cause analysis principles to hydrogen pipeline failures
- LO4: Identify preventive inspection and quality measures for hydrogen pipelines



Competence areas addressed:

Standards interpretation

- ☒ Safety & H₂ working practices
- ☒ Welding inspection
- ☒ Hydrogen degradation mechanisms
- ☒ Accident investigation & decision-making

5.4. Inputs Provided to the Learner

Documentation

- ☐ Welding Procedure Specification (WPS)
- ☐ Inspection & Test Plan (ITP)
- ☐ Weld acceptance records
- ☐ Non-conformance reports (if any)
- ☐ Commissioning and operation logs

Inspection & Site Data

- ☐ Incident timeline and shutdown records
- ☐ Location of rupture relative to welds
- ☐ Metallurgical examination summary
- ☐ NDT reports (RT, UT) performed during construction

Visual Material

- ☐ Accident site photographs
- ☐ Fracture surface images
- ☐ Pipeline section schematic



5.5 Step-by-Step Inspection Workflow

Step 1 – Initial Incident Review

The inspector reviews:

- Time and conditions of the hydrogen release
- Emergency response performance
- Exact failure location

The failure is located adjacent to a girth weld, within the heat-affected zone (HAZ).

Decision Point 1:

- ☐ Treat incident as operational damage only
- ☒ Proceed with detailed weld-related investigation
- ☐ Close investigation

Step 2 – Review of Welding & Inspection History

The inspector evaluates:

- Welding parameters used for the failed girth weld
- Inspection methods applied during construction
- Acceptance criteria used at the time

Findings:

- Weld accepted based on RT only
- No UT/PAUT performed
- Hardness testing was not mandatory

Decision Point 2:

Expected inspector action: Identify inspection gaps relevant to hydrogen service

Step 3 – Failure Mechanism Assessment

Metallurgical examination reveals:

- Crack initiation in the HAZ
- Features consistent with hydrogen-assisted cracking
- Localised high hardness and low fracture toughness



The inspector correlates:

- Welding heat input
- Absence of hydrogen-specific acceptance criteria
- Early-life failure under hydrogen pressure

Decision Point 3:

- ☐ Classify failure as random defect
- ☐ Attribute failure solely to operation
- ☒ Identify hydrogen-weld interaction as root cause

Step 4 – Final Decision & Reporting

The inspector:

- Confirms welding and inspection practices as contributing factors
- Recommends corrective actions for existing pipelines
- Proposes updates to inspection strategies for future projects

5.6. Defects, Risks & Acceptance Criteria

Identified Failure Contributors

- Undetected planar HAZ defects
- Inadequate inspection method selection
- Acceptance criteria not adapted for hydrogen service

Hydrogen-Specific Risks

- Accelerated crack propagation
- Sudden rupture without leak-before-break
- High-energy hydrogen jet flame

Preventive Acceptance Measures

- Mandatory UT/PAUT for hydrogen pipelines
- Stricter hardness limits and verification
- Hydrogen-specific weld acceptance criteria



5.7. AR Interaction Points (Conceptual – Future Use)

Potential AR elements:

- ☐ Reconstruction of hydrogen jet flame release
- ☐ Visualisation of crack initiation and growth
- ☐ Interactive accident timeline
- ☐ Decision-based branching on inspection choices

5.8. Case Study Learning Assessment

The following activities are intended to support formative assessment within the case study and do not replace the formal assessment requirements established for the INSPIRE Competence Units.

Assessment Items

- MCQs on hydrogen pipeline accident causes
- Scenario-based root-cause analysis question
- Written recommendation of preventive actions

Expected Answers

- Hydrogen embrittlement and weld defects contributed to failure
- RT-only inspection was insufficient
- Enhanced inspection and acceptance criteria are required

Scoring Criteria

- Correct identification of root causes
- Understanding of hydrogen accident behaviour
- Quality of preventive recommendations

5.9. Instructor Notes (Internal Use Only)

- Emphasise that hydrogen pipeline accidents often involve multiple contributing factors
- Reinforce inspector's role in accident prevention, not only acceptance
- Encourage discussion on early-life failures vs long-term degradation



5.10. Case Study Summary

This case study illustrates how seemingly acceptable welds can lead to serious hydrogen pipeline accidents when inspection strategies and acceptance criteria are not adapted for hydrogen service.

Welding inspectors play a critical preventive role by identifying hydrogen-related risks before commissioning, not after failure.



