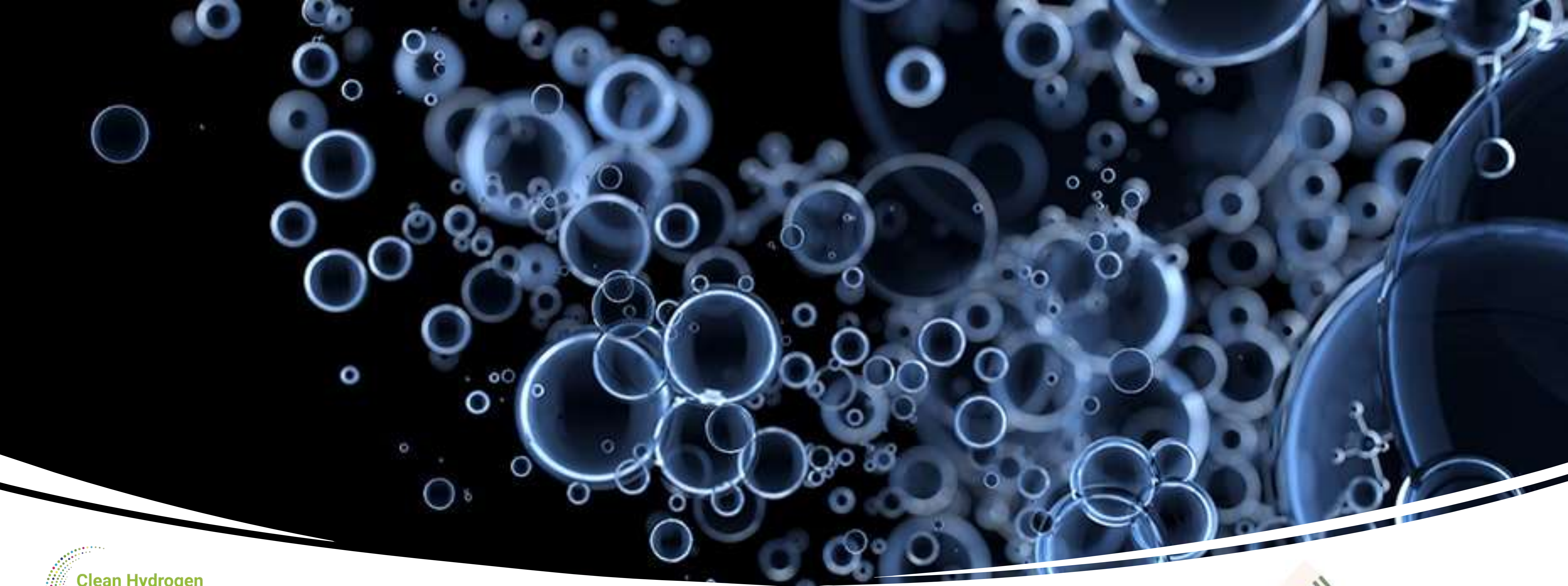


Clean Hydrogen Partnership

Co-funded by the European Union

This project has received co-funding from the European Commission and the Clean Hydrogen Partnership under Grant Agreement No 101137592. This Partnership receives support from the European Union's Horizon Europe Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

PilgrHYm Stakeholder Workshop

December 12th 2025

PilgrHym

natran · cea liten · enagas · Aragon Hydrogen Foundation · fluxys · Fraunhofer · GERG · OCBS · tecnalia · SINTEF · snam · Universidad de Burgos

Agenda

Agenda – PilgrHYm Stakeholder Workshop

10:00 – 10:05	**Welcome** *NaTran*
10:05 – 10:20	**Project scope and objectives** *NaTran*
10:20 – 10:50	**TSO inventory and the selection of the twelve materials** *Fluxys*
10:50 – 11:30	**Tests procedures used for the RRT and RRT first results** *SINTEF, CEA*
11:30 – 12:00	**Numerical modelling (fracture and fatigue) – Models selected & first updates** *IWM*
12:00 – 12:30	**Q&A and closing** *NaTran*

Project scope and objectives

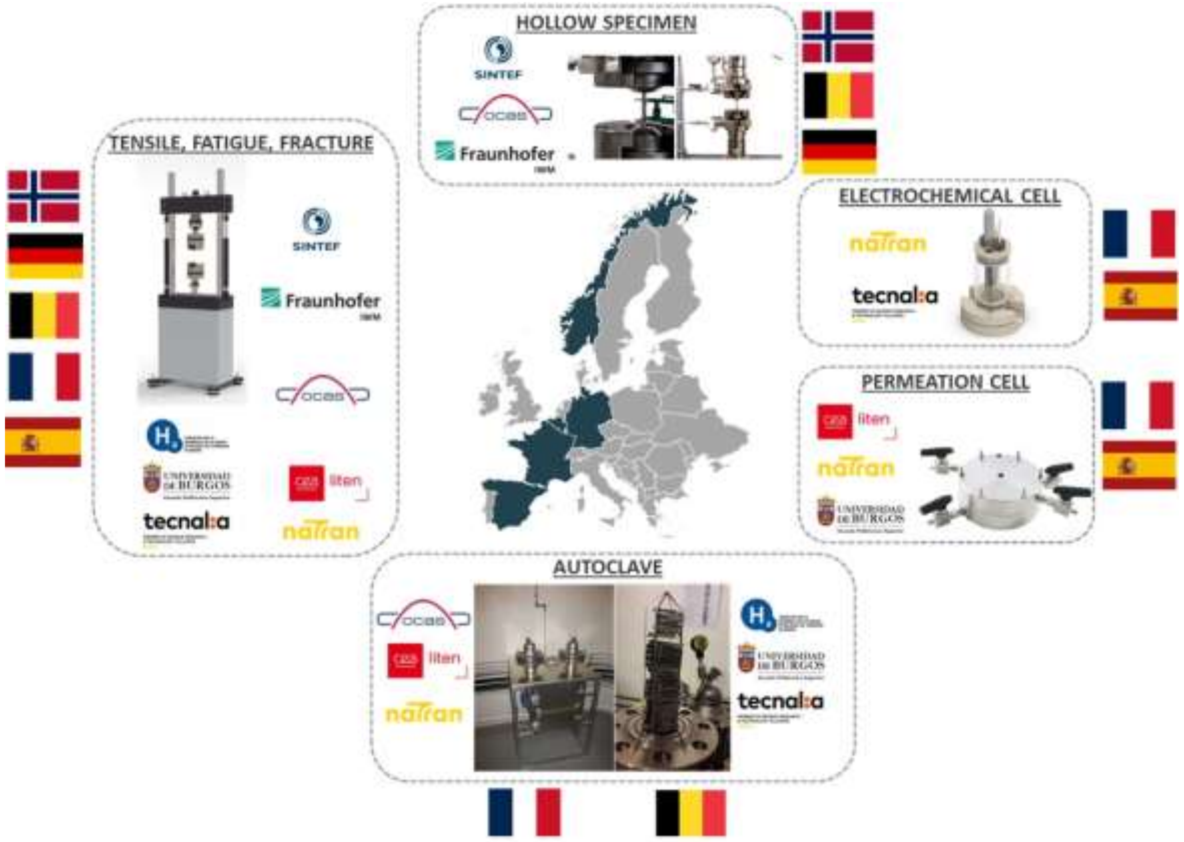
NaTran

The PilgrHYm project

"Pre-normative research on Integrity assessment protocoLs of Gas pipes Repurposed to Hydrogen and Mitigation Guidelines"

natran — Project coordinator
cea liten, enagas, Aragon Hydrogen Foundation, fluxys, Fraunhofer IWM, GERG, ocas, tecnalia, SINTEF, snam, Universidad de Burgos

PilgrHYm aims to provide **a European roadmap** for safely and efficiently **integrating pure H2 into existing natural gas infrastructure**, contributing to the decarbonization of the energy sector.



- **Project start date:** 01.01.2024 / **Duration:** 4 years
- **Budget :** 3 999 073,75 €
- **12 partners / Coordinator : NaTran**
- **Objective** : Develop a pre-normative framework to support the development of a European standard for natural gas pipelines compatibility with H2

The PilgrHYm project

Project goals

PilgrHYm will deliver comprehensive guidelines to transmission system operators to assess the feasibility of using pure H2 in existing natural gas pipelines.

Specific objectives

SO1: Develop a database of material characterization testing on representative steel grades of the EU gas grids, including tensile, fracture toughness and fatigue crack growth (FCG) properties.

SO2: Establish a harmonized testing protocols to support the repurposing of natural gas lines to hydrogen.

SO3: Develop a numerical modelling approach for simulating and predicting hydrogen assisted fracture and fatigue.

SO4: Optimize a more realistic FCGR (Fatigue Crack Growth Rate) master curve for fitness-for-service assessment purpose, in particular for low ΔK values corresponding to the actual operating domain of the EU gas grids.

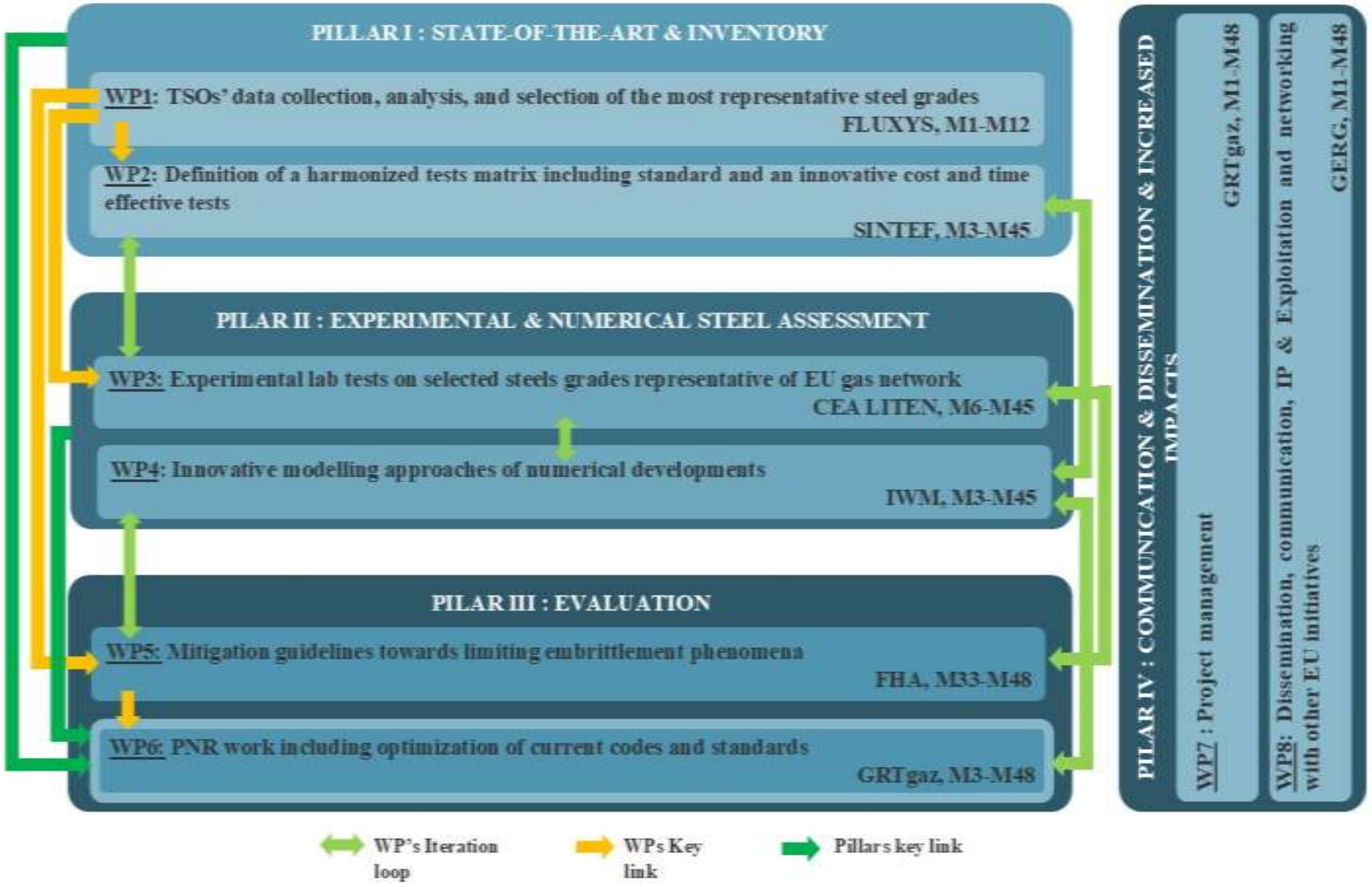
SO5: Identify existing and/or innovative technologies for mitigation compatible with operational constraints.

SO6: Engage with stakeholders to ensure cooperation and awareness.

SO7: To facilitate the uptake and exploitation of PilgrHYm results by the academic community, technology developers and end-users.

The PilgrHYm project

Project structure



The PilgrHYm project
Communication & Dissemination

How to follow the project:

- Project website: https://pilgrhym.eu/
- LinkedIn page: https://www.linkedin.com/showcase/pilgrhym

Upcoming activities

- **Ad-hoc posts/articles** regarding ongoing activities to be published on project website and LinkedIn page.
- **Attendances to conferences & Organization of key Events**.

