COMPATIBILITY ASSESSMENT OF NON-STEEL METALLIC DISTRIBUTION GAS GRID MATERIALS WITH HYDROGEN

CANDHy

D3.2

WP3 Deliverable

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EXECUTIVE SUMMARY

The goal of CANDHy (Horizon No. 101111893) is to evaluate the integrity and tolerance of non-steel metallic natural gas distribution networks that supply H_2/natural gas (NG) mixtures (up to 100 vol% H_2) under long-term operating conditions. Through the application of standardized guidelines, the initiative aims to improve confidence among gas operators, regulators, authorities, and end users by combining scientific data. These guidelines will facilitate easy integration across gas networks and guide prenormative actions in European organizations.

The state-of-the-art review conducted by RINA in Work Package 2 (WP2) highlighted the tests and standards to be used for this environment, as well as the compatibility of metals with hydrogen.

The tests are defined and carried out in Work Package 3 (WP3). The first task was to define the various materials to be tested, as well as the testing machines, depending on the availability of each partner equipment. The second part of this WP involved creating a test matrix, composed by a round robin test and individual tests. The round robin (RR) tests will be conducted by multiple partners for comparison, while the individual tests will be performed independently by each partner. For both RR tests and individuals test, statics loaded test as C-Ring with and without notch and CT-WOL specimens will be carried out by FHa, RINA and GRTgaz. Dynamic loaded tests as fatigue crack growth tests, SSRT with and without notch and Fracture toughness tests will be done by RINA, GRTgaz and Tecnalia.

In total, 14 materials will be tested, including vintage and new materials. All new and vintage materials will be collected by SIDSA, from Redexis, Itaglas and Inrete distribuzione and then distributed to RINA to machine the specimens for the RR tests and to the other partners for the individual test. Base metal and a weld will be tested.

This report details the initial and final test matrix, explaining the modifications that had to be made due to constraints related to material thickness or testing machine. It also explains the purpose of each test, as well as the testing parameters and standards that will be applied within the framework of CANDHy.

1. INTRODUCTION AND OBJECTIVES

The CANDHy Work Package 3 (WP3) is intended to design, develop, and perform an experimental campaign to test the most relevant non-steel metallic materials found in CANDHy under different hydrogen levels to assess their tolerance towards this gas at operating conditions usual for the distribution grid. Six partners and laboratories are involved: FHa (leader), GRTgaz, REDEXIS, TECNALIA, RINA and SIDSA.

Moreover, the goal of Task 3.2 is to define the most relevant tests according to materials specified in Work Package 2 and prepare an experimental matrix according to different tests, environments, pressure, materials, and available partners' equipment. GRTgaz is the leader of this task.

This report is aimed to give information concerning the mechanical tests, as the materials used, the different tests performed and the number of each, the geometry of the specimens to each test, and the partner involved. To simplify the comprehension, a matrix has been developed with every parameter quoted before. According to the materials, the testing machines or other parameters, this matrix had to be changed to fit the requirements. In a first part, the initial matrix and the changes made, and their reasons are described. Then the final matrix with the geometries chosen are reported, as well as the tests conditions.

A second part defines the test and the purpose, mechanically speaking, of each test. In addition, since some permeation tests would be performed by University of Bergamo, a description of those tests is presented in this report.

2. TEST MATRIX

2.1 Available materials

First, information regarding the most relevant non-steel metallic materials of the gas distribution grid was gathered from the survey conducted in WP2 and collected in deliverable D2.1. On the other hand, in Task 3.1 of WP3, External Advisory Board (EAB) members and CANDHy partners have been surveyed to know the availability of non-steel metalic materials for use in CANDHy. Based on this information, two lists, one for vintage materials (*Figure 1*) and one for new materials (*Figure 2*) have been created by CANDHy partners. These tables have been completed with information such as the type of sample (i.e. pipe, gas regulator, etc.), the size (diameter and length) and the thickness. In the case of vintage materials, information related to the installation year has also been collected.

Materials	Type	SPOOL No	OD, mm	OD REAL	WT, mm	REAL WT	Length, m	Installation year
Ductile cast iron	Pipe	1	80	98	6	4.76-5.01-4.99-5.02-5.2	2,4	1988 - 2024
	Pipe	2	150	170	6,3	6.11 (pipe body) 12.20 on Bell Section (around 150 mm)	2,13	1989 - 2024
	Pipe	3	100	118	6,1	9.14 – 8.50	1,33	1989 - 2024
	Pipe	Spools 7,4.	200	222	6,4	6.59-5.16 (body pipe Spool 4)	3,82	1983 - 2021
			Elbow 45º			7,72	0,3	
			Elbow 90º			7,72	0,48	
			Coupling			9,65	1,25	
	Pipe	5	80	98	6	5.03 (pipe body)	1,97	1988 - 2024
			Elbow 45º			6,15	0,25	
			Elbow 45º			6,25	0,25	
	Pipe	6	200	222	6,4	5,75	1,77	1982 - 2024
Aluminium/Zinc	Gas regulator	8	See tables					
Gray cast iron	pipe	9	200		9		0,5	1970
Ductile iron	pipe	10	DN200		7		2	1970
Grey cast iron	pipe	11	DN 4"		10		5	
Lead	pipe	12	DN 2"		5		4	

Figure 1 : List of vintage materials.

Materials	Welds	ID	Type	OD, mm - nominal	OD, mm	WT, mm	Length, m
DUCTILE IRON PIPE FGS		1	EN545/969 K12	100	118	7.2	.4-6
DUCTILE IRON PIPE FGS			EN545/969 K12	150	170	7.8	.4-6
DUCTILE IRON PIPE FGS			EN545/969 K12	250	274	9	.4-6
DUCTILE IRON PIPE FGS			EN545/969 K12	350	378	10.2	.4-6
DUCTILE IRON PIPE FGS		2	EN545/969 K12	500	532	12	.4-6
DUCTILE IRON ELBOW FGL			EN545/969 K12	100	118	7.2	6 PCS
DUCTILE IRON ELBOW FGL			EN545/969 K12	150	170	7.8	6 PCS
DUCTILE IRON ELBOW FGL			EN545/969 K12	250	274	9	4 PCS
DUCTILE IRON ELBOW FGL			EN545/969 K12	350	378	10.2	4 PCS
DUCTILE IRON ELBOW FGL		3	EN545/969 K12	500	532	12	4 PCS
GREY CAST IRON BLANK FLANGE FGL		4	EN545/969 K12 / PN16	100	118	19	6 PCS
GREY CAST IRON BLANK FLANGE FGL			EN545/969 K12 / PN16	150	170	19	6 PCS
GREY CAST IRON BLANK FLANGE FGL		5	EN545/969 K12 / PN16	250	274	22	4 PCS
GREY CAST IRON BLANK FLANGE FGL			EN545/969 K12 / PN16	350	378	26.5	4 PCS
GREY CAST IRON BLANK FLANGE FGL			EN545/969 K12 / PN16	500	532	31.5	4 PCS
GREY CAST IRON TEE FGL			EN545/969 K12	100	118	7.2	6 PCS
GREY CAST IRON TEE FGL	WELDED SECTION WALL: 9 mm / TOTAL LENGTH 1250 mm		EN545/969 K12	150	170	7.8	6 PCS
GREY CAST IRON TEE FGL	WELDED SECTION WALL: 11.5 mm / TOTAL LENGTH 1100 mm		EN545/969 K12	250	274	9	4 PCS
GREY CAST IRON TEE FGL	WELDED SECTION WALL: 13.5 mm / TOTAL LENGTH 2350 mm		EN545/969 K12	350	378	10.2	4 PCS
GREY CAST IRON TEE FGL	WELDED SECTION WALL: 15 mm / TOTAL LENGTH 2750 mm	6	EN545/969 K12	500	532	12	4 PCS
DUCTILE TRANSITION FGL			EN545/969 K12	100	118	7.2	6 PCS
DUCTILE TRANSITION FGL			EN545/969 K12	150	170	7.8	6 PCS
DUCTILE TRANSITION FGL			EN545/969 K12	250	274	9	4 PCS
DUCTILE TRANSITION FGL			EN545/969 K12	350	378	10.2	4 PCS
DUCTILE TRANSITION FGL		7	EN545/969 K12	500	532	12	4 PCS
BRASS		8		DN 25			1 PCS

Figure 2 : List of new materials, chosen materials in highlight in yellow.