6. Case Study 05 – Measuring of Hardness of Pipeline Welds

6.1 Case Study Identification

Case Study ID: INSPIRE-CS-H2-05

Title: Hardness Measurement and Evaluation of Girth Welds in a High-Pressure Hydrogen Pipeline

Related Competence Unit (CU):

- CU-H2-01A – H₂ Material Integrity and Safety
- CU-H2-02B – Inspection & Testing for Hydrogen Pipelines

EQF Level: 5 / 6

Estimated Learner Time: 75–90 minutes

6.2. Context & Scenario Description

A new onshore hydrogen transmission pipeline is under construction to supply an industrial cluster with pure hydrogen. The pipeline is DN 500 (508 mm OD) with a wall thickness of 12.7 mm, manufactured from API 5L X65 / ISO 3183 L450MB line pipe. The material certificates declare a carbon equivalent CEV (IIW) of 0.43 %. The design pressure is 80 bar and the pipeline is intended for 100 % hydrogen service.

Girth welds are produced on site: root pass by SMAW with basic-coated low-hydrogen electrodes (E7018 H4R), fill and cap passes by mechanised GMAW. The qualified WPS requires a minimum preheat of 100 °C, a maximum interpass temperature of 250 °C and a heat input between 0.8 and 1.5 kJ/mm.

The Inspection and Test Plan (ITP) makes hardness testing a mandatory acceptance activity for hydrogen service. It requires HV10 hardness surveys on the macro-sections of the procedure qualification in accordance with ISO 9015-1, and a portable hardness survey using the ultrasonic contact impedance (UCI) method on 10 % of the production girth welds. The project specification limits the hardness of both weld metal and heat-affected zone to 250 HV10.

During week 12 of construction the third-party Welding Inspector performs the scheduled hardness survey on production welds. Several welds produced during a night shift, at an ambient temperature of 4 °C, show hardness values above the specified limit. All of these welds had already been accepted on visual inspection and on radiographic and ultrasonic testing. The inspector must evaluate the results, confirm the validity of the measurement method and decide on acceptance.



6.3. Learning Objectives & Competence Links

After completing this case study, the learner will be able to:

- LO1: Explain why hardness is a critical acceptance parameter for welds in hydrogen service
- LO2: Select and apply the appropriate hardness testing method, test force and measurement locations for pipeline girth welds
- LO3: Evaluate hardness survey results against hydrogen-specific acceptance limits and identify the welding causes of excessive hardness
- LO4: Decide and justify corrective action (re-testing, laboratory verification, repair, replacement) on a standards basis

Competence areas addressed:

- ☒ Industrial standards interpretation
- ☒ Welding inspection
- ☒ Hydrogen degradation mechanisms
- ☒ Hardness testing and measurement validity
- ☒ Inspection decision-making & responsibility

6.4. Inputs Provided to the Learner

Documentation

- ☐ Welding Procedure Specification (WPS) – preheat, interpass and heat input limits
- ☐ Procedure Qualification Record (PQR) including the HV10 macro hardness survey
- ☐ Welder Qualification Records (WPQ)
- ☐ Inspection & Test Plan (ITP) – hardness testing scope and frequency
- ☐ Hardness testing procedure for the portable UCI method
- ☐ Line pipe material certificates (chemical composition, CEV)
- ☐ Extracts from the applicable standards (ISO 6507-1, ISO 9015-1, ASME B31.12, EN 12732)



Inspection & Site Data

- ☐ PQR macro-section hardness survey results (HV10)
- ☐ Portable UCI hardness survey results for the production girth welds
- ☐ Welding records: preheat, interpass temperature, heat input
- ☐ Ambient conditions and welding shift records
- ☐ Laboratory HV10 verification results on a cut-out weld
- ☐ RT and UT reports for the same welds

Visual Material

- ☐ Weld macro-section showing the indentation positions
- ☐ Hardness traverse diagram (BM – HAZ – WM – HAZ – BM)
- ☐ Site photographs of portable hardness testing on the weld cap
- ☐ Sketch of the measurement lines at cap, mid-thickness and root

6.5 Step-by-Step Inspection Workflow

Step 1 – Review of Hardness Testing Requirements and Method

The inspector reviews:

- The hardness limit stated in the project specification: 250 HV10 maximum, for weld metal and heat-affected zone
- The hardness testing requirements of the ITP: full macro survey on the PQR and a portable survey on 10 % of the production girth welds
- The qualified WPS values for preheat, interpass temperature and heat input
- The calibration certificate of the portable hardness instrument and the qualification of the operator