Events attended in 2025

- MESSIAH seminar: 24-25 September 2025, Paris
- SteelyHydrogen conference: 14-16 October 2025, Ghent, Belgium (Poster)

Events projected in 2026

- PRCI Research Exchange : 3-4 March 2026, Orlando (Poster)
- European Hydrogen Energy Conference (EHEC) : 11-13 March 2026, Seville
- H2science conference : 3-4 June 2026, Trondheim
- International Pipeline Conference (IPCE) : 21-25 September 2026, Calgary (abstract to be submitted)
- EGATEC 2026 : 25-26 November 2026, Vienna (Poster)

TSO inventory and the selection of the twelve materials

FLUXYS

TSO inventory & Selection of materials

Objectives of WP1

Objectives

- *O1: Completely map the EU natural gas pipeline grid with technical characteristics and current operation modes, as well as potential reuse for hydrogen transmission and intended operating strategies with hydrogen*
- *O2: Carefully determine criteria to restrict the number of tested materials to 12 (8 base metals, 2 welds and 2 heat affected zones)*
- *O3: Collect and dispatch the 12 steel materials to be investigated experimentally*

Deliverable		Deadline	
1.1	TSO Inventory	~~M9~~ M10	✓
1.2	List of steel grades	~~M9~~ M10	✓

Milestone		Deadline	
2	Questionnaire for TSOs is available	M3	✓
5	All material samples have been received by testing laboratories	~~M12~~ M24	✓

TSO inventory

Information on received questionnaire replies

- 23 onshore TSO replied to the questionnaire → Global length of 182469 km of steel pipelines (proposal target: 156054 km)
  - ✓ *All TSO members of the project Advisory Board sent a reply*
  - ✓ *GASSCO (Norway) sent a reply about offshore pipelines (interesting for comparison with onshore pipelines)*
- Detailed characteristics received on 130830 km of onshore pipelines
  → Legitimate analysis and conclusions + fair representation of all extended Europe

Austria	GAS CONNECT AUSTRIA
Austria	TAG
Belgium	FLUXYS
Czech Republic	NET4GAS
Denmark	ENERGINET
Finland	GASGRID
France	GRTgaz
France	TERÉGA
Germany	ONTRAS
Germany	OGE
Greece	DESFA
Hungary	FGSZ

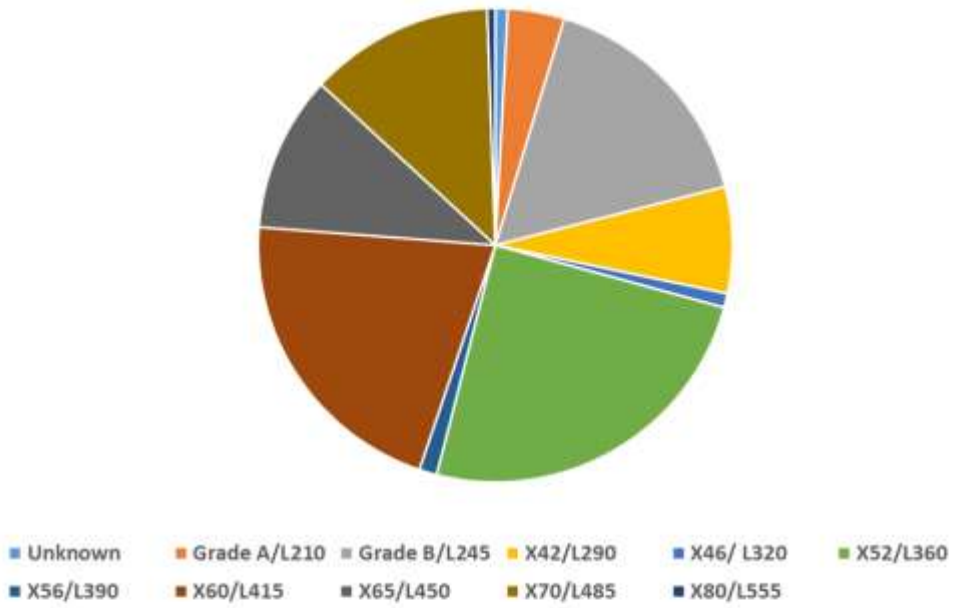
Italy	SNAM RETE GAS
Latvia	CONEXUS BALTIC GRID
Lithuania	AMBER GRID
Luxembourg	CREOS LUXEMBOURG
Netherlands, The	GASUNIE
Poland	GAZ-SYSTEM
Slovakia	EUSTREAM
Spain	ENAGÁS
Switzerland	TRANSITGAS
Ukraine	GAS TSO OF UKRAINE
United Kingdom	NATIONAL GAS

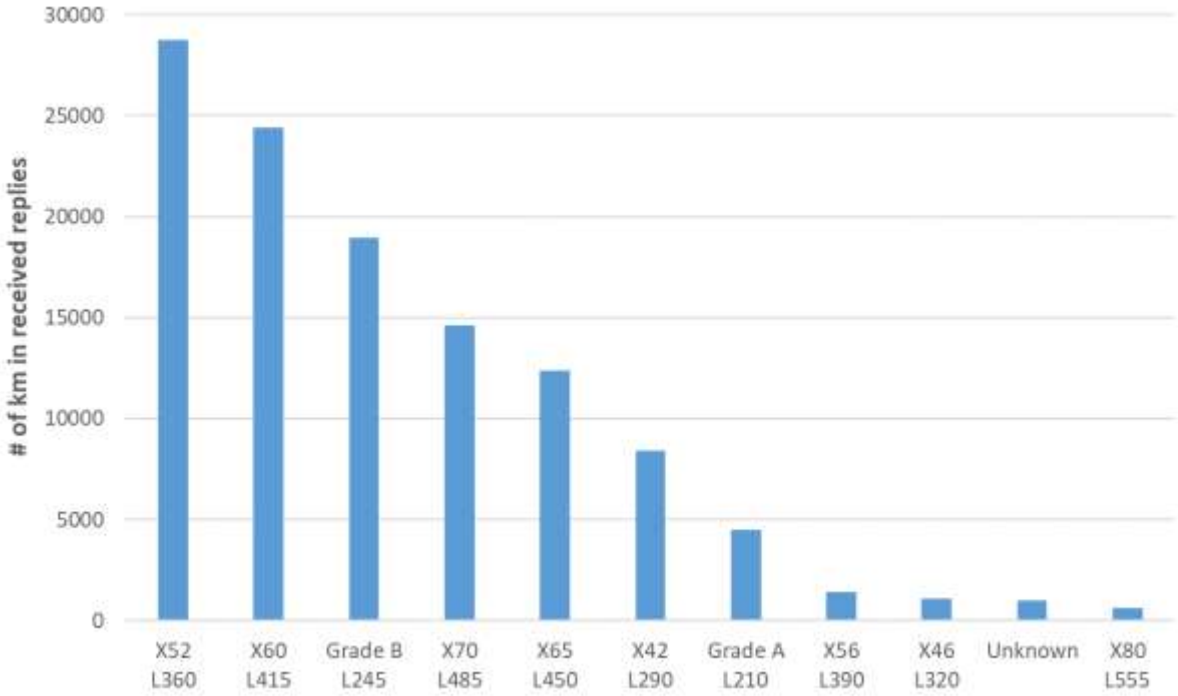
TSO inventory

Analysis of replies - steel grade distribution

Most European network steels are compliant with either API 5L (USA) or ISO 3183 (Europe) standards, so the classification has been carried out according to grade names from both of these standards.

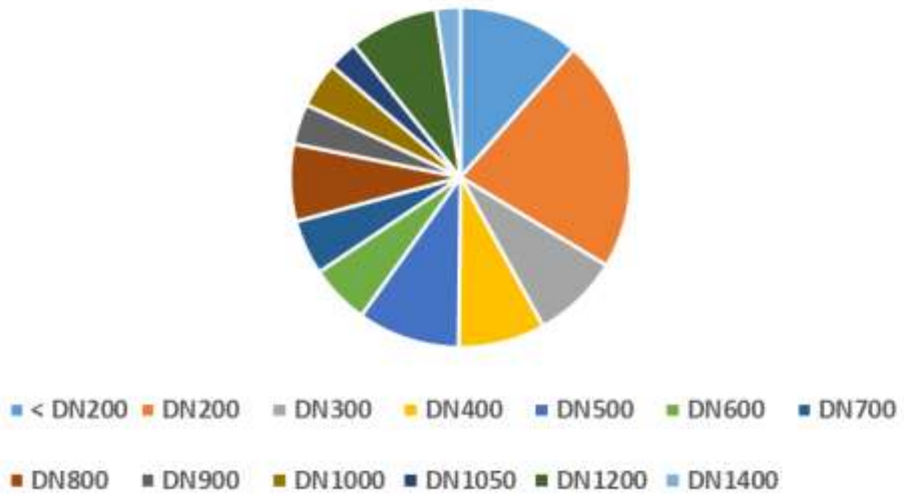
When other standards were used (for instance national standards or Soviet Union/Russian standards), the materials have been accounted for in the most comparable category from API 5L/ISO 3183.

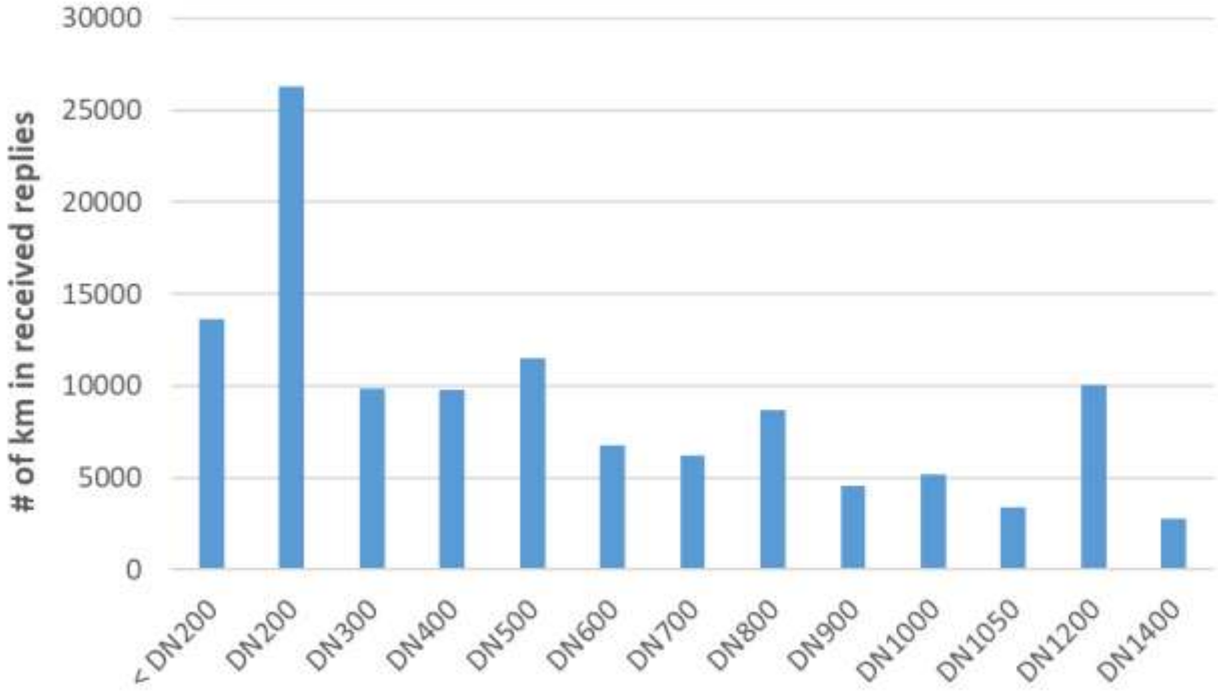




TSO inventory

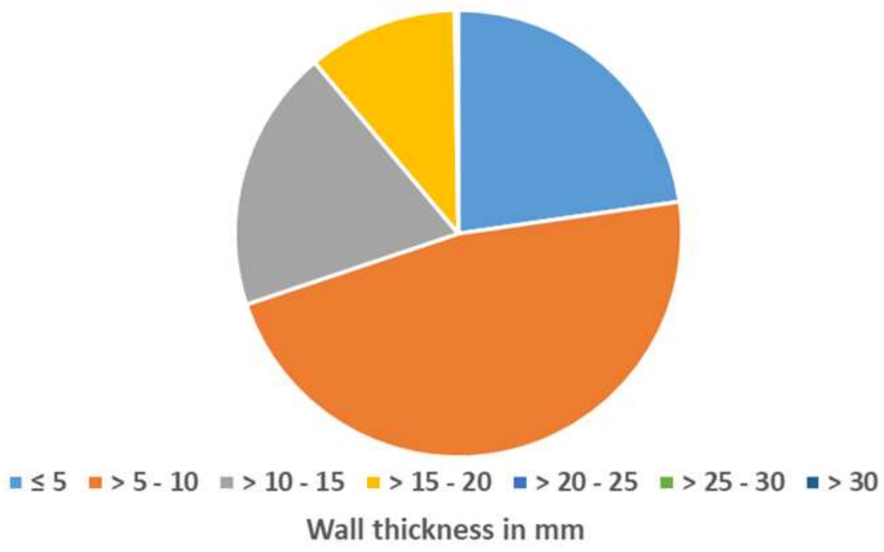
Analysis of replies - diameter distribution