3. Initial test Matrix

3.1 Changes concerning type of tests

Material		Condition	Static loaded								Dynamic loaded								Fatigue tests			
			C-Ring				CT-WOL				Fracture Toughness (FT)				SSRT				Fatigue Crack Growth (FCG)			
			Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec
RR tests on ductile iron (pipes)	Gr xxx for RR tests	<15% blend										3										
	Gr xxx for RR tests	20%blend	3	3	3		6	6	6			3		3		6				3		
	Gr xxx for RR tests	100%H2	3	3	3		6	6	6			3	3	3		6	6	6		3		
	Gr yyy for RR tests	<15% blend										3										
	Gr yyy for RR tests	20%blend	3	3	3		6	6	6			3		3		6				3		
	Gr yyy for RR tests	100%H2	3	3	3		6	6	6			3	3	3		6	6	6		3		
Individual tests (Cooper, Brass, Aluminium, Lead,...) (pipes)	Material type 1	<15% blend										3										
	Material type 1	20%blend	3				6					3				6						
	Material type 1	100%H3	3				6					3				6						
	Material type 2	<15% blend											3									
	Material type 2	20%blend	3				6						3				6					
	Material type 2	100%H3	3				6						3				6					
	Material type 3	<15% blend												3								
	Material type 3	20%blend	3				6							3				6				
	Material type 3	100%H4	3				6							3				6				
Fittings	Ductile iron Gr xxx - reduction	20%blend																			2	
	Ductile iron Gr xxx - reduction	100%H4																			2	
	Ductile iron Gr xxx - elbow	20%blend																			2	
	Ductile iron Gr xxx - elbow	100%H4																			2	
	Ductile iron Gr xxx - tee	20%blend																			2	
	Ductile iron Gr xxx - tee	100%H4																			2	
	Ductile iron Gr yyy - reduction	20%blend																				
	Ductile iron Gr yyy - reduction	100%H4																				2
	Ductile iron Gr yyy - elbow	20%blend																				
	Ductile iron Gr yyy - elbow	100%H4																				2
	Ductile iron Gr yyy - tee	20%blend																				
	Ductile iron Gr yyy - tee	100%H4																				2
	TOTAL		30	12	12	0	60	24	24	0	0	27	15	21	0	36	24	24	0	12	12	6

Figure 3 : Initial matrix.

A test matrix was defined during the response to the call for project, with optimized expectations in terms of number of materials and blends to be tested and considering R&D platforms availability and budget. *Figure 3* illustrates this initial matrix. A larger one is available in *Annex 1*. In total, each lab had to test initially:

- FHa should carry out 90 tests, in particular static loaded tests with 30 C-Ring and 60 CT-WOL,

- RINA should carry out 111 tests, in particular 12 C-Ring and 24 CT- WOL tests for static loaded test, 27 FT and 36 SSRT for dynamic loaded tests, and 12 fatigue tests (FCG),
- GRTgaz should carry out 87 tests, in particular 12 C-Ring and 24 CT- WOL tests for static loaded test, 15 FT and 24 SSRT for dynamic loaded tests, and 12 fatigue tests (FCG),
- TECNALIA should carry out 51 tests, 21 FT and 24 SSRT for dynamic loaded tests and 6 fatigue tests.

According to the materials availability (see *Section 2.1*), the feasibility of some specimens to be tested was compromised and the initial test matrix was modified to be aligned to this feedback. Some decisions made to adapt the test matrix according to the limitations are exposed below.

To make the comparison possible, reference tests were added. Two additional tests in air were added for each dynamic loaded test.

Due to the low thickness of vintage materials, some CT-WOL was replaced by C-RING with notch, and FT by Slow Strain Rate Testing (SSRT) with notch. Tests with notch will be different that test with a crack (CT-WOL and FT). They will not permit to calculate a toughness value as proposed by standards with a crack, but they could highlight the sensitivity of material to hydrogen in presence of a notch (and so a stress concentration). It also has been proposed to also perform test with SSRT with a notch on a new material from the Round Robing (RR) test to compare the effect of hydrogen on a SSRT with notch specimen and a 'classical' CT specimen.

3.2 Changing concerning gas

Initially, it was planned to perform the tests under 15 vol.%, 20 vol.% and 100 vol.% of hydrogen (H2). As it was said before (Section 3.1.1), it has been decided to carry out some test under air in order to have references.

Moreover, to optimize the number of tests with the maximum number of material and parameter configurations, one gas mixture (20 vol.% H2 – 80 vol.% CH4) and pure hydrogen (100 vol.% H2) have been agreed as the test configurations. Lower gas mixture concentration under 20 vol.% of hydrogen are discarded since it is preferable to test more materials than gas mixture, also because standards and studies reported that below this value there are usually no changes in materials behavior, which is aligned to EAB feedback.

The test pressure has been chosen to match the maximum pressure of the distribution network, which is 16 bar.

3.3 Changes concerning tests on welds

No welds are available in the vintage material list and even if vintage material containing a weld will have been found, dimensions of pipe (especially thickness) will have not be sufficient to machine specimens. It has then been decided to create welds using new material for the experimental testing campaign.

4. Final test Matrix

	Material	Condition	Static loaded											Dynamic loaded									Fatigue tests		
			C-Ring				C-Ring with notch			CT-WOL				Fracture Toughness (FT)			SSRT with notch			SSRT			FCG		
			Fha	Fha (2nd load)	RINA	GRT	Fha	RINA	GRT	Fha	Fha (2nd load)	RINA	GRT	RINA	GRT	Tec	RINA	GRT	Tec	RINA	GRT	Tec	RINA	GRT	Tec
RR tests on ductile and grey cast iron (pipes)	Vintage ductile iron - spool 3	20%blend															3				3				
	Vintage ductile iron - spool 3	Air															2	2	2	2	2	2			
	Vintage ductile iron - spool 3	100%H2															3	3	3	3	3	3			
	Vintage ductile iron - spool 1	20%blend	3		3	3	3	3	3																
	Vintage ductile iron - spool 1	100%H2	3	3	3	3	3	3	3																
	New ductile iron - ID 2	20%blend								3		3	3	3						3					
	New ductile iron - ID 2	Air												2	2	2	2			2	2	2	1		
	New ductile iron - ID 2	100%H2								3	3	3	3	3	3	3	3			3	3	3	2		
	New ductile iron - ID 1	20%blend	3		3	3	3																		
	New ductile iron - ID 1	100%H2	3	3	3	3	3																		
Individual tests (Cooper, Brass, Aluminium, Lead,…) (pipes)	New grey cast iron - ID 5	20%blend											3	3						3					
	New grey cast iron - ID 5	Air												2						2			1		
	New grey cast iron - ID 5	100%H2										3		3						3			2		
	New grey cast iron - ID 4	20%blend				3																			
	New grey cast iron - ID 4	100%H2			3																				
	Vintage ductile iron - spool 2	20%blend				3							3		3						3				
	Vintage ductile iron - spool 2	Air													2						2			1	
	Vintage ductile iron - spool 2	100%H2			3							3			3						3			2	
	Vintage gray cast iron - spool 11	20%blend	3				3												3			3			
	Vintage gray cast iron - spool 11	Air																	2			2			
	Vintage gray cast iron - spool 11	100%H2	3	3			3												3			3			
	Ductile iron pipe - spool 10	20%blend	3				3																		
	Ductile iron pipe - spool 10	100%H2	3	3			3																		
	New grey cast iron - ID 6	20%blend								3				3						3					
	New grey cast iron - ID 6	Air												2						2			1		
	New grey cast iron - ID 6	100%H2								3	3			3						3			2		
	Brass bar - ID 8	20%blend								3						3						3			
	Brass bar - ID 8	Air														2						2			
	Brass bar - ID 8	100%H2								3	3					3						3			
Fittings	Vintage ductile iron - spool 7 - Elbow 45°	Air																						1	
	Vintage ductile iron - spool 7 - Elbow 45°	100%H2																						2	
	Vintage ductile iron - spool 7 - Elbow 90°	Air																						1	
	Vintage ductile iron - spool 7 - Elbow 90°	100%H2																						2	
	Vintage ductile iron - spool 7 - Coupling	Air																						1	
	Vintage ductile iron - spool 7 - Coupling	100%H2																						2	
	New ductile iron Elbow FGL - ID 3	20%blend								3															
	New ductile iron Elbow FGL - ID 3	Air																							1
	New ductile iron Elbow FGL - ID 3	100%H2								3															2
	New gray cast iron Tee FGL - ID 6	20%blend								3															
	New gray cast iron Tee FGL - ID 6	Air																					1		
	New gray cast iron Tee FGL - ID 6	100%H2								3													2		
	New Ductile transition FGL - ID 7	20%blend								3															
	New Ductile transition FGL - ID 7	Air																							1
	New Ductile transition FGL - ID 7	100%H2								3															2
	TOTAL		24	12	18	18	24	6	6	36	9	12	12	24	13	13	13	5	13	29	21	26	12	12	6