The inspector confirms the methodology to be applied:

- Reference method: Vickers HV10 on macro-sections in accordance with ISO 6507-1 and ISO 9015-1
- Measurement lines: 2 mm below the cap surface, at mid-thickness and 2 mm above the root
- Each line includes indentations in the base metal, in the coarse-grain HAZ adjacent to the fusion line, and in the weld metal, on both sides of the joint
- Site method: portable ultrasonic contact impedance (UCI) testing on locally ground weld surfaces, used as a screening tool only

- Surface preparation: local grinding without overheating the surface, five readings per measurement zone, mean and maximum value reported

The inspector notes that the procedure qualification gave a maximum of 241 HV10 in the root-side coarse-grain HAZ, i.e. below the specified limit of 250 HV10. The procedure is therefore acceptable, but with a margin of only 9 HV.

Table 1 – PQR macro-section hardness survey, HV10 (preheat 100 °C, heat input 1.2 kJ/mm)

Measurement line	Base metal	HAZ (side A)	Weld metal	HAZ (side B)	Base metal
2 mm below cap	198	232	221	228	201
Mid-thickness	195	224	215	220	197
2 mm above root	203	241	226	238	205

Maximum recorded value: 241 HV10 (root-side HAZ). Acceptance limit: 250 HV10. Result: procedure qualification accepted.

Decision Point 1:

- ☐ Accept the hardness testing scope without further review
- ☒ Confirm methodology, acceptance limit and equipment calibration before testing
- ☐ Waive hardness testing on production welds because the PQR was accepted

Step 2 – On-Site Hardness Survey of Production Girth Welds

The inspector carries out the survey:

- 14 of the 140 completed girth welds (10 %) are tested with the calibrated UCI instrument
- Three zones are measured per weld: weld cap, HAZ on each side at 2–3 mm from the fusion line, and the adjacent base metal
- Five readings are taken per zone; the mean and the maximum single reading are recorded
- Any reading deviating by more than 10 % from the mean of the zone is repeated after re-preparation of the surface

Table 2 – Portable UCI hardness survey of production girth welds (maximum values, HV10 equivalent)

Weld ID	Welder	Shift	Preheat recorded (°C)	Max HAZ	Max WM	Assessment
GW-101	W-07	Day	105	228	212	Within limit
GW-103	W-11	Day	100	236	219	Within limit
GW-106	W-07	Day	110	233	217	Within limit
GW-109	W-11	Day	100	244	225	Within limit
GW-112	W-07	Day	105	231	214	Within limit
GW-114	W-19	Night	45	297	268	Above limit
GW-115	W-19	Night	50	288	261	Above limit
GW-117	W-19	Night	40	305	274	Above limit
GW-119	W-11	Day	100	240	223	Within limit
GW-122	W-07	Day	105	237	220	Within limit
GW-125	W-11	Day	110	229	213	Within limit
GW-128	W-19	Day	100	247	231	Within limit (marginal)
GW-131	W-07	Day	105	234	218	Within limit
GW-134	W-11	Day	100	238	221	Within limit

Findings of the survey:

- 3 of the 14 welds exceed the 250 HV10 limit, with maximum HAZ values of 288 to 305 HV10
- All three welds were produced by the same welder during the same night shift, at an ambient temperature of 4 °C with wind
- The preheat recorded for these welds is 40–50 °C, against a WPS minimum of 100 °C
- One further weld (GW-128) is close to the limit at 247 HV10
- The highest values are consistently in the HAZ and not in the weld metal
- All 14 welds had previously been accepted on RT and UT



Decision Point 2:

Expected inspector action: treat the results as a systematic deviation rather than isolated readings, stop welding under the same conditions, extend the hardness survey to 100 % of the welds produced during the affected shifts, and request laboratory verification of the highest readings by the reference method.

Step 3 – Evaluation of Results and Hydrogen-Specific Assessment

The extended survey covers all 22 welds produced during the two night shifts:

- 7 welds exceed 250 HV10 in the HAZ, with a maximum of 311 HV10
- 4 welds fall between 240 and 250 HV10
- 11 welds are below 240 HV10

A cut-out from weld GW-114 is sectioned and tested by the reference method (HV10, ISO 6507-1 and ISO 9015-1) in an accredited laboratory:

Table 3 – Laboratory HV10 verification of weld GW-114

Measurement line	Base metal	HAZ (CG, side A)	Weld metal	HAZ (CG, side B)	Base metal
2 mm below cap	199	271	244	266	202
Mid-thickness	197	283	251	279	200
2 mm above root	204	302	262	296	206

Maximum laboratory value: 302 HV10 in the root-side coarse-grain HAZ, against a limit of 250 HV10. The site UCI maximum for the same weld was 297 HV10, a deviation of 5 HV, which confirms that the portable survey was correctly applied. The laboratory HV10 result is the governing value.