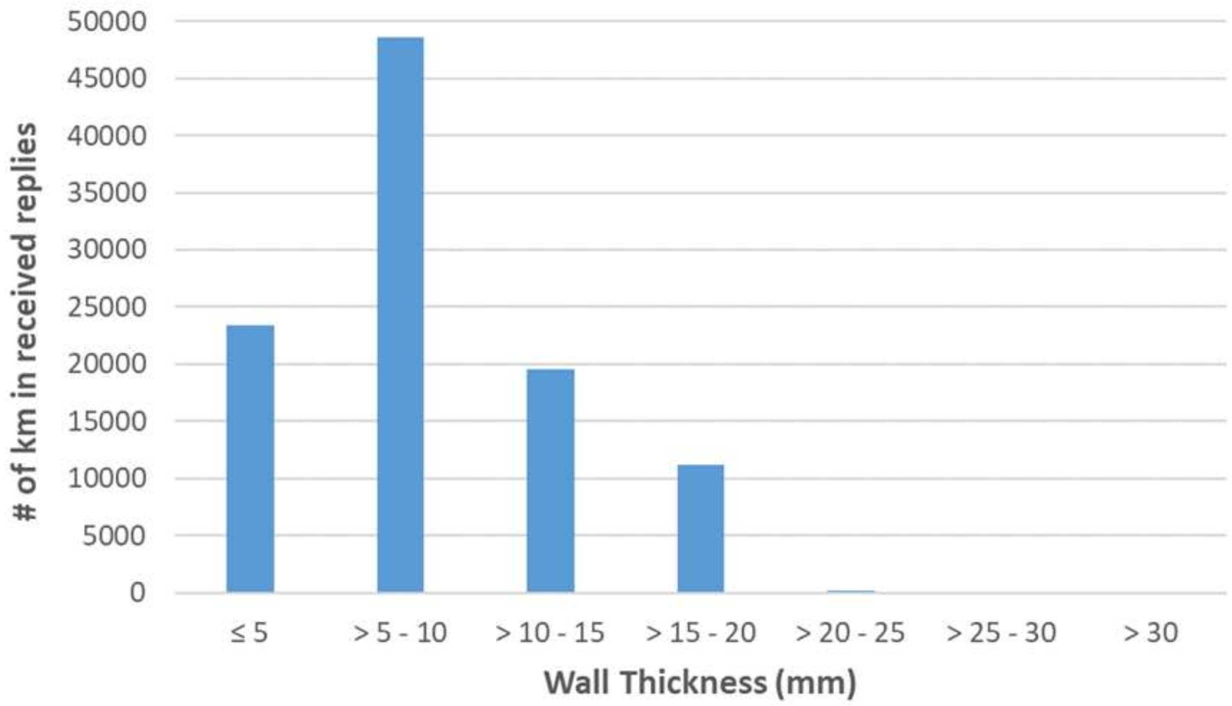




TSO inventory

Analysis of replies - wall thickness distribution

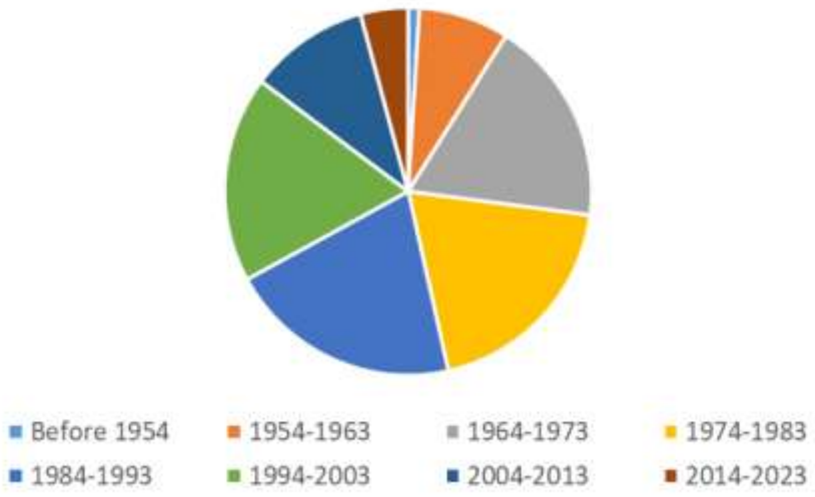


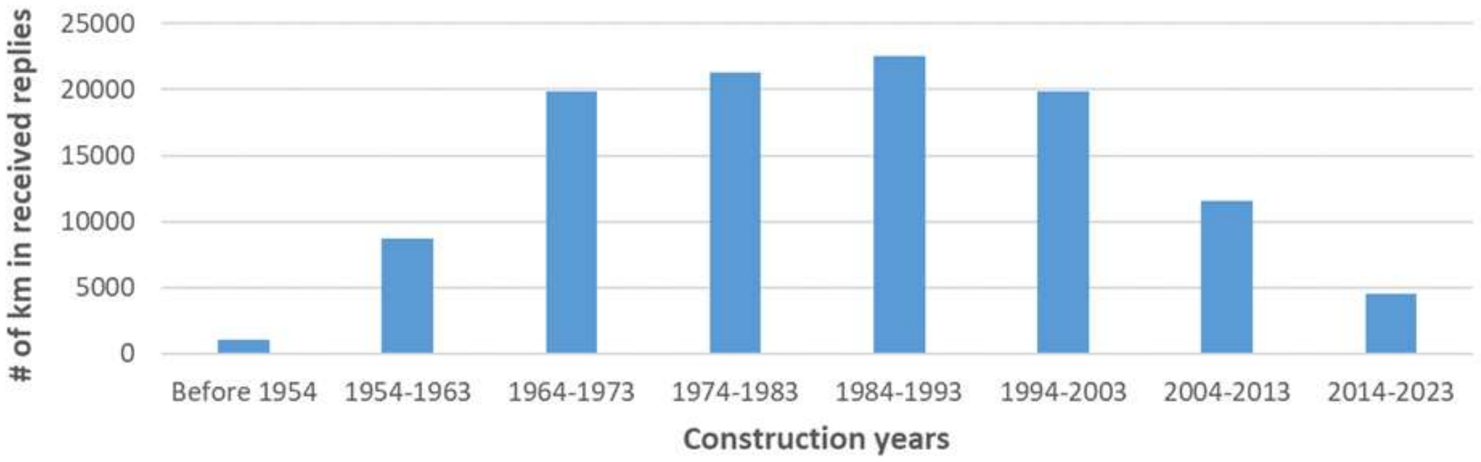


- The 3 categories below 15 mm represent 89% of all replies
- Very few replies are above 20 mm (not even directly visible)

TSO inventory

Analysis of replies - construction year





TSO inventory

Analysis of replies - other info

- Trends about pipeline fabrication (not enough detailed data for statistical analysis):
  - ✓ Seamless (SMLS), Electric Resistance Welded (ERW) and High-Frequency Induction Welded (HFI) pipelines are commonly found for small diameters (up to DN500 or DN600).
  - ✓ Submerged Arc Welded Longitudinal (SAWL) and Submerged Arc Welded Helicoidal (SAWH) are commonly found for large diameters (DN500 and up).
- Operating pressures with natural gas:
  - ✓ For the majority of TSOs: Maximum Operating Pressure (MOP) lies in the range from 65 to 85 barg (boundary replies: 55 barg and 100 barg).
  - ✓ Some TSOs operate their network with rather constant pressure whereas others have higher daily pressure variations (typically 10-30% of the MOP). Current operating modes are not necessarily representative of future operations with pure H_2 and give only rough estimations on possible daily pressure variations with H_2.
- Plans for H_2 repurposing/retrofitting:
  - Almost all TSOs have plans for specific natural gas pipelines to be repurposed to pure H_2 transmission in the future, always with adapted operating conditions. Some state that the MOP will be reduced with pure H_2 and some state that it will remain the same, but all agree that pressure variations will be controlled. Several TSOs plan to carry out an engineering (critical) assessment on each case before conversion to H_2 transport.
  - Concerning retrofitting plans (use of the pipelines to transport mixtures of H_2 with natural gas), the answers are more diverse: some TSOs do not consider retrofitting at all, a majority of TSOs keep this option open but only to limited percentages of H_2 (maximum 2-5 vol. %) and only a few consider up to 20% H_2 in the mixture.

Selection of materials

List of steel grades to be tested, then identification, preparation and dispatching of samples to testing laboratories

Arbitration of various parameters (8 base metals, 2 welds, 2 heat affected zones ; grades well represented in Europe ; wall thickness ; age of pipelines ; geographical origin ; wishes expressed by TSOs ; already tested materials ; available materials at TSOs) led to this list of 12 materials to be tested in PilgrHYm:

		List of materials	OD (mm)	WT (mm)	Metal/Weld/HAZ	Fabrication year
RR	**1**	L415/X60 SAWL	1022,6	18,2	Metal	2008
RR	**2**	L450/X65 SAWL	923	26,5	Metal	1982
	3	X67 (~L485/X70) SAWL	1420	18,7	Metal	1986
	4	X67 (~L485/X70) SAWL	1420	18,7	Seam Weld (SAWL)	1986
	5	X67 (~L485/X70) SAWL	1420	18,7	HAZ (SAWL)	1986
	6	L450/X65 QT	406,4	15,88	Metal	Modern
	7	CSN 13030/P295GH (~X42) QT	711	10,5	Metal	1979-1980
	8	L245/Grade B	355,6	12,7	Metal	2021
	9	L245/Grade B	355,6	12,7	Seam Weld (HFI)	2021
	10	L245/Grade B	355,6	12,7	HAZ (HFI)	2021
	11	L450/X65 (onshore)	1219	16,1	Metal	1992
	12	St 60.7 (~L415/X60)	863,6	12,7	Metal (SAWL)	1972

TSO inventory & Selection of materials

- To all TSOs that replied to our questionnaire
- To all TSOs that offered to donate pipeline samples to the project
- And last but not least to the TSOs that donated (and prepared) pipeline samples to the project

Testing procedures used for the RRT and RRT first results

SINTEF, CEA

Testing procedures

Objectives of WP2

2024 2025 2026 2027
M3 M45

Objectives

- ❑ *SO1: Review of test procedure (standardized and non-)*
- ❑ *SO2: Robust inter-comparison methodology definition for existing data*
- ❑ *SO3: Definition of robust experimental procedures;*
- ❑ *SO4: Definition of experimental set-up based on time- and cost- effective approach.*

1

T2.1 Literature and standard review (M3 - M6)

Objective : State of the art review of experimental methods for hydrogen compatibility of materials ✓
Link WP : WP1, WP3

2

T2.2 Interlaboratory proficiency (M6 - M12)

Objective : Definition of test matrix for interlaboratory proficiency testing (Round Robin) ✓
Link WP : WP3

3

T2.3 Internal guidelines and testing condition definition (M13 - M42)

Objective : Definition of internal guidelines and test conditions
Link WP : WP1, WP3, WP4, WP5

4

T2.4 Test protocol development (M13 - M42)

Objective : Definition of test set-up based on efficient test approach
Link WP : WP3, WP4, WP5, WP6

Milestones		Deadline
MS7	Overall test protocol guideline completed and delivered to WP3	M12 ✓
MS10	Cost and time effective testing procedure with assessment of conservatism completed.	M36

Deliverables		Deadline
D2.1	Literature and relevant standard review	M6 ✓
D2.2	Report on cost-and time- efficient test methodologies	M42

Testing procedures

Literature review

Progress

- ❑ **Task 2.1 Literature and standard review completed**
  - ❑ Internal draft version D2.1 available as planned (M6)
  - ❑ After resolving copyright issues, final version of D2.1 was uploaded to the F&T portal on 23/12/2024
    - Approval of Project Officer pending
    - Publication on web planned afterwards – latest on project mid-term
  - ❑ Monitor ongoing developments and option to update
    - Proposal: as part of WP6 (Allocated resources WP2T1 have been used)

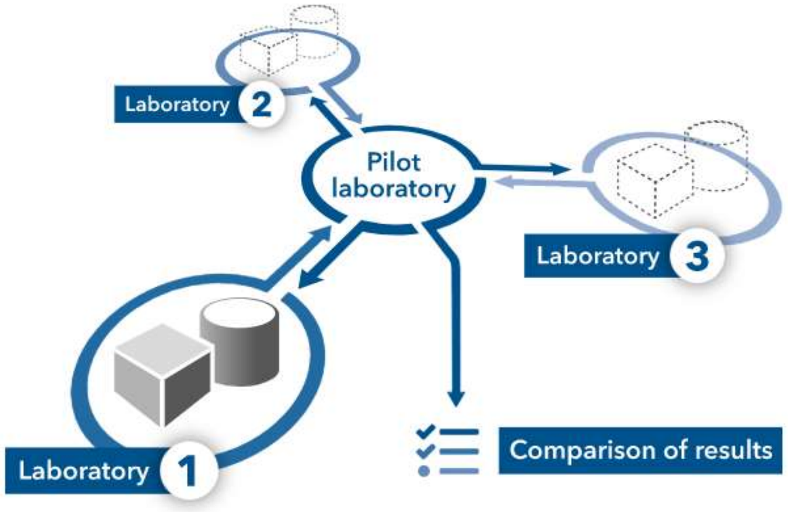
Deliverable type	R – Document, Report
Deliverable number	D2.1
Work Package contributing to the deliverable	WP2
Due Date	M6 postponed to M12
Actual submission date	M12 (23/12/2024)
Responsible organization	OCAS
Editor (merging contributions from multiple authors)	Dennis Van Hoecke
Dissemination level	PU – Public
Revision	V1
Page Number	72

Testing procedures for the RRT

Testing protocols for RRT

Progress

- ❑ **Task 2.2 Determination of experimental inputs for WP3**
  - ❑ MS7 Overall test protocol guideline completed
    - ❑ Submission date M12 (23/12/2024)

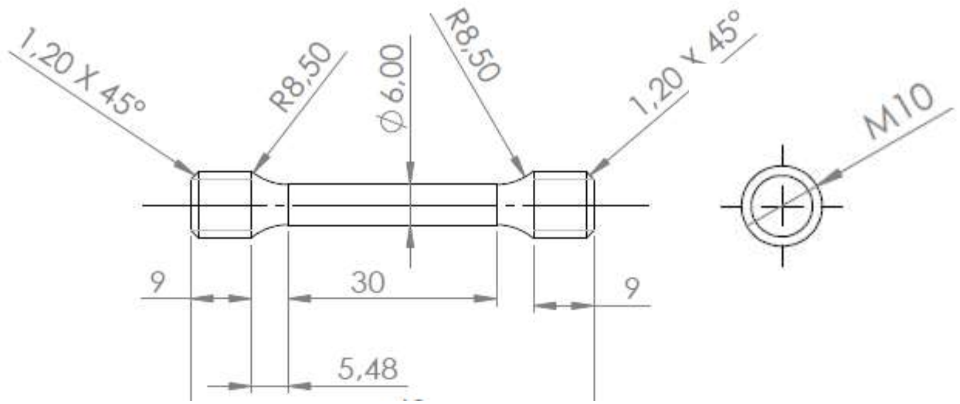


Milestone number	7
Work Package contributing to the Milestone	WP2
Due Date	M12
Actual submission date	M12 (23/12/2024)
Responsible organization	SINTEF
Editor	Antonio Alvaro
Revision	V1
Page Number	8

Testing procedures for the RRT

Testing protocols for RRT

- **T2.2 → T3.2.1: SSRT specimen**
  - *Specimen geometry*



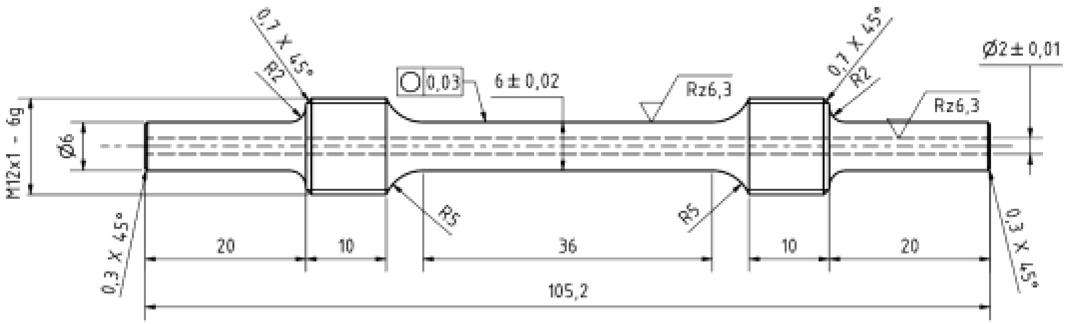
- *Testing conditions*
  - Gaz : N2 and H2 (purity 6.0)
  - Room temperature (23°C)
  - Test pressure: 85 bar
  - Cross head velocity leading to a strain rate corr. to $10^{-5}s^{-1}$
  - Gas inlet procedure: Each lab follows and reports own procedure.
  - H2 precharging: 30 min at target pressure
  - Specimen orientation : T direction (if possible)
  - Each lab measure O2 content, when possible, target: ≤ 1volppm