Figure 4 : Final matrix.

The *Figure 4* represents the final matrix. A bigger one is available in *Annex 1*. After all modifications considered, and respecting the requirements in terms of budget and machine-time, the distribution of tests is such that:

- FHa will carry out 105 tests, still static loaded tests only, with 24 C-Ring plus 12 C-Ring tested with a second load, 24 C-Ring with a notch and 36 CT-WOL plus 9 CT-WOL with a second load.
- RINA will carry out 114 tests, 18 C-Ring plus 6 C-Ring with notch and 12 CT- WOL tests for static loaded test, 24 FT and 29 SSRT plus 13 SSRT with notch for dynamic loaded tests, and 12 fatigue tests (FCG),
- GRTgaz will carry out 87 tests in total, 18 C-Ring plus 6 C-Ring with notch and 12 CT-WOL tests for static loaded test, 13 FT and 21 SSRT plus 5 SSRT with notch for dynamic loaded tests, and 12 fatigue tests (FCG),
- TECNALIA will carry out 58 tests, 13 FT and 26 SSRT plus 13 SSRT with notch for dynamic loaded tests and 6 fatigue tests.

Additionally, tests such as tensile test, hardness test (from the inner zone to the external one), and metallographic analysis will be performed to characterize the materials prior to start the test campaigns. The distribution of these trials will be defined according to everyone's budget.

4.1 Selection of materials

Vintage materials:
Vintage materials correspond to materials that have already been in service, i.e. exposed to a gas under pressure.

It must be noted that the real diameter and thickness of vintage materials are also collected in *Figure 1*. SIDSA has completed this information by measuring the samples received in their workshop. Thanks to the report provided by SIDSA [1], the materials for each test have been chosen.

Chosen materials for each kind of test are presented below.

- Round Robin test
  - FHA's autoclave for static load tests has a diameter of 10", therefore the autoclave cannot accept specimens over 250 millimeters of diameter. For this reason, the ductile cast iron with OD 98 has been selected for the **C-Ring tests, with and without notch, that is the spool 1**. FHa will test with a second load C-Ring without notch specimen as individual test.
  - Concerning the **SSRT tests, with and without notch**, the thickness of the specimen should not be too thin to avoid bending during machining, so the material thickness was the most important parameter to choose the spool. Thus, **spool 3** matched expectations (even if minimal wall thickness is closer to 7mm than 8.5mm as measured by SIDSA).
- Individual test
  - **Spool 2** (Ductile cast iron, OD 150, WT 6.3mm) has been chosen for several test:
    - The **spool 2 bell** would be used to machine the **FT** and the **CT-WOL** since the thickness is more than 10 mm,
    - It is possible to take **C-Ring** and **SSRT without notch** (M6) specimens onto the **spool 2 pipe**.
  - It has been decided to use **the spool 11** (DN 4", length 5m, WT 10 mm) to perform the following tests:
    - **C-Ring with and without notch**,
    - **SSRT with and without notch** (M8).
  - The **spool 10** could be tested on
    - **C-Ring with and without notch.** FHa will test with a second load C-Ring without notch specimen.
- Fitting tests:
  - The **spool 7** (vintage ductile iron, OD 200, WT 6.4) will be used to the **FCG** test (fatigue test). All the pieces, elbows (45° and 90°), and coupling will be used.

New materials

A large quantity of new materials was proposed (see *Figure 2*), based on the inventory carried out during the project and the relevance of materials (materials currently used for pipelines). More information are available in D2.2 report [2]. Thus, it was decided to choose equivalent materials as the vintage ones, for the comparison.

Chosen materials for each kind of test are presented below.

- Round robin test
    - To do the **C-Ring without notch** tests, it is mandatory to have a small radius to enter in the autoclave, as explained before. The **ID 1** (OD 100, WT 7.2) was chosen.
        - **C-Ring with notch** will be tested by FHa as individual tests.
    - In order to machine the dimensions requested, the same material (**ID 2**) with greater thickness (OD 500, WT 12) was selected to do several tests:
        - **CT-WOL** test,
        - **FT** tests,
        - **SSRT without notch**. SSRT with notch will be tested by Tecnalia as individual test,
        - **FCG** tests.
- Individual test
    - **ID4** will be used to prepare **C-Ring without notch samples,**
    - Another **grey cast iron, ID 5** with a greater thickness (OD 250, WT 22) will be used to perform:
        - **CT-WOL** tests,
        - **FT** tests,
        - **SSRT without notch** tests.
    - **Grey cast iron, ID 6** was chosen to elucidate the behavior of welds under hydrogen environment. Several tests will be performed with this material:
        - **CT-WOL** test, a second load will be tested by FHa,
        - **FT** tests,
        - **SSRT without notch** tests,
        - **FCG** tests.

- A piece of brass, corresponding to **the ID 8**, was also proposed to be used. With this material the following tests were decided to be performed:
    - **CT-WOL without notch** tests. FHa will test with a second load as the individual test,
    - **FT** tests,
    - And **SSRT test without notch** tests.

Fitting tests:

- **CT-WOL** tests and **FCG** tests will be performed with three different materials:
    - A **ductile iron, ID 3** (OD 500, WT 12, **elbow**),
    - A **grey cast iron, ID 6** (OD 500, WT 12, **Tee**),
    - A **ductile transition**, **ID 7** (OD 500, WT 12)

4.2 Conditions of the tests

This section aims to present the conditions of each test. The geometry of the specimens, the gas concentration, standard used, and test parameters are detailed. Further information concerning the tests' purposes is available on *section 5*.