The inspector correlates the results with the welding and site records:

- Preheat of 40–50 °C instead of the qualified minimum of 100 °C
- Ambient temperature of 4 °C with wind, which shortened the cooling time $t_{8/5}$
- Heat input at the lower end of the qualified range (0.85 kJ/mm)
- Base metal CEV (IIW) of 0.43 %, which makes the coarse-grain HAZ sensitive to martensite formation at high cooling rates
- No non-conformance had been raised at the time of welding, because preheat verification was not a recorded hold point in the ITP



Hydrogen-specific considerations:

- Hardness above approximately 250 HV in the HAZ indicates a hard, low-toughness microstructure that is highly susceptible to hydrogen-assisted cracking
- Hydrogen diffuses preferentially towards the hard, highly stressed HAZ, where it lowers local fracture toughness and the threshold stress intensity for crack growth
- A weld that is acceptable for natural gas service on volumetric NDT alone may be unacceptable for hydrogen service on the hardness criterion alone
- No defect exists at the time of inspection, so RT and UT cannot reveal the risk, hardness is the only practical measurable indicator of susceptibility
- Hardness is therefore a preventive acceptance parameter, not a documentation formality

Decision Point 3:

- ☐ Accept the welds because the RT and UT results are acceptable
- ☐ Accept with monitoring during operation
- ☒ Reject the welds exceeding 250 HV10 and require corrective action

Step 4 – Final Decision & Reporting

The inspector:

- Issues a non-conformance report (NCR) for the 7 welds exceeding 250 HV10
- Requires the affected welds to be cut out and re-welded under the qualified WPS, with preheat verified by contact thermometer and recorded for each weld
- Rejects local post-weld heat treatment as a remedy, since no PWHT is included in the qualified welding procedure and no PWHT qualification exists for the project
- Extends hardness testing to 100 % of the welds produced at ambient temperatures below 10 °C
- Confirms the laboratory HV10 result as the governing value, with the portable UCI survey retained as a screening tool
- Requires the ITP to be revised so that preheat verification becomes a recorded hold point and hardness testing is completed before weld acceptance, not after the pressure test
- Reports the hardness results, the deviation from the WPS and the corrective action in the inspection release documentation



6.6. Defects, Risks & Acceptance Criteria

Identified Failure Contributors

- Maximum HAZ hardness of 302–311 HV10 against a specified limit of 250 HV10
- Hardness peak located in the coarse-grain HAZ on the root side of the joint
- Preheat applied below the qualified minimum (40–50 °C instead of 100 °C)
- Heat input at the lower limit of the qualified range combined with a low ambient temperature
- Hard, crack-sensitive microstructure that is not detectable by RT or UT
- Systematic deviation linked to one welder, one shift and one set of ambient conditions

Hydrogen-Specific Risks

- Hydrogen-assisted cracking in a hard, low-toughness heat-affected zone
- Reduced fracture toughness and a lower threshold for crack initiation in hydrogen
- Crack growth under pressure fluctuations without prior leakage (loss of leak-before-break)
- Failure risk that is not revealed by volumetric NDT at the time of construction
- Early-life failure of a pipeline that was formally accepted on NDT

Standards & Acceptance Criteria

- ISO 6507-1 – Vickers hardness test: test force, indentation spacing, surface condition and reporting of HV10 values
- ISO 9015-1 – hardness testing of arc welded joints: measurement lines and indentation positions in base metal, HAZ and weld metal
- DIN 50159-1 – hardness testing with the UCI method: portable results are indicative and must be verified by the reference method where the limit is approached or exceeded
- ISO 15614-1 – welding procedure qualification: hardness testing required for the qualification of the procedure on hardness-sensitive materials
- ASME B31.12, Hydrogen Piping and Pipelines – contains hardness limitations for welds in hydrogen service; the project specification adopts 250 HV10 as the maximum for weld metal and HAZ
- EN 12732 and EN 1594 – welding and testing requirements for steel gas pipelines, including hardness testing of hardness-sensitive joints



- ISO 3183 / API 5L – line pipe requirements, including limits on carbon equivalent
- EN 1011-2 – guidance on preheat, heat input and cooling rate for avoiding hard, crack-sensitive HAZ microstructures

All acceptance decisions are standard- and specification-based: the measured value is compared with the specified limit using the reference method, and any deviation from the qualified welding procedure is treated as a non-conformance in its own right, independently of the hardness result.