- *Expected results*
  - Stress-strain curve
  - $Rp_{0,2}$
  - UTS
  - Reduction of area
  - Image of fracture surface

Testing procedures for the RRT

Testing protocols for RRT

- **T2.2 → T3.2.1: Hollow SSRT specimen**
  - *Specimen geometry*



- *Testing conditions*
  - Gas: N_2 and H_2 (purity 6.0)
  - Test pressure: 85 bar
  - Test Temperature: RT (23 °C)
  - Strain rate: Constant cross head velocity corr. to $10^{-5}s^{-1}$.
  - H_2 precharging: 30 min at target pressure
  - Gas inlet: Each lab follows and reports own procedure
  - Each lab measure O_2 content, when possible, target: ≤ 1 volppm

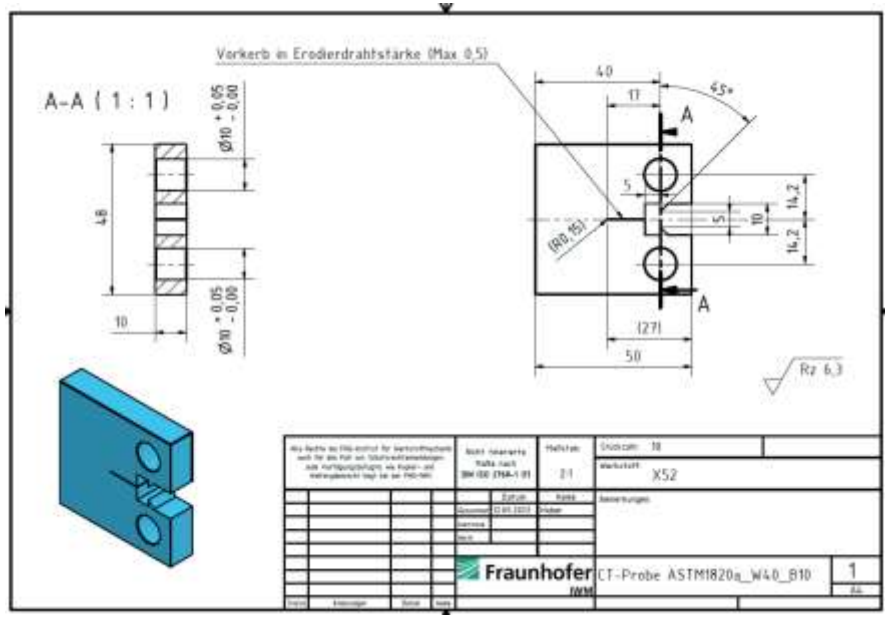
- *Expected results*
  - Stress-strain curve
  - $Rp_{0,2}$
  - UTS
  - Reduction of area
  - Image of ruptured specimen and fracture surface

Testing procedures for the RRT

Testing protocols for RRT

❑T2.2 → T3.2.1: CT specimen for fracture toughness

- ❑ *Specimen geometry*
  - ❑ For compliance measurement: Side grooves machined after precracking (10% depth on each side → BN = 8 mm)
  - ❑ Geometry of the edges can be adapted by each partner depending on its own COD



- ❑ *Specimen machining protocol*
  - ❑ Specimen orientation: TL
  - ❑ Specimen degreased prior to testing
  - ❑ Specimen kept in a desiccator before testing

- ❑ *Testing conditions*
  - ❑ Gas: N2 and H2 (purity 6.0)
  - ❑ Testing pressure: 85 bar
  - ❑ Gas inlet: Each lab follows and reports own procedure.
  - ❑ Each lab measure O2 content, when possible, target: ≤ vol1 ppm
  - ❑ Precracking: Following E1820 (in air at f=10 Hz and R = 0.1.)
  - ❑ H2 precharging: 30 min before at target pressure
  - ❑ Loading rate: K rate of 1. $MPa.m^{0.5}$/min in the elastic range
  - ❑ Crack length measurement : DCPD and/or compliance method

- ❑ *Expected results*
  - ❑ J-Δa curve
  - ❑ $J_{Q0.2}$
  - ❑ Image of fracture surface

Testing procedures for the RRT

Internal guidelines and testing condition definition

Next steps

- T2.3 Internal guidelines and testing condition definition (M13-M42)
  - Step 1 a FCGR test methodology (M18)
  - Step 1 b Evaluate results from the Round Robin test program in collaboration with WP3 and WP4 (SSRT, Fracture Toughness, Hollow SSRT) (M18)
  - Step2 Based on Round Robin program, develop internal guidelines for testing and test conditions. (M36)
- T2.4 Test protocol development
  - T2.4 will be launched after RRT
- Ongoing work
  - Definition of a general FCGR test methodology (M18)
  - Continue interaction with WP3 and WP4 for the definition of Fatigue Crack Growth rate procedure
  - Publication from the Literature and standard review is ongoing

Testing campaign

Objectives of WP3

2024 2025 2026 2027
M6 M45

PilgrHym

Objectives

- *Provide experimental data / Intercomparison between labs / Influence of relevent parameters / Data for model calibration / Optimized testing procedure / Comparison with litterature review (WP5)*

1 — cea liten

Task 3.1 (M6 - M30)

Objective : Materials supply, Tests coordination
Link WP : WP1

2 — naTran

Task 3.2 (M6 - M36)

Objective : Development of a data base
Exp. intercomparison / Tests for baseline dvpt
Link WP : WP2

3 — cea liten

Task 3.3 (M12 - M40)

Objective : Effect of main parameters / Model calibration and validation
Link WP : WP2, WP4, WP6

4 — Fraunhofer IWM

Task 3.4 (M20 - M45)

Objective : Validation of experimental procedure
Link WP : WP2

Milestones		Deadline
MS4	Act the beginning of the test	M6 ✓
MS8	From Inter laboratory results, validation of the tests dispatching between the labs	~~M18~~ M25

Deliverables		Deadline
D3.1	Labs intercomparison	~~M18~~ M25
D3.2	Standard baseline	M36
D3.3	HE sensitivity analysis	M40
D3.4	Method validation	M45

Testing campaign

Materials supply

T3.1 – Materials supply – tests coordination (M6-M30)

- ❑ **Choice of materials to be tested**
  - ❑ 12 materials = 8 base materials + 2 HAZ + 2 weld materials (to confirm)
    - ❑ Tests for baseline development - Matrix of experiments

	SSRT		FT		FCG		
	Number of tests		Number of tests		Number of tests		
	H2	Air	H2	Air	H2	Air	Partner involved
Material 1 (RRT)	0	2	0	3	3	3	OCAS (2 materials) SINTEF (2 materials) CEA (2 materials) TECNALIA (3 materials) UBU (2 materials) GRTgaz (1 material)
Material 2 (RRT)	0	2	0	3	3	3	
Material 3	3	2	3	3	3	3	
Material 4	3	2	3	3	3	3	
Material 5	3	2	3	3	3	3	
Material 6	3	2	3	3	3	3	
Material 7	3	2	3	3	3	3	
Material 8	3	2	3	3	3	3	
Material 9	3	2	3	3	3	3	
Material 10	3	2	3	3	3	3	
Material 11	3	2	3	3	3	3	
Material 12	3	2	3	3	3	3	

  - ❑ 2 materials for the round robin test (RRT) selected – See next slide
  - ❑ Other materials have been identified and delivered to labs

Testing campaign

Round robin test

T3.2 – Development of a database (M6-M36)

- T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

  - 2 materials selected for the RRT
    - One L415 SAWL modern steel (2008) - OD = 1022.6 mm, WT = 18.2 mm
    - One X65 SAWL vintage steel (1982) - OD = 923 mm, WT = 26.5 mm

Number of tests per partner (RRT)	SSRT		Fracture Toughness testing		Hollow SSRT	
	H2	N2	H2	N2	H2	N2
Material #1	3	3	3	3	3	3
Material #2	3	3	3	3	3	3
Labs involved	CEA Liten, SINTEF, NaTran, Tecnalia, UBU, OCAS				IWM, SINTEF, OCAS, Tecnalia	
Machining of specimens	One machining workshop per type of specimen for RRT					

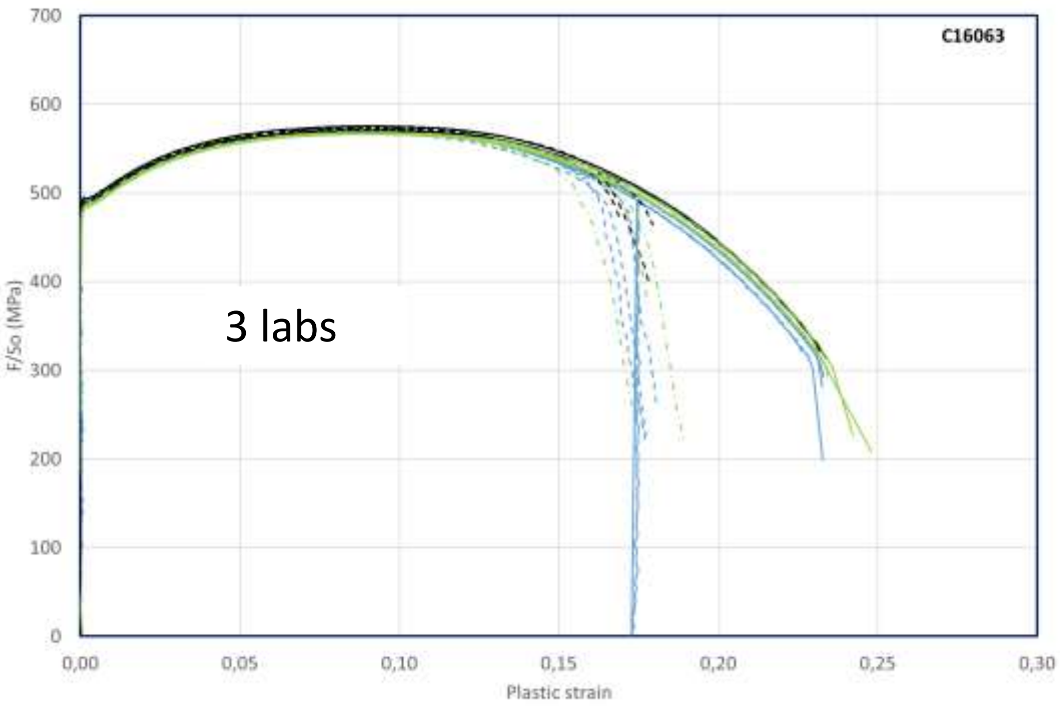
  - RRT ongoing
    - Testing conditions from WP2
    - Comparison: Tensile tests curves, J_Q value, Fracture surface analysis (SEM, one per condition)

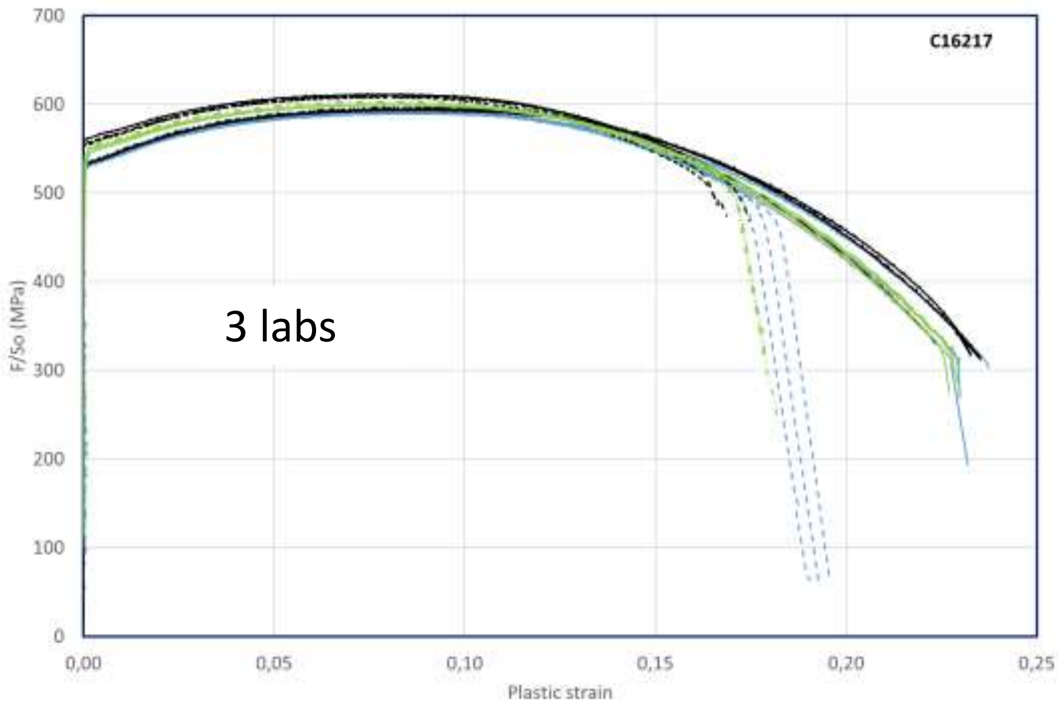
Testing campaign
Round robin test

T3.2 – Development of a database (M6-M36)