SSRT

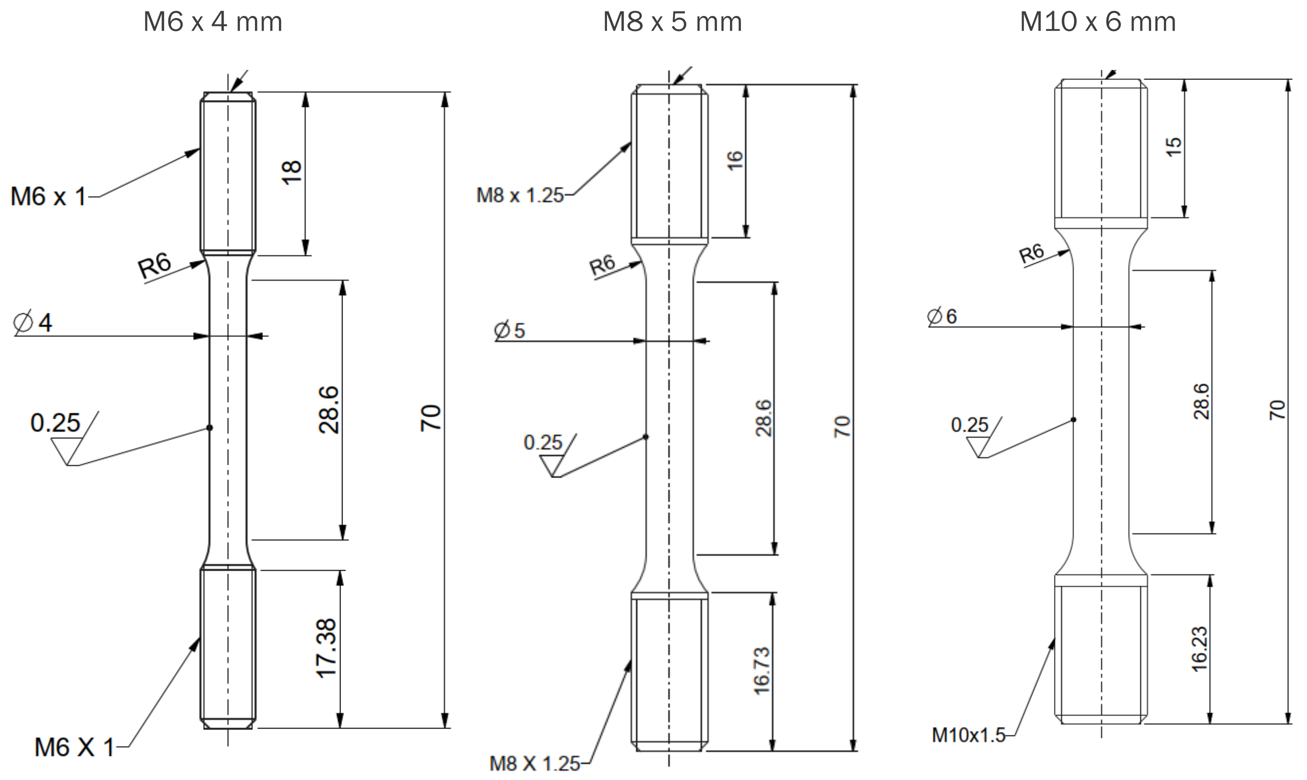


Figure 5: SSRT without notch specimen plans, proposed by RINA.

For this test, several geometries have been proposed (*Figure 5*). In fact, M10 specimen cannot be collected in every material because of their thickness. Thus, three geometries of SSRT without notch specimen were chosen, according to the material:

- M10 x 6 mm for **all the new materials chosen**,
- M8 x 5 mm for **spool 11.**
- M6 x 4 mm for **spool 2 and spool 3**. The diameter of the gauge length is not lower than 4 mm to avoid fracture during machining.

The geometry of those specimens was chosen in accordance with the **ASTM E8** [3].

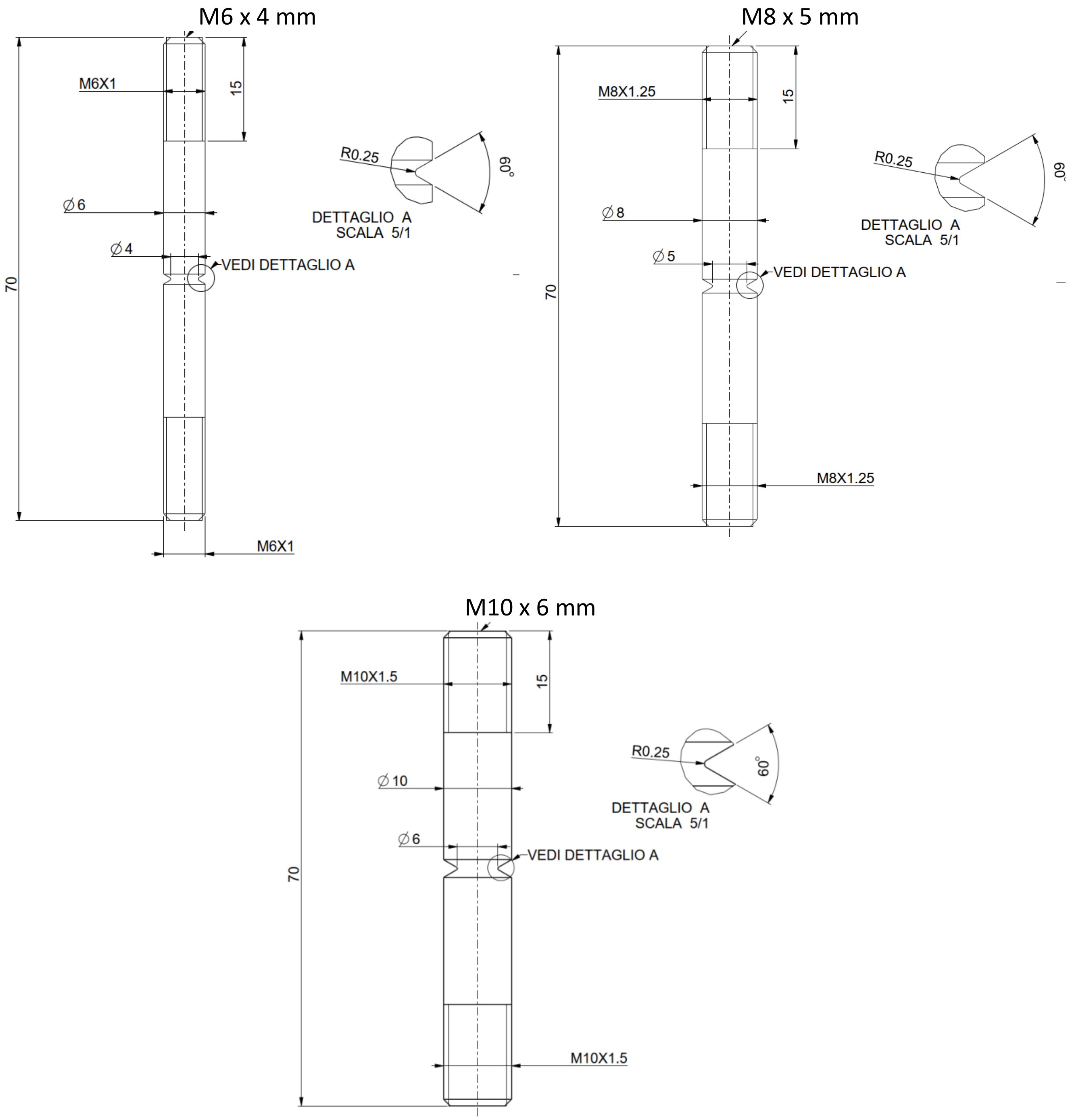


Figure 6: SSRT with notch specimen plan, notch radius: 0.25 mm, proposed by RINA.

For the SSRT specimen with notch, two geometries were selected (*Figure 6*):

- M10 with a 2 mm notch (so 6 mm diameter, to have the same diameter as the smooth specimen) for the **ID 2** (OD 500, WT 12),
- M8 with a 1.5 mm notch (so 5 mm diameter, to have the same diameter as the smooth specimen) for **spool 11.**

- M6 with a 1 mm notch (so 4 mm diameter, to have the same diameter as the smooth specimen) for **spool 3.**

The geometry proposed is based on **ASTM E8** and **ASTM G142** [4] proportion. The notch radius is 0.25 mm.

The duration of the tests (with and without notch) should be selected to respect the constraint of one test per day. Thus, the speed of the test would be calculated to match the duration.

SSRT with notch tests will be performed under 100 vol.% H2 and air to compare with CT geometry.