6.7. AR Interaction Points (Conceptual – Future Use)

Potential AR elements:

- ☐ Virtual placement of hardness indentations along the BM – HAZ – WM traverse on a weld macro-section
- ☐ Interactive hardness map of the girth weld, colour-coded above and below the 250 HV10 limit
- ☐ Simulation of the effect of preheat and ambient temperature on cooling rate and resulting HAZ hardness
- ☐ Guided use of a portable UCI probe, including surface preparation and probe alignment
- ☐ Visualisation of hydrogen diffusion towards the hard HAZ and of subsequent crack initiation
- ☐ Feedback on accept / reject decisions against the specified hardness limit

6.8. Case Study Learning Assessment

The following activities are intended to support formative assessment within the case study and do not replace the formal assessment requirements established for the INSPIRE Competence Units.

Assessment Items

- MCQs on hardness testing methods, test force and measurement locations
- Interpretation task: evaluate the hardness survey tables against the 250 HV10 limit
- Scenario-based acceptance decision for weld GW-114
- Short written justification of the corrective action with reference to the applicable standards



Expected Answers

- The reference method is Vickers HV10 to ISO 6507-1 and ISO 9015-1; portable UCI results are a screening tool and must be confirmed by the reference method
- The highest hardness is expected in the coarse-grain HAZ adjacent to the fusion line, on the root side
- The welds exceeding 250 HV10 must be rejected; acceptance on RT and UT does not compensate for excessive hardness
- The root cause is insufficient preheat combined with a low ambient temperature and low heat input, which increased the cooling rate in a base metal with CEV 0.43 %
- The corrective action is cut-out and re-welding under the qualified WPS with verified preheat, plus 100 % hardness testing of the welds produced under the same conditions

Scoring Criteria

- Correct application of the hardness test method and measurement locations
- Correct comparison of measured values with the specified acceptance limit
- Understanding of the link between hardness, microstructure and hydrogen-assisted cracking
- Quality of the decision-making and of the standards-based justification
- Safety awareness and completeness of the reporting

6.9. Instructor Notes (Internal Use Only)

- Common learner error: reporting a single reading instead of the mean and maximum of a defined set of indentations
- Common misconception: "the weld passed RT and UT, so it is acceptable", hardness is an independent acceptance criterion
- Common error: accepting portable UCI values as the final result without laboratory verification by the reference method
- Emphasise that the hardness peak is in the HAZ, not in the weld metal, and that indentations must be positioned close to the fusion line
- Emphasise that a deviation from the qualified preheat is itself a non-conformance, regardless of the hardness result
- Discussion points: why 250 HV10 rather than the higher values used in conventional service; whether local PWHT can be an acceptable remedy; how ambient conditions should be controlled in the ITP

6.10. Case Study Summary

This case study shows that hardness is not a secondary laboratory parameter but a primary acceptance criterion for hydrogen pipeline girth welds. A weld that is fully acceptable on visual, radiographic and ultrasonic testing can still be unacceptable for hydrogen service, because a coarse-grain HAZ that is too hard is highly susceptible to hydrogen-assisted cracking.



The Welding Inspector must therefore know the reference test method, the correct measurement locations, the validity limits of portable equipment and the specified acceptance limit, and must be able to trace an out-of-limit hardness result back to the welding parameters that caused it.



7. Conclusion

The case studies developed within INSPIRE provide a practical bridge between the learning outcomes defined in the project's Competence Units and their application to realistic hydrogen pipeline welding inspection scenarios. By addressing hydrogen-specific safety, standards, weld defects, inspection methods and decision-making, the case studies support learners in applying technical knowledge to situations reflecting professional inspection practice.

Developed according to a common structure, the case studies combine learning objectives, technical inputs, inspection workflows, decision points and formative assessment activities. They also identify opportunities for Augmented Reality interaction, providing a structured basis for the subsequent development of interactive training experiences.

Together, these resources support a scenario-based approach to VET in hydrogen pipeline welding inspection and provide trainers and training providers with adaptable materials that can complement the INSPIRE Competence Units and facilitate the integration of Augmented Reality into training delivery.