- ❑ T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

<u>SSRT results</u>





- ❑ Tests done for 4 labs, 2 labs will provide results by end of 2025

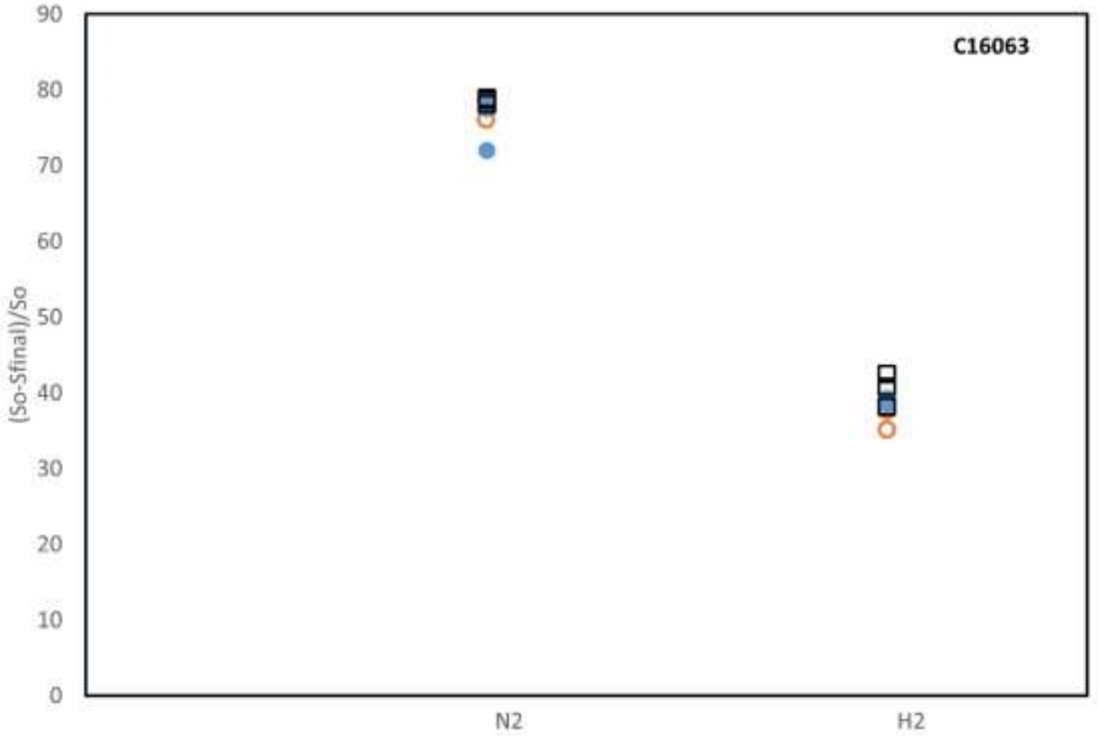
Testing campaign
Round robin test

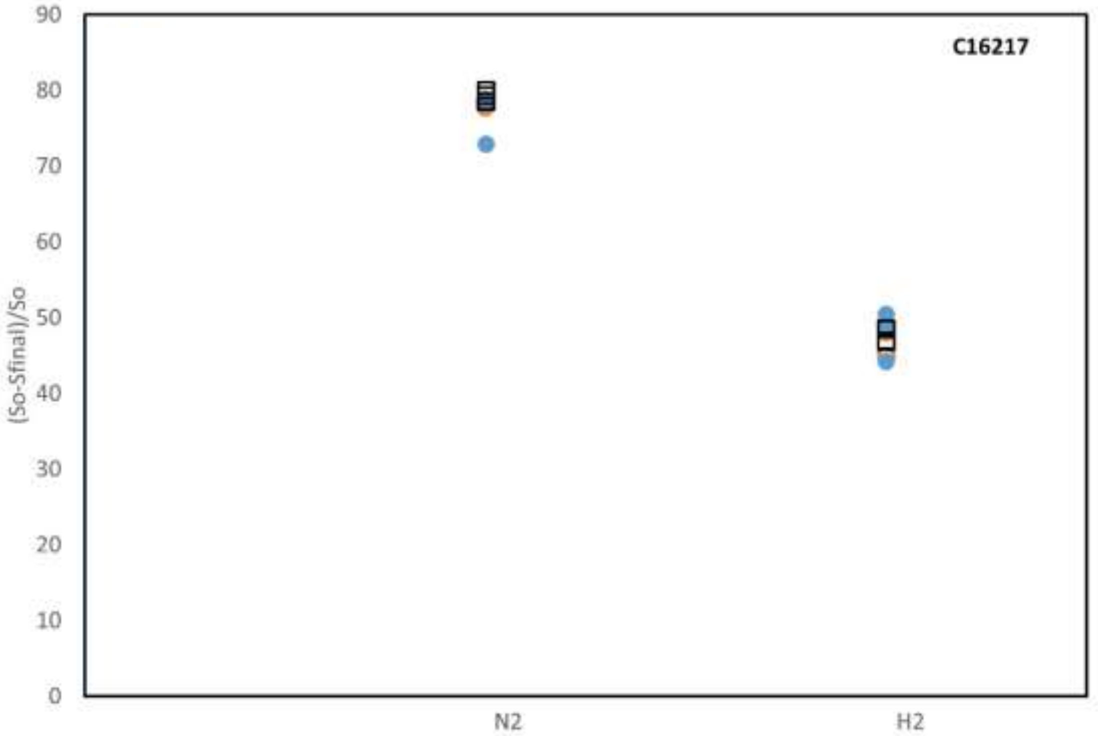
T3.2 – Development of a database (M6-M36)

- T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

<u>SSRT results</u>: Reduction of area

Condition: 85 bar, $10^{-5}s^{-1}$





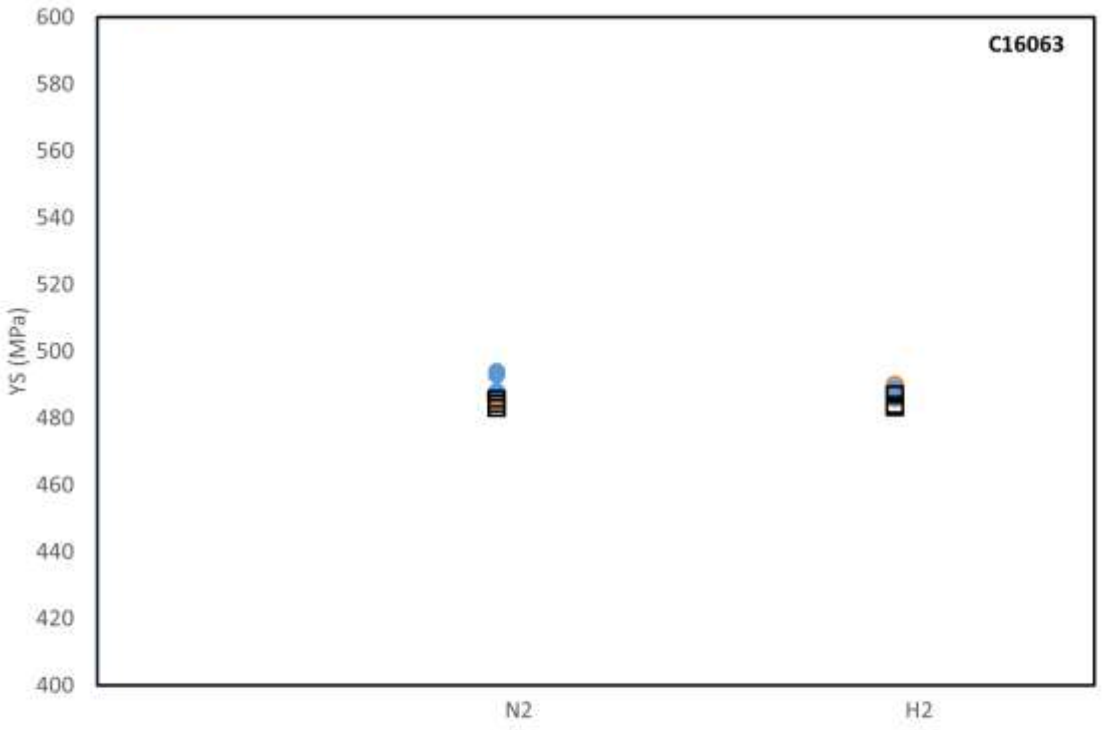
Testing campaign
Round robin test

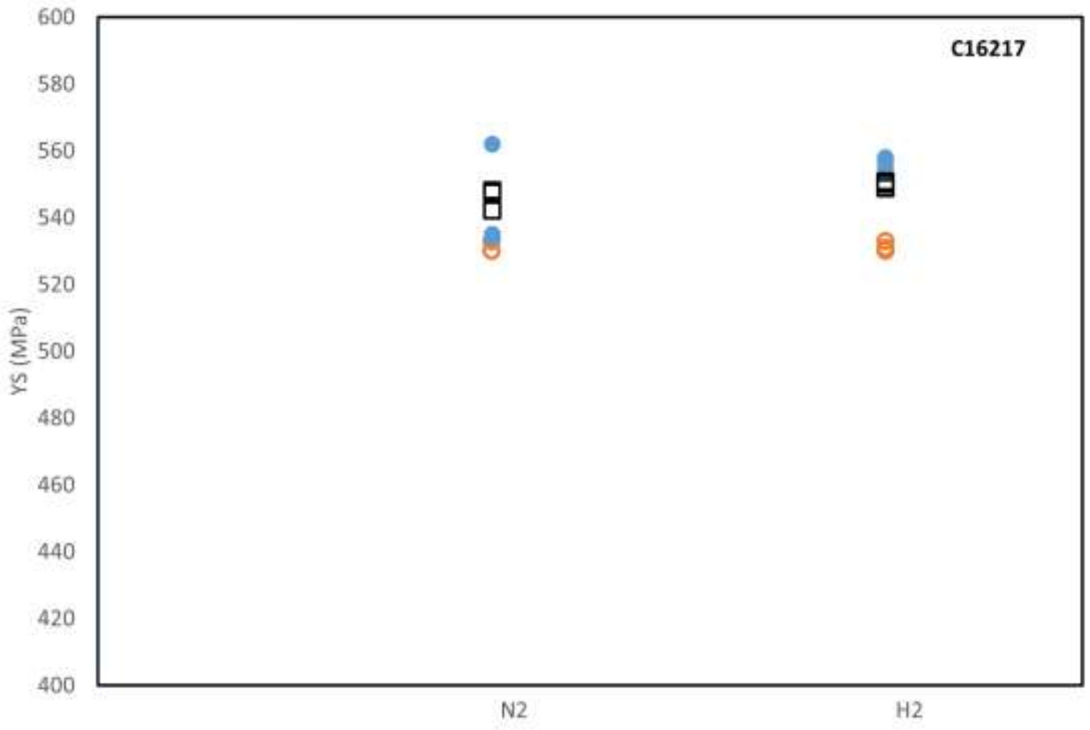
T3.2 – Development of a database (M6-M36)

- ❑ T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

<u>SSRT results</u>: yield stress

Testing conditions: 85 bar, $10^{-5}s^{-1}$





Testing campaign

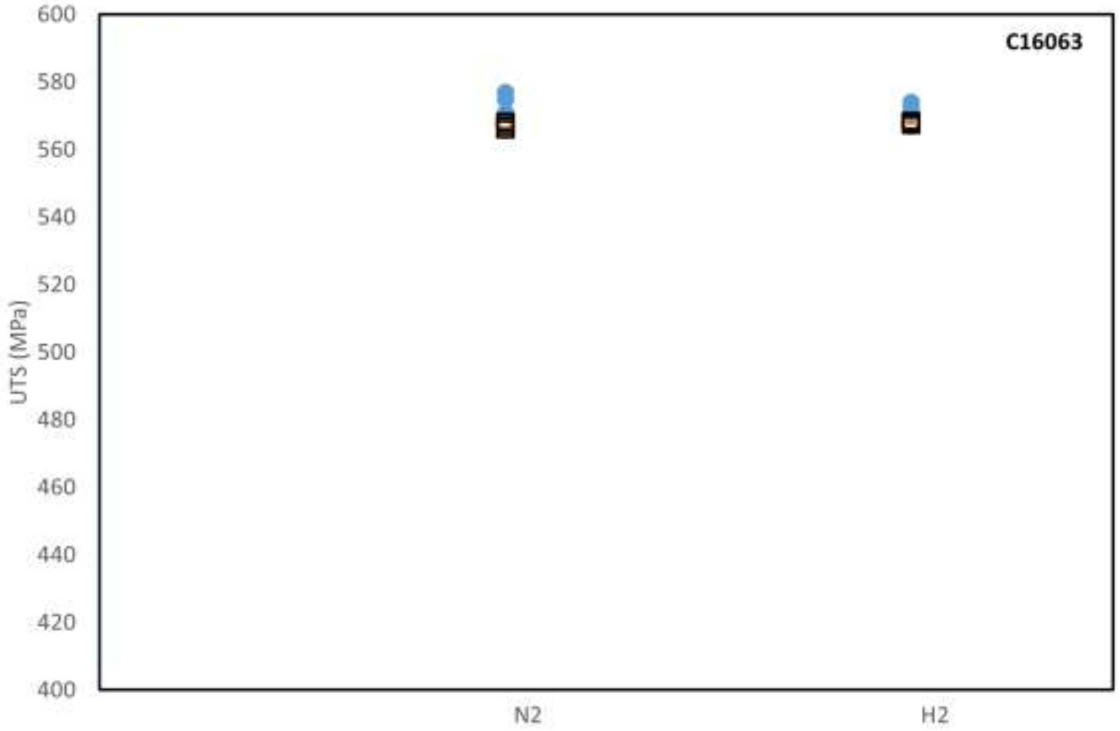
Round robin test

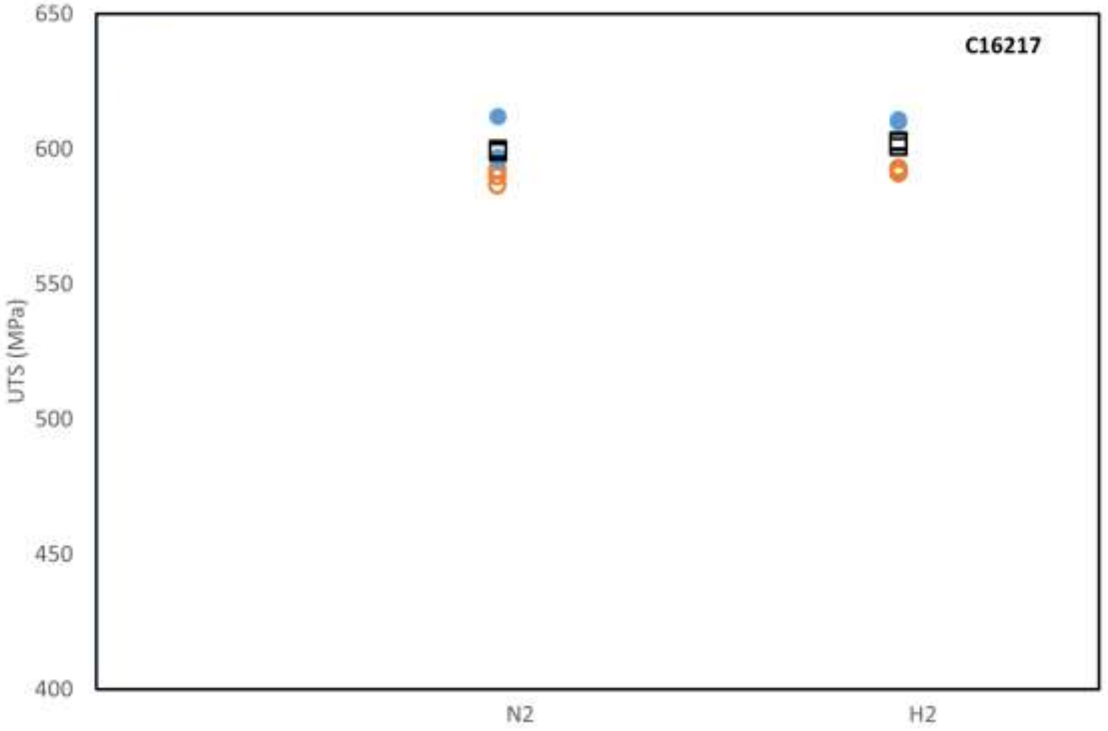
T3.2 – Development of a database (M6-M36)