FCG

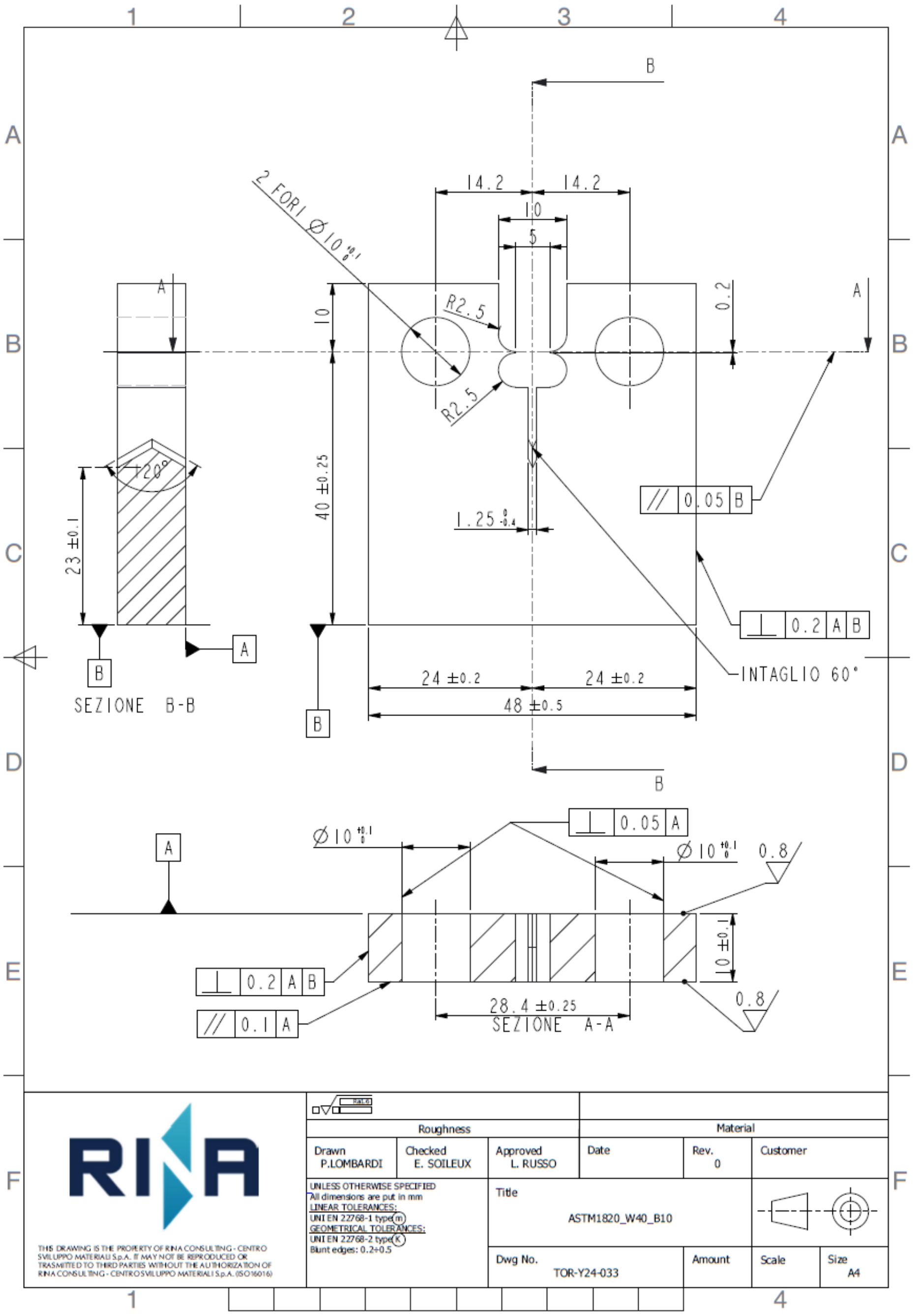


Figure 7: FCG specimen plan, proposed by RINA.

FCG test (*Figure 7*) will be performed with a frequency of 1Hz and a R ratio of 0.1. The geometry of the edges could be adapted by each partner depending on its own COD. Thickness could be adapted according to the materials geometry.

Concerning gas concentration, this test will be carried out at 100 vol.% hydrogen and under air for reference.

The test will be performed according to **ASTM E647 (or equivalent ISO)** [5].

CT-WOL

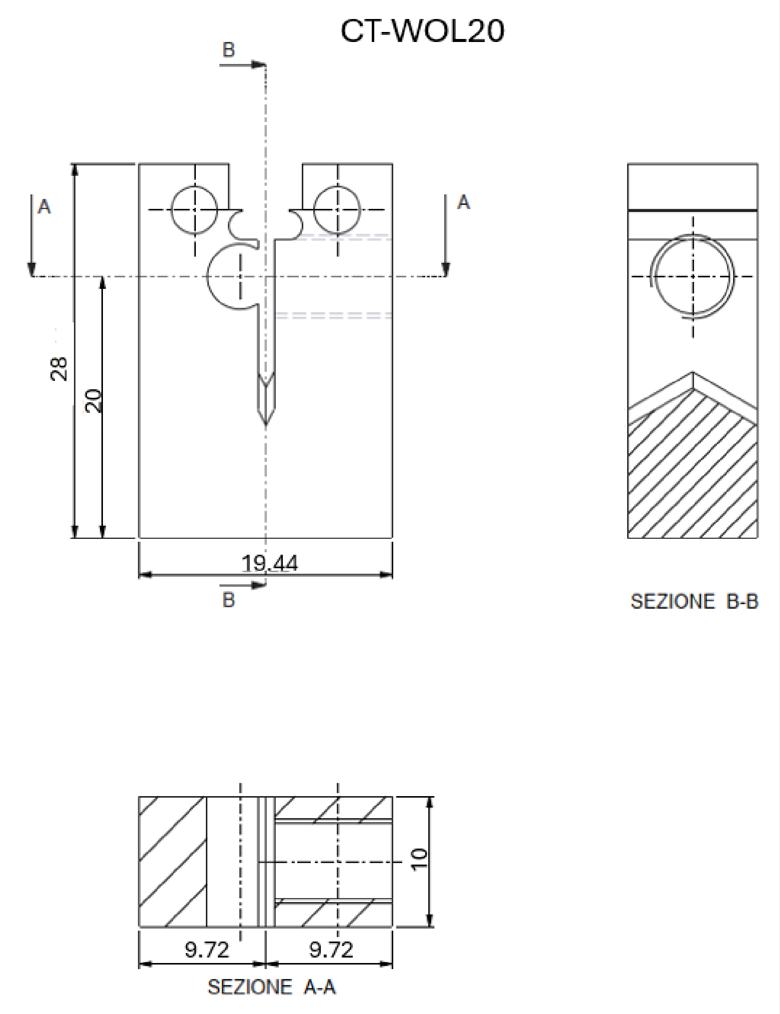


Figure 8: CT-Wol specimen plan, proposed by RINA.

RINA proposed a $W/_B$ ratio equal to 2 with $W = 20\ mm$, $B = 10\ mm$ and $H = 9.72\ mm$ (see *Figure 8*).

The pre-cracking will be done with $R = 0.1$, to obtain a crack length target $a/_W = 0.30\ to\ 0.95$, with a K_{max} as low as possible to have a crack as sharp as possible. The test will be performed according to **Article KD-10 of ASME BPVC** [6] and **ASTM E1681** [7]. K applied must be confirmed regarding material properties, defined during the characterization tests.

Concerning the gas concentration, this test will be performed under 20 vol.% and 100 vol.% of hydrogen.

Fha will test a second mechanical loading for C-ring and WOL in 100 vol.% H2 as individual tests.