❑ T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

SSRT results: UTS

Testing conditions: 85 bar, $10^{-5}s^{-1}$





- So far, good reproducibility for modern steel, as expected
- Vintage steel : small scattered with two groups of results → Microstructural heterogeneity (to be confirmed)
- Fracture toughness : Intercomparison just started (1 lab)

Testing campaign

Round robin test

T3.2 – Development of a database (M6-M36)

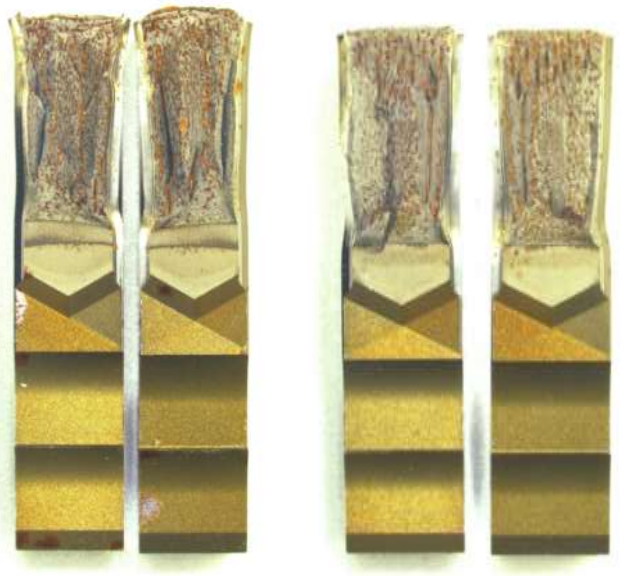
- ❑ T3.2.1 ***Experimental intercomparison of the labs results (Round Robin test)***

<u>SSRT</u>
4 labs : done
2 labs : end of December 2025

<u>Hollow Specimen</u>
1 lab : done
3 labs : end of January 2026

<u>Fracture Toughness</u>
3 lab : done
1 lab : in progress
2 labs : end of January 2026

J0,2	C16063	C16217
N2	463,6	402,7
	510,1	374,8
	357	375,1
H2	66,2	46,6
	79,9	52,3
	69,9	52,6



Testing campaign
Influence of main parameters

- ❑ T3.3.1 : ***Influence of the main parameters*** (6 labs involved)

Addressed parameters	µstructure	Specimen Geometry	Loading rate	R ratio	Pressure	O_2 content
Fracture Toughness	Modern / vintage	CT / SENT	2 loading rates		30 - 300 bar	
FCG	BM / MZ	CT		0.1 / 0.5	30 - 300 bar	Static or continuous flow

+ WOL 1 material, 2 conditions (H2&H2+inhibitor), <12 samples in total (base material+weld)

Testing campaign

Data for model calibration and validation

- T3.3.2 : ***Providing dedicated data for model validation and calibration***

Type of tests	CEA	SINTEF	UBU
Gas permeation	8 (< 10 bar)	0	12 (< 100 bar)
TDS		6	12
Hot Melt Extraction	2 mat x 3	2 mat x 3	

- Identification of the testing conditions still to be clarified
- Hot extraction tests of samples pre-exposed at high-pressure (30, 100 and 300 bar) to determine solubility (K_{eff}). The exposure time should be long enough to ensure saturation (assuming D_{eff} from literature). Size and shape of samples TBD.

Testing campaign

Next step

- Finalising SSRT and Hollow specimen tensile interlab tests
- Comparing SSRT and HSTT results and drawing conclusions

- Finalising FT interlab tests (by end of January 2026)
- Comparing FT results and drawing conclusions

- Fatigue Crack Growth : definition of a common procedure (85bar H_2, 1Hz, rising ΔK, R = 0,1)

- Starting data base tests

Numerical modelling (fracture and fatigue) – Models selected & first updates

IWM

Numerical modelling

Objectives of WP4

2024 2025 2026 2027
M3 M45

PilgrHym

Objectives

- *O1: support testing campaign; O2: to improve FCG-master curves; O3: to achieve less conservative FCG-master curves; O4: to support for the creation of a design criteria*

1 Fraunhofer IWM

Task Literature review (M3 - M9)

Objective : Literature review of state-of-the-art numerical models of coupled hydrogen diffusion that can potentially be implemented ✓
Link WP : WP3

2 SINTEF

Task Determination of experimental inputs from WP3 (M6 - M12)

Objective : Select model from T4.1, determine experimental testing required for model calibration and validation ✓
Link WP : WP2, WP3

3 Universidad de Burgos

Task Model development for fracture (M12 - M24)

Objective : Formulation, verification, calibration, and validation of a hydrogen-induced fracture mechanics model selected in task 4.2
Link WP : WP2, WP3, WP6

4 Fraunhofer IWM

Task Model development for fatigue (M24 - M45)

Objective : Models, possibly from task 4.3, will be selected and/or extended for fatigue crack growth under hydrogen induced degradation
Link WP : WP2, WP3, WP6

Milestones		Deadline
M6	Numerical model selection	M12 ✓

Deliverables		Deadline
D4.1	Literature review	M9 ✓
D4.2	Design criteria for hydrogen resistant failure	M45
D4.3	Optimized master curves for fracture	M45
D4.4	Optimized master curves for FCG	M45

Numerical modelling

Deliverable 4.1 Numerical modelling of fracture and fatigue - Literature review

- Comprehensive literature review on numerical models for predicting hydrogen damage.
- More than 30 papers reviewed.
- Particular attention paid to (1) how hydrogen embrittlement is modelled, (2) fracture and fatigue, (3) primary damage mechanisms of pipeline steel alloys.

	Description	Strengths	Limitations
GTN model	➢ Model ductile fracture through void nucleation and growth. ➢ Hydrogen affected yield function.	✓ Captures ductile fracture and microvoid evolution in the presence of hydrogen. ✓ Suitable for simulating complex stress states.	❖ Detailed calibration of material parameters required. ❖ Computationally intensive. ❖ Mesh dependent.
Cohesive zone model	Ø Cohesive elements to define the potential crack path. Ø Hydrogen degradation of the cohesive properties.	✓ Models crack initiation and propagation. ✓ Direct implementation of hydrogen degradation by modifying the traction-separation laws. ✓ Suitable for detailed fracture studies.	❖ Detailed calibration of cohesive parameters required. ❖ Pre-determined path. ❖ Less effective for capturing bulk material behavior.
Phase field model	Ø Crack represented as a diffusive interface Ø Hydrogen degradation of the fracture energy.	✓ Handles complex crack patterns naturally. ✓ No need for explicit crack tracking. ✓ Lower computational demand compared with more complex models.	❖ Characteristic length scale could lack of physical meaning. ❖ Detailed parameter calibration for phase field-hydrogen coupling required
Contour Integral	Ø J-integral or stress intensity factor of existing crack. Ø Hydrogen affected material parameters.	✓ Precise quantification of stress intensity factors. ✓ Straightforward implementation in finite element software.	❖ Limited to pre-existing cracks. ❖ Can not predict crack initiation. ❖ Primarily applicable to linear elastic fracture scenarios. ❖ Less effective for plastic or ductile fracture.

Numerical modelling

Task 4.2 - Determination of experimental inputs from WP3 (M6 – M12) - leader: SINTEF

Model selection - Milestone 6, December 2024:

- Cohesive zone model – for fatigue
- Phase field model – for fracture
- Both models to be implemented using ABAQUS and Intel Compiler for easy use between partners

Experimental inputs:

- Working documents created for Task 4.3 and Task 4.4
- Ongoing coordination with WP2 and WP3 to maximize already planned round robin and experimental tests for numerical model calibration and validation
- Ongoing coordination with WP2 and WP3 to identify any further required testing for numerical model calibration and validation, supported in Task 3.3.2 (ex: cyclic tensile tests for fatigue model)

Introduction to Task 4.3

Model calibration with experimental results

First version of H-PF

M16

M20

2025

M14

- Collection of available codes for H-PF fracture
- Choice of implementation approach

M18

- Validated H-PF model
- Influence of parameters on J-Δa curves

M20-M24

- Extension to 3D?
- Case of interest (cracked pipe?)
- Design-oriented simulation (K_{TH})

The commercial FEM software ABAQUS has been agreed in previous meetings:

- **User subroutines** are needed
- Two files will be shared: .for (model) + .inp (geometry, material, BCs)
- ABAQUS must be linked to *Intel Fortran Compiler* + *Visual Studio* (check compatibility of versions)

Implementation alternatives

3 approaches are identified in ABAQUS

- ❑ **UEL**: $\mathbf{u}$, ϕ and C_L are solved with the corresponding Jacobian matrix and residual vector
  - Pros: available code for elastic-brittle phase field
  - Cons: difficult implementation of plasticity (high coding effort)
- ❑ **UELMAT**: $\mathbf{u}$, ϕ and C_L are solved with the corresponding Jacobian matrix and residual vector
  - Pros: available code with plasticity (but without hydrogen)
  - Cons: it must be modified to include hydrogen

Second option

- ❑ **UMAT** + **UMATHT**: $\mathbf{u}$ is solved in the UMAT; ϕ and C_L in the UMATHT
  - Pros: available and versatile codes with only constitutive behaviour (less coding effort)
  - Cons: temperature degree of freedom must be duplicated (duplicated mesh)

First option

Introduction to Task 4.3

First version of H-PF

M17

Model calibration with experimental results

M20

2025

M14

- Collection of available codes for H-PF fracture
- Choice of implementation approach

M19

- Validated H-PF model
- Influence of parameters on J-Δa curves

M20-M24

- Extension to 3D?
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- Design-oriented simulation (K_{TH})

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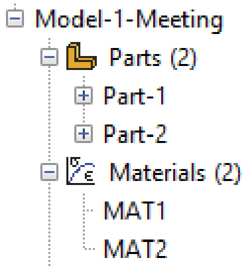
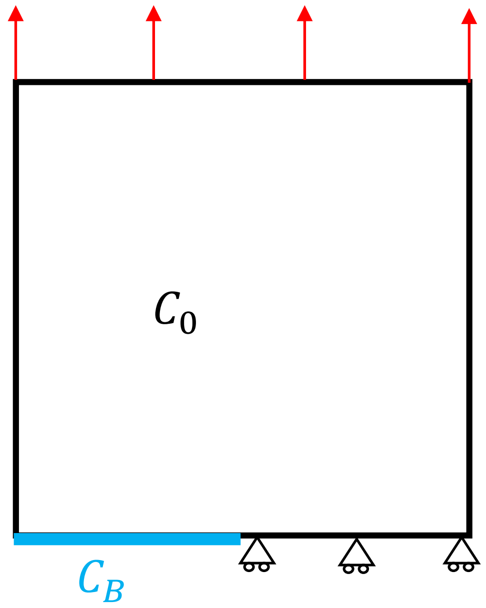
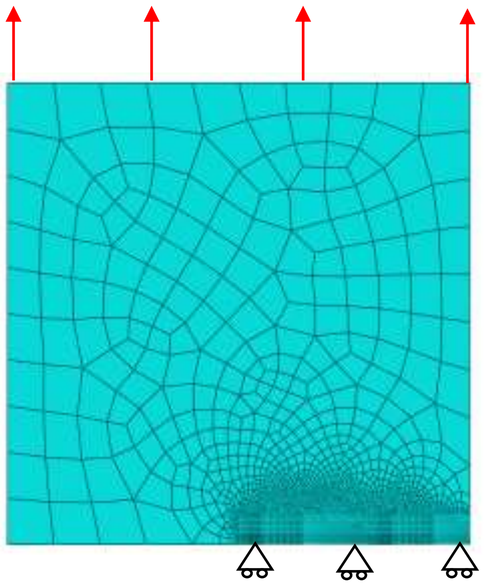
First version of H-PF model

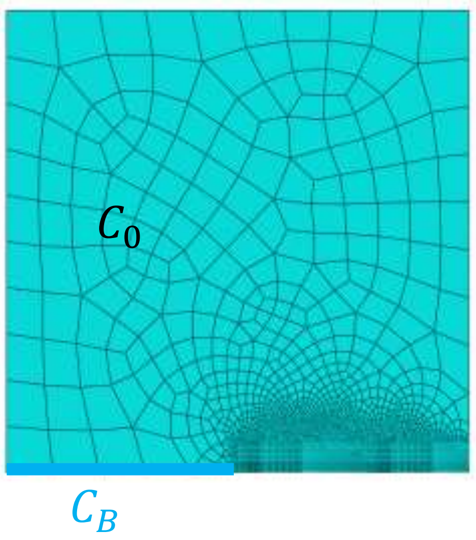
First case study: single-edge notched plate





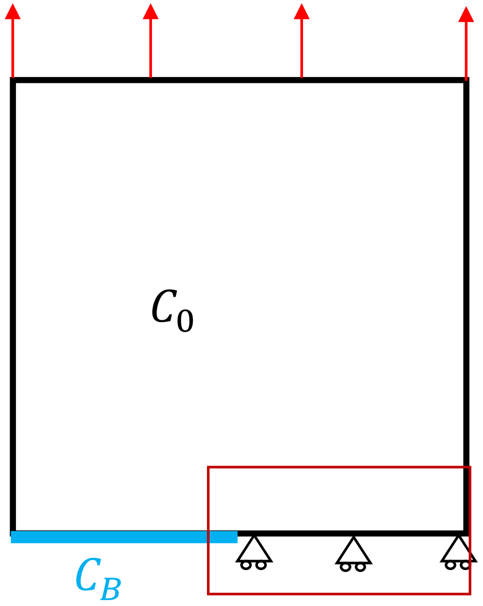


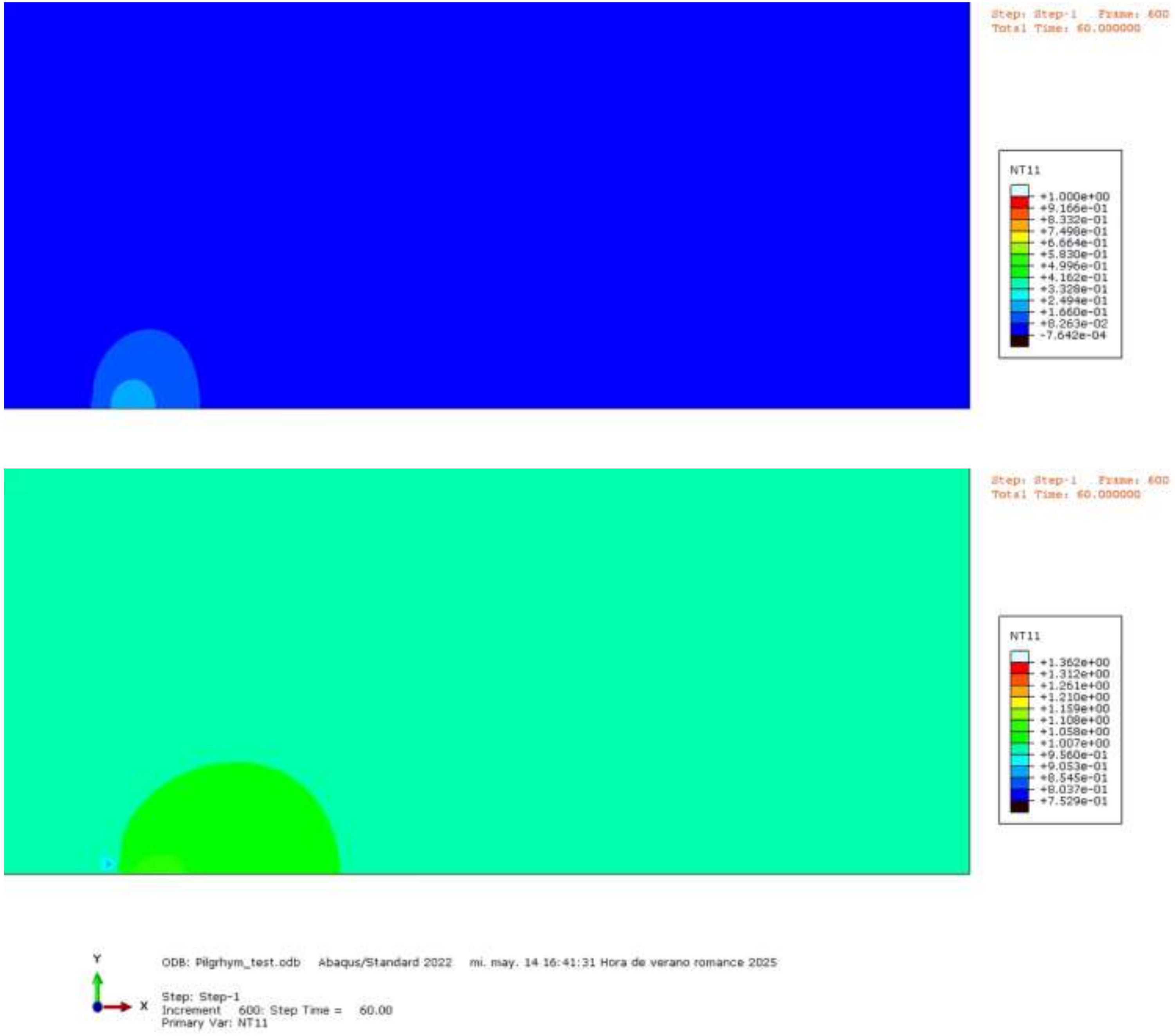
Part-1 and MAT1 (Phase Field)



Part-2 and MAT2 (H diffusion)

First case study: single-edge notched plate





Introduction to Task 4.3

2025

First version of H-PF

M17

Model calibration with experimental results

M20

M14

- Collection of available codes for H-PF fracture
- Choice of implementation approach

M19

- Validated H-PF model
- Influence of parameters on J-Δa curves

M20-M24

- Extension to 3D?
- Case of interest (cracked pipe?)
- Design-oriented simulation (K_{TH})

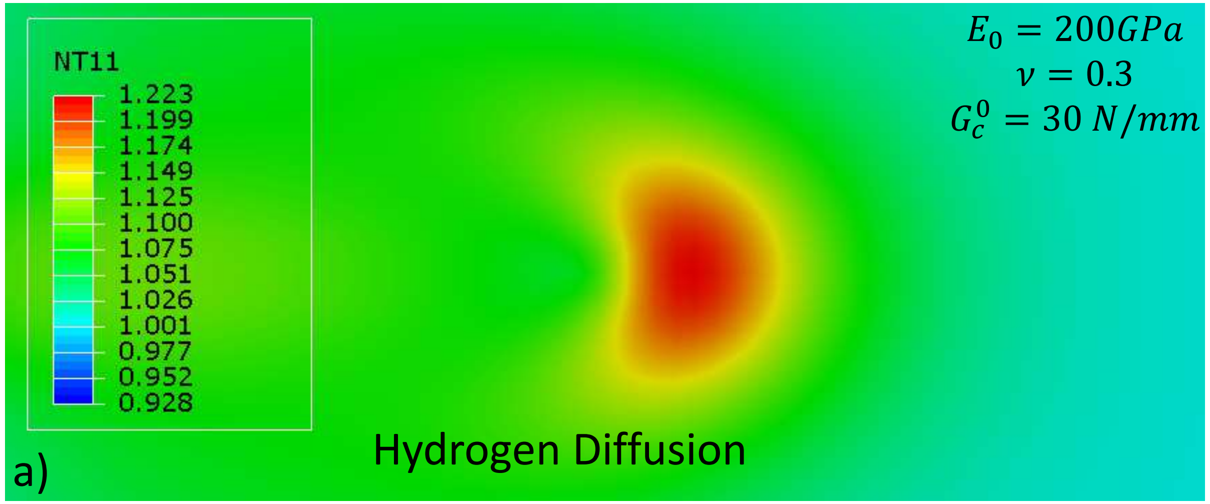
The commercial FEM software ABAQUS has been agreed in previous meetings:

- **User subroutines** are needed
- Two files will be shared: .for (model) + .inp (geometry, material, BCs)
- ABAQUS must be linked to *Intel Fortran Compiler* + *Visual Studio* (check compatibility of versions)

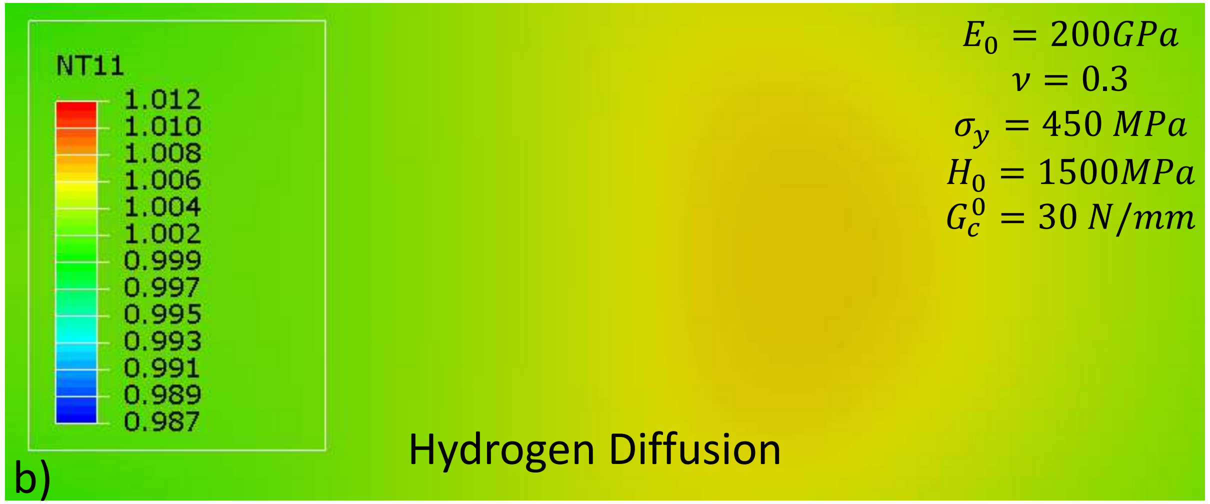
H-PF model – extension to plasticity

Elastic model

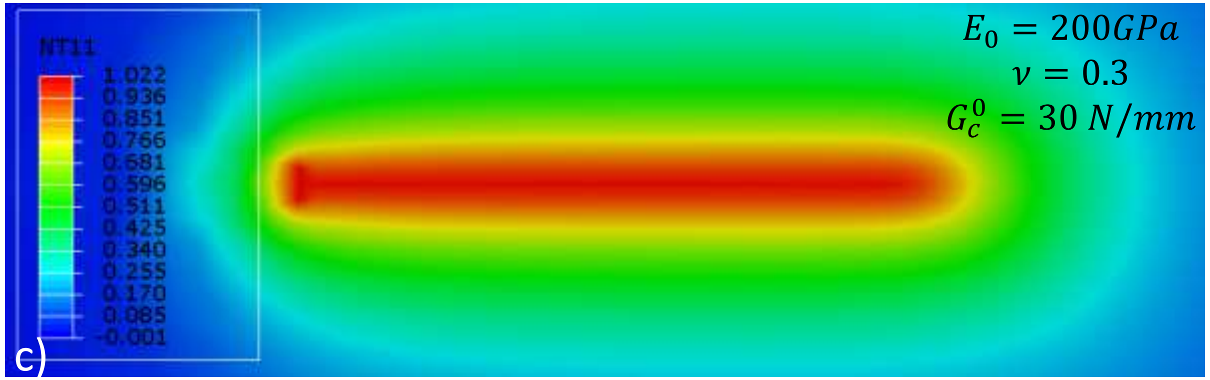
Plastic model



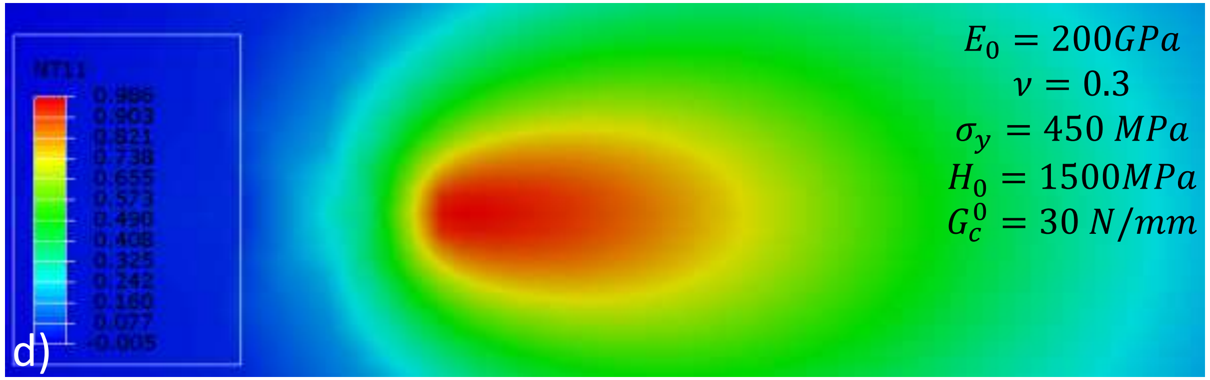
Hydrogen Diffusion



Hydrogen Diffusion

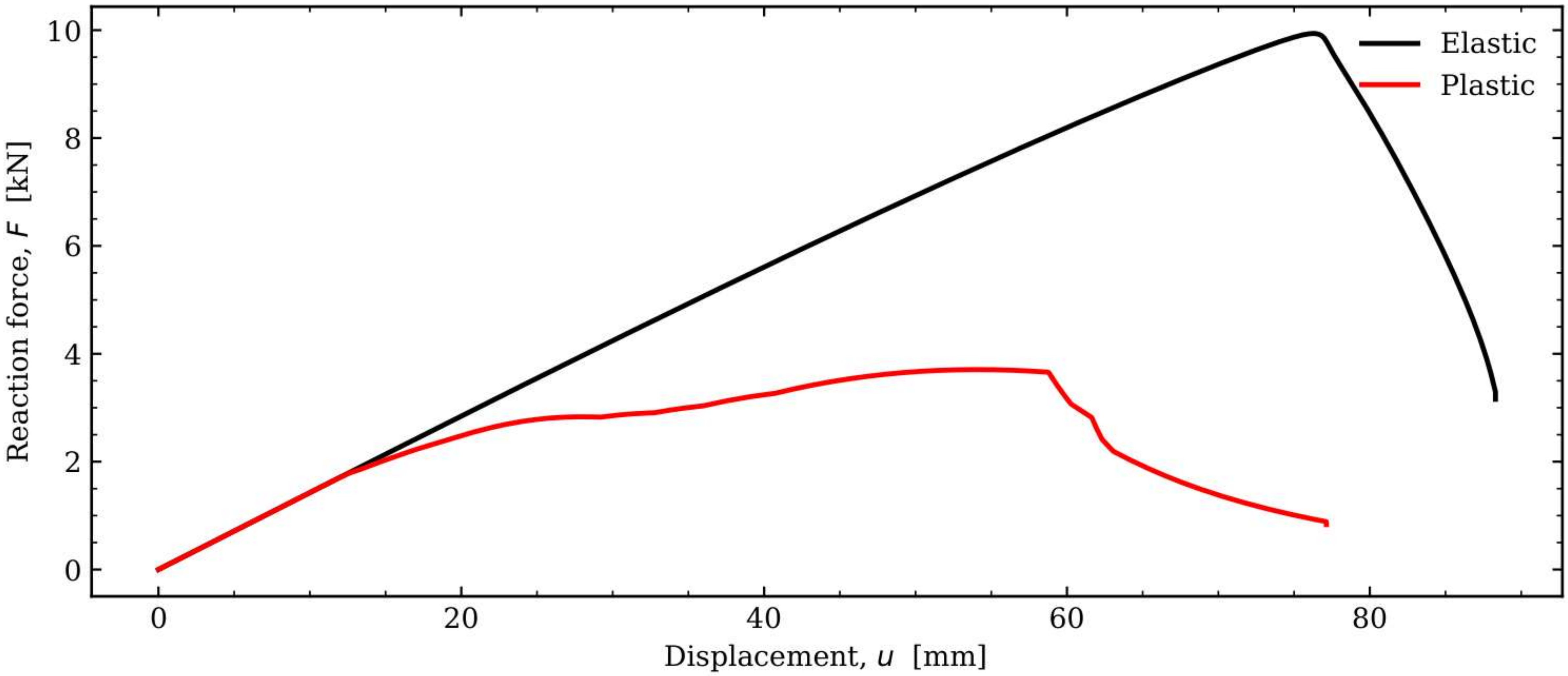


Phase-field variable



Phase-field variable

H-PF model – extension to plasticity



Timeline for Task 4.3

- Case study: notched plate
- Validation: in progress

M21

First version of H-PF

M17

2025

M14

- Collection of available codes for H-PF fracture
- Choice of implementation approach