C-Ring

C-Ring C-Ring with notch

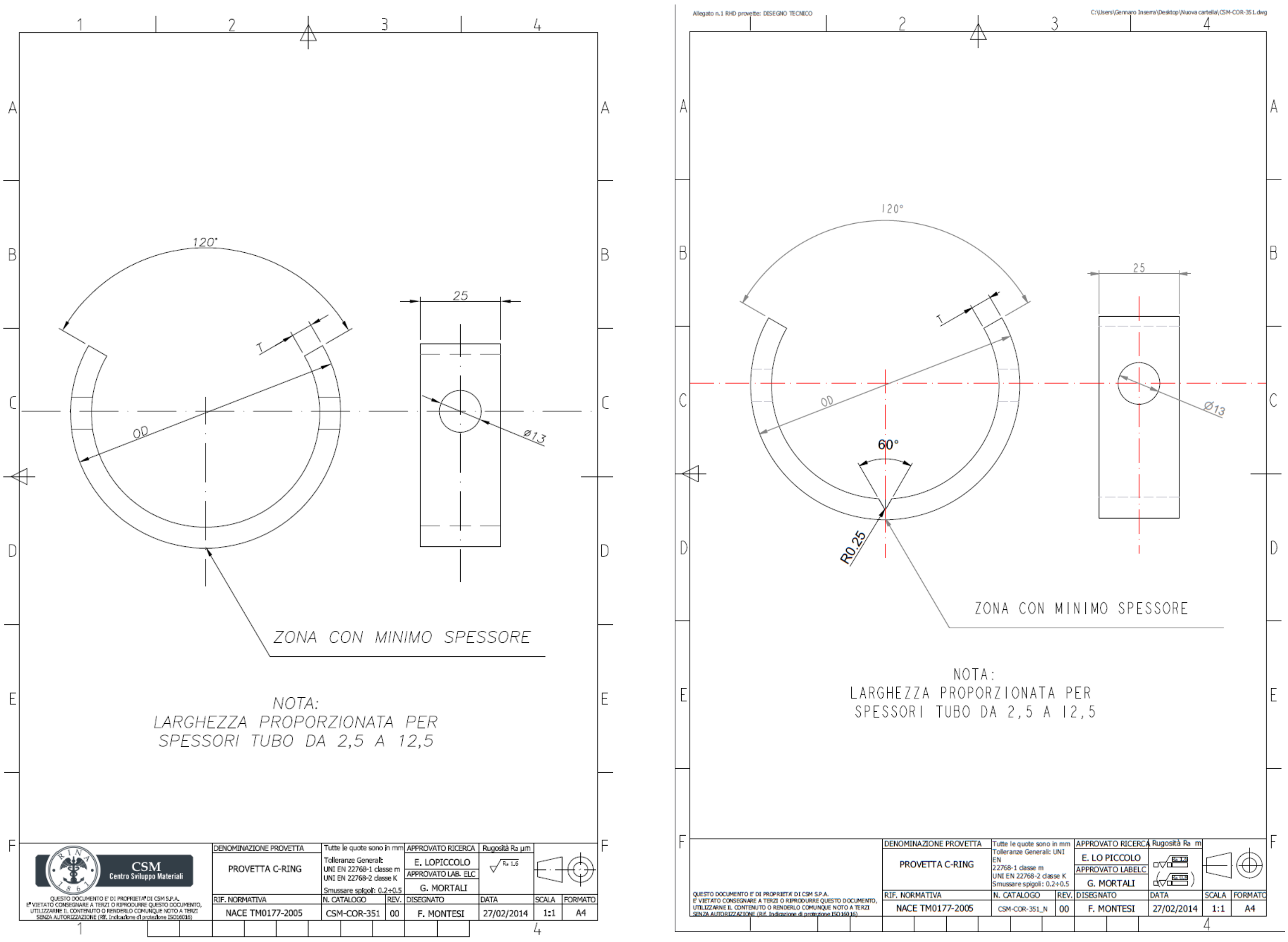


Figure 9: C-Ring with and without notch specimens plans, proposed by RINA.

Specimen dimensions will be as shown in *Figure 9*.

It was proposed to have the same notch dimensions as the SSRT with notch specimen and adapt the depth to have the same K_t to be comparable.

To be comparable to the WOL tests, the C-Ring with notch tests will be performed under 20 vol.% H_2 and 100 vol.% of hydrogen.

The tensile surface will be the inner surface, which is the surface in contact with hydrogen.

Specimens will be stressed at a stress level comprised between 75 and 100% of the elastic limit of the material.

FHa will test a second mechanical loading for C-ring and WOL in 100 vol.% H_2 as for individual tests.

FT

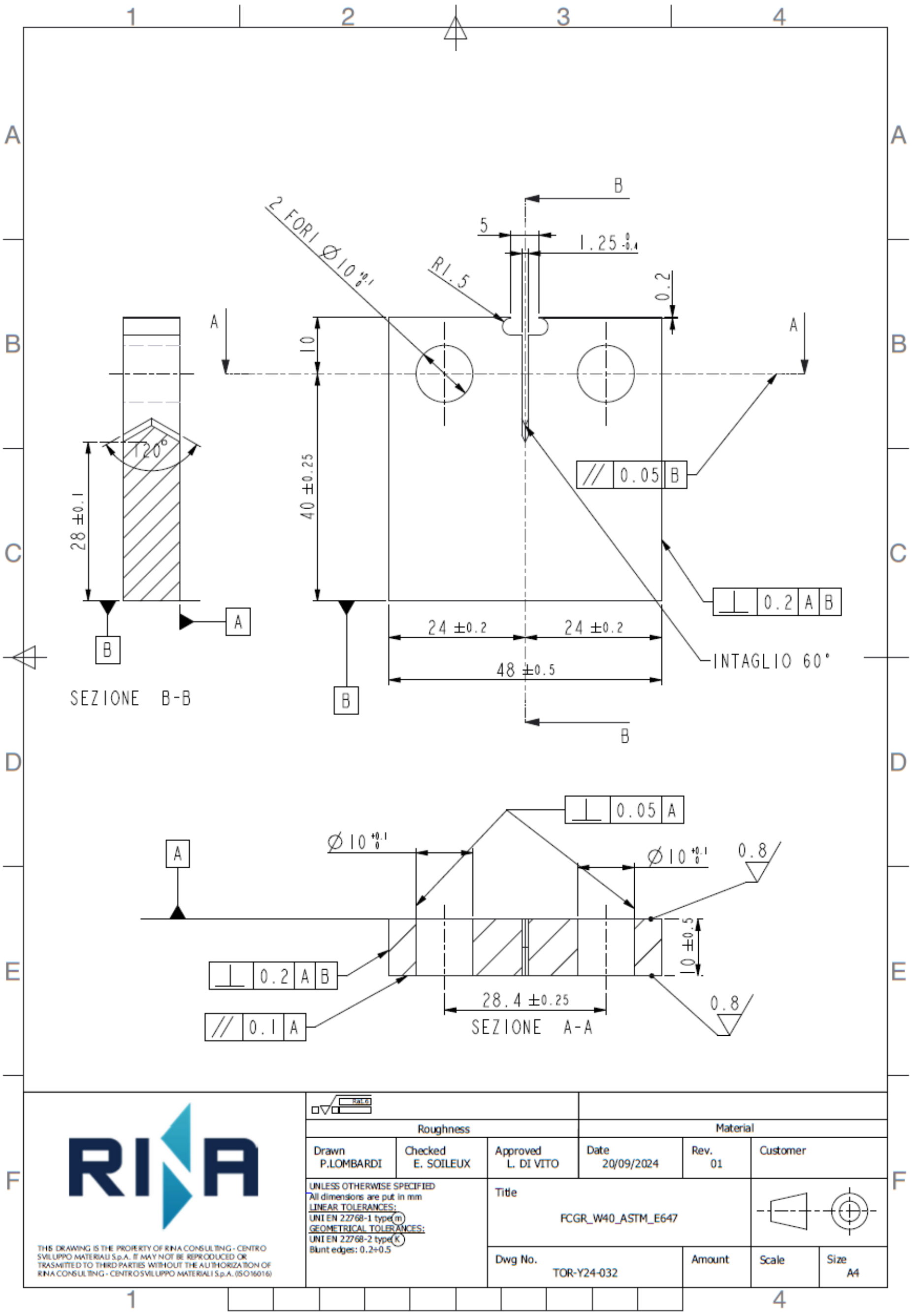


Figure 10: Drawing of toughness specimen, proposed by RINA.