M19

- Include plasticity
- Second version of H-PF

M22-M24

- R-curves (parametric study)
- Constraint effects
- Extension to 3D
- Design-oriented simulation

Model calibration with experimental results

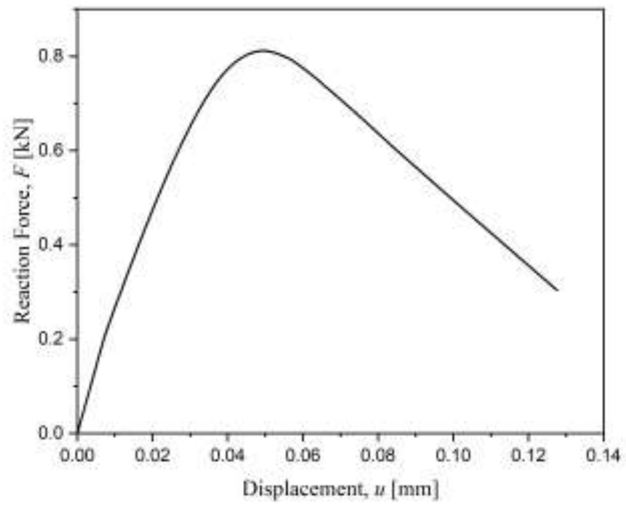
A second version is uploaded to the shared folder:

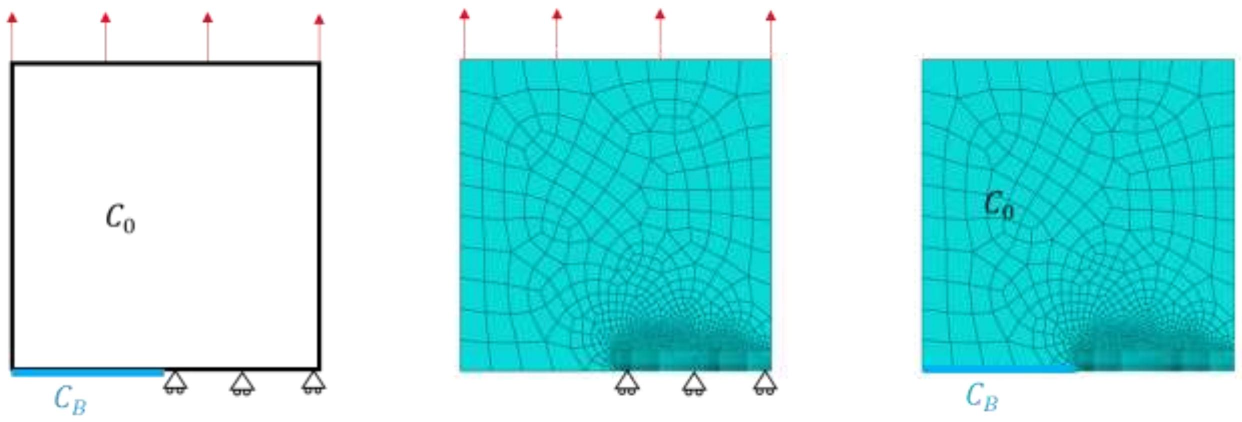
- `HPF_plastic.for` (model)
- Plate_plastic.`inp` (geometry, material, BCs)

Case study: notched plate

Crack propagation in a plastic material

- ❑ Case study of a notched plate
  - A J2 classical plasticity with isotropic linear hardening is implemented (easy to adapt to real hardening)
  - Stable crack propagation is found
  - Strong edge effects
  - Convergence issues

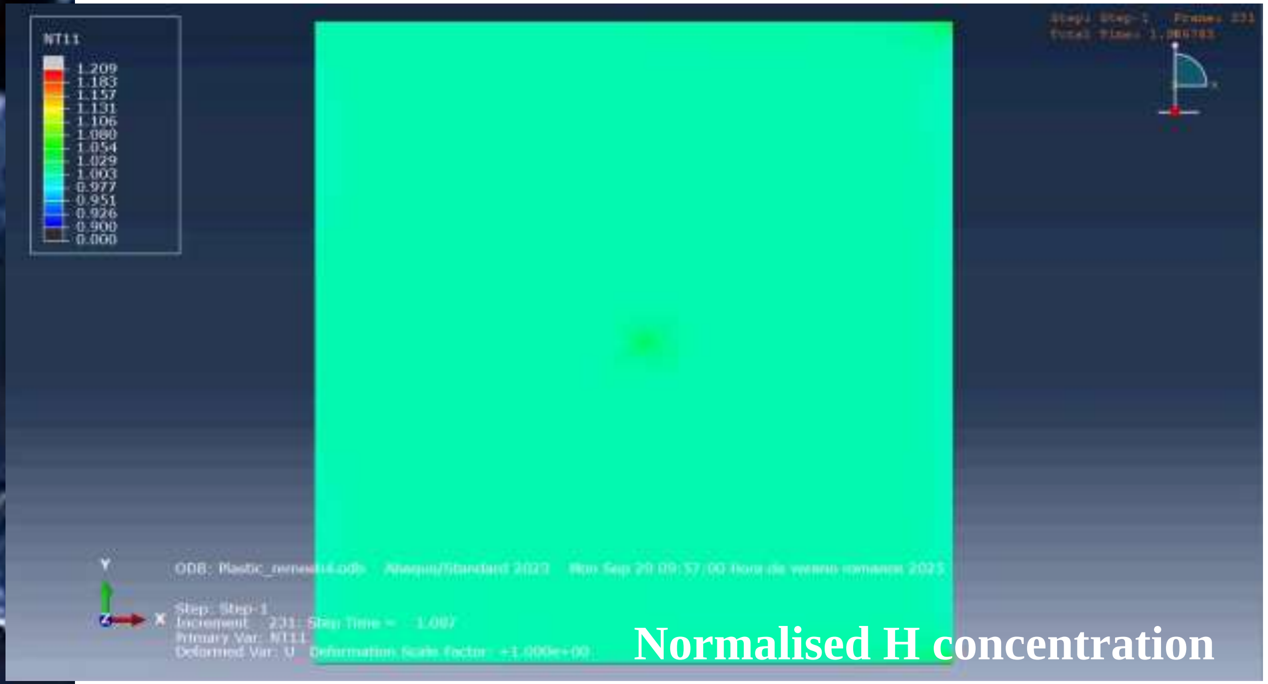


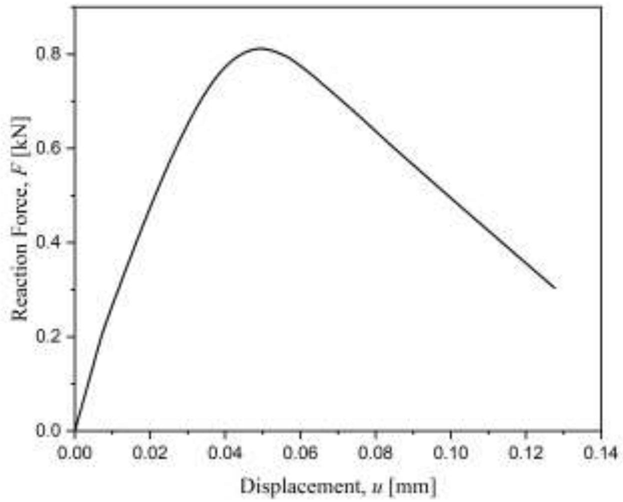


Part-1 and MAT1 (Phase Field)   Part-2 and MAT2 (H diffusion)


NT11
1.018
0.933
0.848
0.763
0.679
0.594
0.509
0.424
0.339
0.254
0.170
0.085
0.000
$E_0 = 210$ GPa
$\nu = 0.3$
$\sigma_y = 630$ MPa
$H_0 = 6.3$ GPa
$G_c^0 = 10$ N/mm
Phase-field variable


NT11
Diffusion→Red
Crack→Rainbow
Combined


NT11
1.209
1.183
1.157
1.131
1.106
1.080
1.054
1.029
1.003
0.977
0.951
0.926
0.900
0.000
Normalised H concentration


Reaction Force, F [kN]
0.0
0.2
0.4
0.6
0.8
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Displacement, u [mm]

Timeline for Task 4.3

2025

M14

- Collection of available codes for H-PF fracture
- Choice of implementation approach

M17

First version of H-PF

M19

- Include plasticity
- Second version of H-PF

M21

- Case study: notched plate
- Validation: in progress

M22-M24

- R-curves (parametric study)
- Constraint effects
- Extension to 3D
- Design-oriented simulation

Model calibration with experimental results

❑ **Upcoming Meetings / Actions :**

- ❑ Meeting M24 (early December)
- ❑ Parametric study on R-curves
- ❑ Draft paper focused on constraint effects

WP5 (FHA) Mitigation guidelines
WP6 (NaTran) PNR work

Mitigation guidelines

Objectives of WP5

2024 2025 2026 2027
M33 M48

PilgrHym

Objectives

- *Definition of adapted operational parameters compatible with the safe operation of hydrogen grids.*
- *Determination of the inhibitors (O_2, CO, etc.) content threshold value for a selection of steel grades, regarding its capacity to mitigate the effects of gaseous hydrogen embrittlement.*
- *Understanding of the mitigation capacity of internal coatings in steel pipes of different grades depending on the material and thickness.*

1

Task 5.1 (M33 - M48)
L: FHa
P : NaTran, Fluxys, UBU, CEA Liten, Tecnalia, OCAS

Objective : Reviewing the main operating conditions in hydrogen grids (hydrogen maximum pressure, pressure cycling, mechanical loading, etc.)
Link WP : WP1, WP3

2

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Task 5.2 (M33 - M48)
L: UBU
P : FHa

Objective : Reviewing the effect of internal coatings and inhibitors on the performance of gas pipes under hydrogen service

Link WP : WP3

Milestones		Deadline
MS9	First update on results from WP3	M35
MS11	Comprehensive review of at least 3 coating techniques and the effect of 1 inhibitor	M42
MS12	Final update on results from WP3	M44

Deliverables		Deadline
D5.1	Operational parameter guidelines for the safe operation of transport pipelines	M40
D5.2	Preliminary report on innovate technology	M48

PNR work

Objectives of WP6

2024 2025 2026 2027
M36 M48

Pilgrhym

Objective

- *O1: Recommend guideline as support for the writing/revision of a European standard / O2: Design a criterion against hydrogen-assisted fracture / O3: Develop a less conservative master-curve for fatigue crack growth assessment with a focus on the low ΔK portion/ O4: Analyze the gaps on defect acceptance criteria for repurposed natural gas pipelines*

1

Task 6.1 (M36 - M45)

tecnalia

P : NaTran, FHA, UBU, OCAS, FLUXYS, ENAGAS, SNAM

Objective : Inventory on existing codes and standards (Duration: 6 months)
It will serve as a basis for a gap analysis of the existing criteria for flaw assessments, and for a clear identification of where over conservatism exists.
Link WP :

2

Task 6.2 (M40 - M45)

naTran

P : CEA, SINTEF, FHA, UBU, OCAS, FLUXYS, TECNALIA, ENAGAS, IWM, SNAM

Objective : Gathering and analysis of results from WPs
* Conservatisms of standards in Task 6.1 challenged & a new less conservative master curve addressed.
- Compatibility of pipeline steel grades with hydrogen established as a function of network operating conditions and mitigation Techniques

Link WP : WP1, WP2, WP3, WP4, WP5

3

Task 6.3 (M42 - M48)

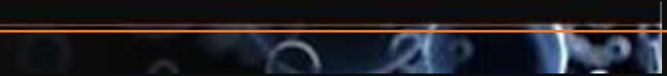
naTran

P : All

Objective : Recommendations for optimising current codes & standards (Aim: Revision of existing standards / Dissemination through WP8)
Guideline integrating * design criteria including the allowed size of defects , * a time- and cost-effective experimental procedure for material characterization under H2 and
* recommendations regarding the compatibility of transmission gas grid with H2 (function of steel grades, operating conditions and mitigations measures)
Link WP : All / Outcomes from tasks 6.1 and 6.2

Milestones		Deadline
M13	Gaps analysis on defect acceptance criteria for repurposed natural gas pipelines (L: NaTran)	M45
M14	Writing of recommendations (L: NaTran)	M47

Deliverables		Deadline
D6.1	General PNR report (PU) – L: Tecnalia	M45
D6.2	Matrix H2-readiness assessment (PU) – L: NaTran	M45
D6.3	Optimised master curves (PU) – L : IWM	M45



Q&A and Closing

NaTran

Clean Hydrogen Partnership

Thank You

Co-funded by
The European Union