For FT tests (*Figure 10*), a side groove will be done and will represent 10% of the thickness each side.

The geometry of the edge could be adapted by each partner according to their own COD.

The duration of the tests should be selected to respect the constraint of one test per day. Thus, the speed of the test would be calculated to match the duration.

Concerning the FT specimens sampled from the brass bar, the geometry could be adapted to machine disc-shaped specimens, as shown in *Figure 11*, following the appendix 3 in the standard **ASTM E1820** [8]. With the dimensions of the brass bar, it is possible to machine a specimen with W = 40 mm, which correspond to a CT specimen of 50 mm long and 48 mm high, which is in line with the dimensions proposed by GRTgaz, *Figure 10*.

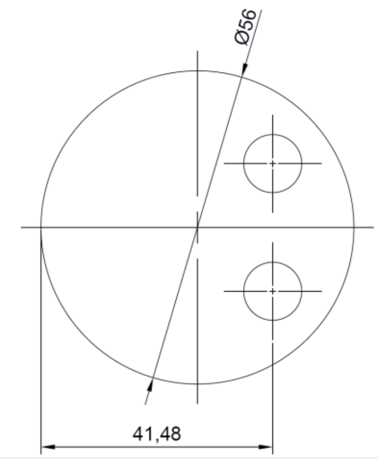


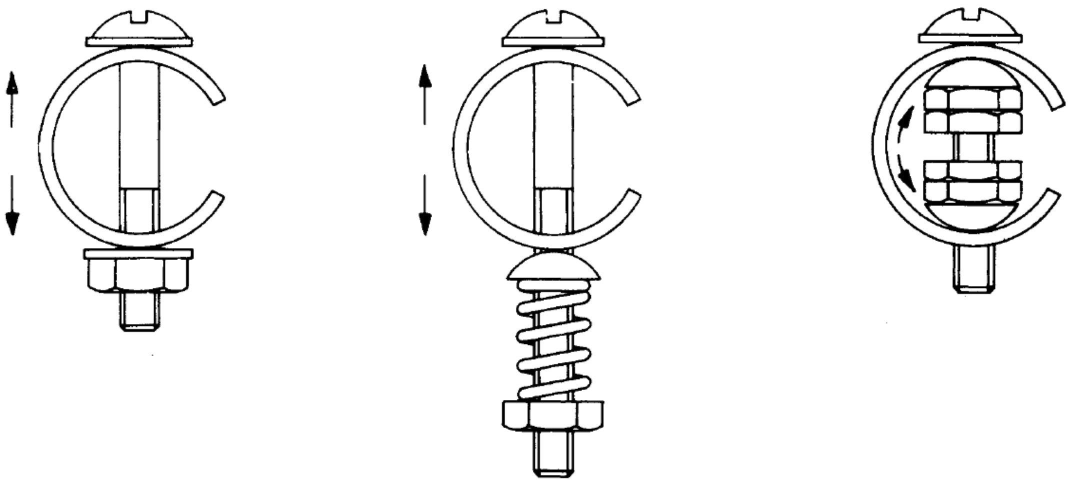
Figure 11: Geometry proposed by Tecnalia for CT specimens from brass bar.

5. Test characteristics

5.1 C-Ring

This type of specimen is usually used to determine the sensibility of the stress corrosion cracking of a material. It can be exposed to almost any kind of corrosive environment. In CANDHy project, C-ring specimen will be exposed to hydrogen environment. It is particularly adapted to pipelines tests. [9]

The principle of this test is to apply a constant or increasing strain or a stress (*Figure 12*). The environment or the increasing load applied is supposed to create a crack. The purpose of this test is to determine the crack initiation.



a) Constant strain b) Constant stress c) Constant strain

Figure 12: Differents loading methods.

The tensile surface can be the external (*Figure 12 a and b*) or the internal surface (*Figure 12 c*). It will depend on the loading direction. If the system is in traction, the tensile surface would be the inner surface.

5.2 CT-WOL

WOL (Wedge-Opening-Load) is a type of fracture mechanics specimens.

The principle is to open the specimen thanks to a screw up to a certain stress and let it age in this configuration for a defined duration.

The initial opening is defined to match a chosen stress intensity factor K_I, which is supposed to be lower than the final factor K_{IH}. Under hydrogen, the crack grows, and this factor decreases. K_{IH} factor is calculated at the end of the test.

5.3 Slow Strain Rate Testing (SSRT)

In SSRT test, a tensile specimen is subjected to a steadily increasing stress in the environment of interest. The test is continued until the specimen fails. The ductility and strength parameters coupled with the surface morphology of the fracture provide information about the mode of failure. In hydrogen environment, it is particularly useful for hydrogen embrittlement categorization, based on notched tensile strength (NTS) and reduction of area (RA) ratios.

5.4 Fracture Toughness (FT)

The toughness is the material capability to resist crack propagation, that is, the amount of stress needed to propagate a crack.

The parameter K_{IC} is the critical stress-intensity factor and represents the fracture toughness of a material (in the fracture mode I).

The stress intensity factor K_I depends on the loading, the crack, and the specimen dimensions and is defined by:

$$K_I = \sigma\beta\sqrt{\pi a}$$

Being a the crack size, σ the stress applied and β a correction factor depends on specimen geometry.

If a defect is large enough, its stress intensity factor K_I would reach a critical stress intensity K_{IC} and leads to the immediate failure of the material. This is the fracture toughness. [10]

5.5 Fatigue Crack Growth (FCG)

FCG (Fatigue Crack Growth) test aim is to investigate the behavior of the materials in the event of a crack growth in cycling.

The principle of this test is to apply a dynamic stimulation (cyclic, sinusoidal most of the time), where the stress reached is under the yield stress of the material. The effect is the growth of the crack.

The data recovered is the crack advancement as a function of the cycle number. The frequency of cycling is equal to the number of cycles per time unit, $\frac{da}{dN}$. Thus, it is possible to identify the crack growth speed $\frac{da}{dt}$ [11].

Paris [12] shows that fracture crack growth as a function of cycle number is directly linked to the stress intensity factor K_I, with this equation:

$$\frac{da}{dN} = C(\Delta K_I)^m$$

5.6 Hydrogen Solubility test

Further tests to determine the hydrogen solubility in spheroidal cast iron will be performed by Bergamo University to obtain data which are not present in literature. Cylindrical specimens of the different cast irons will be saturated with hydrogen by electrochemical charge at fixed potential in carbonate/bicarbonate buffered solution at pH 10 without hydrogen recombination poisons, than the diffusible hydrogen content will be measured by integration of the total discharge current, whereas the total hydrogen content will be measured by thermal desorption (Leco analysis). The kinetic of the diffusible hydrogen desorption will be evaluated by the measure of the residual diffusible hydrogen content after different waiting time in dry air. The experimental layout and procedure are illustrated in *Figure 13*.

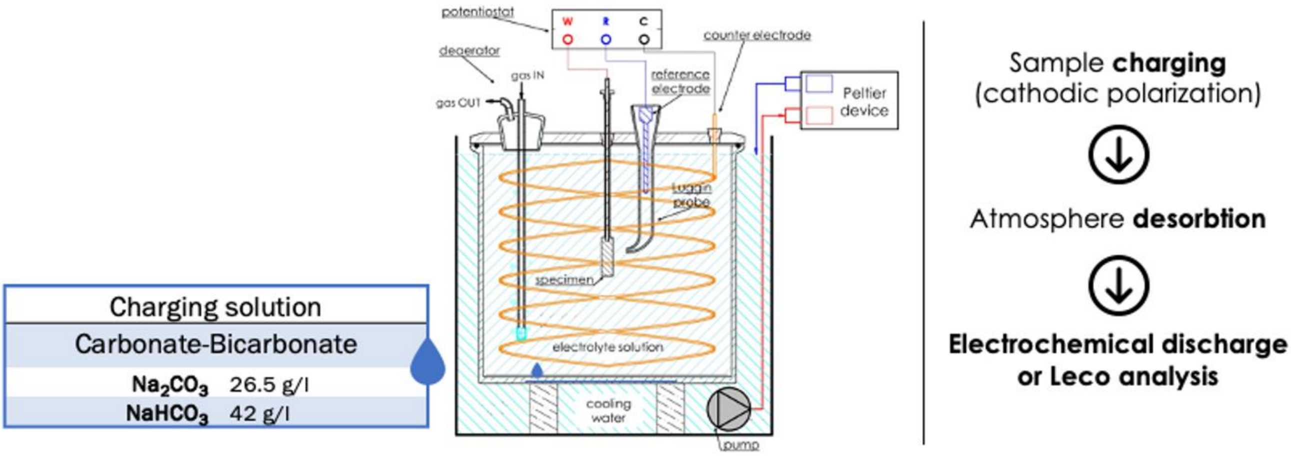


Figure 13 : experimental layout and procedure of the solubility tests.

Some hydrogen content measurements will be performed by gaseous hydrogen charging; knowledge of the hydrogen exit kinetic will allow to minimize the error due to the loss of part of the total hydrogen gas absorbed during the recovery phases of the specimens from the charging autoclave. The hydrogen content will be related to the microstructure of the cast iron (size and dimension of the graphite) and to the results of the hydrogen embrittlement tests performed by the partners.

6. ORGANIZATION

As regards the machining of specimens for RR tests, SIDSA, which has collected all the samples, will send them to RINA's premises, where the specimens will be machined. Then, RINA will send each batch of specimens to the corresponding laboratory.

For the individual tests, fatigue tests and tests of fittings, each laboratory machines their own specimens according to the RINA procedure. The tests will be performed following this report.

The circulation of samples is summarized in the scheme from the grant agreement shown on *Figure 14*.

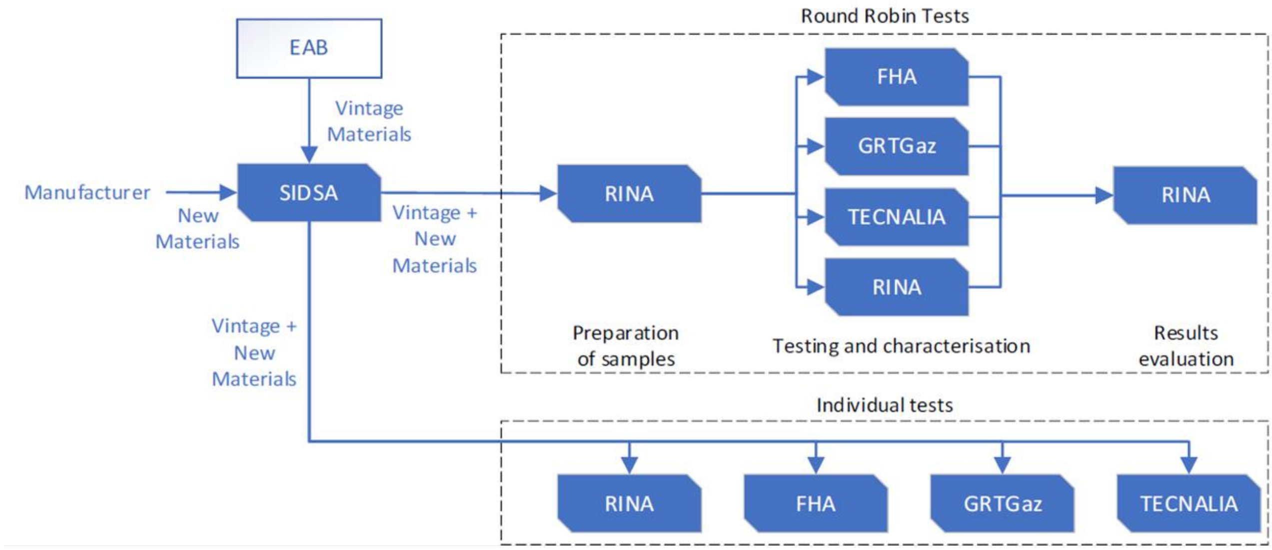


Figure 14: Scheme representing the different steps to perform and analyse tests.

Concerning the characterization, RINA will perform the characterization of the material used on the RR tests. For the other materials, the distribution of the characterization tests is such as represented on the *Figure 15*.

	Materials	Fha	RINA	GRT	TECNALIA
RR tests	All materials (4)		x		
Individuel tests	ID 5		x		
	ID 4			x	
	Spool 2			x	
	Spool 11	x			
	Spool 10	x			
	ID 6		x		
	ID 8				x
	Spool 7 - Elbow 45°			x	
	Spool 7 - Elbow 90°			x	
	Spool 7 - Coupling			x	
	ID 3				x
	ID 7				x

Figure 15: Distribution of the material characterization for each lab.

Finally, Bergamo University will perform solubility tests according to their procedure.

To summarize, the table below (*Figure 16*) indicates the quantity of each specimen to machine, by materials:

Material		Spool/ID	Static load: C-Ring	Static load: C-Ring with notch	Static load: CT-WOL	Static load: CT-WOL with notch	Dynamic loaded: Fracture Toughness (FT)	Dynamic loaded: SSRT with notch M10 x 6 mm	SSRT with notch M8 x 5 mm	SSRT with notch M6 x 4 mm	SSRT M10 x 6 mm	SSRT M8 x 5 mm	SSRT M6 x 4 mm	Fatigue tests: FCG
RR tests on ductile and grey cast iron (pipes)	Vintage ductile iron	spool 3								15 3			15 3	
	Vintage ductile iron	spool 1	18 3	18										
	New ductile iron	ID 2			18 3		15 3	5			15 3			3
	New ductile iron	ID 1	18 3	6										
Individual tests (Cooper, Brass, Aluminium, Lead,…) (pipes)	New grey cast iron	ID 5			6		8				8			3
	New grey cast iron	ID 4	6											
	Vintage ductile iron - bell	spool 2			6		8							3
	Vintage ductile iron - pipe	spool 2	6										8	
	Vintage gray cast iron (DN4'' WT10)	spool 11	9	6					8		8			
	Ductile iron pipe (DN200 WT7mm)	spool 10	9	6										
	New grey cast iron- Weld	ID 6			9		8				8			3
	Brass bar	ID 8				9	8				8			
Fitting tests	Vintage ductile iron - Elbow 45°	spool 7												3
	Vintage ductile iron - Elbow 90°	spool 7												3
	Vintage ductile iron - Coupling	spool 7												3
	New ductile iron Elbow FGL	ID 3			6									3
	New gray cast iron Tee FGL	ID 6			6									3
	New Ductile transition FGL	ID 7			6									3
		Total	72	36	60	9	50	5	8	18	50	0	26	30

Figure 16: Summary table of sample quantities by material. The color gradient indicates tests in RR tests and individual tests.

In *Figure 17*, a summary of the planned tests is proposed by material and by lab. Based on that, it is possible to determine the number of specimens to machine by each lab. To take into account possible experimental issues, some back up specimens will be machined if possible (depending on the available budget). *Figure 18* presents a summary of the number of specimens to machine for each material and for each lab. The dispatching of machining could be adapted to fit with each lab budget.

Finally, based on this table, the material needed have been calculated for each lab and each material. A summary of the pipe length needed for each material is proposed in *Figure 19* with the minimal length needed to machine all the specimens. In addition to that, a piece of each material will be sent to the University of Bergamo to perform solubility tests as described before. To this, a 100 mm x 100 mm plate of each material will be sent.

TESTS

Material	Material ID	Fha		RINA		GRTgaz		Tecnalia
New ductile iron	ID 1	- 6 Cring with notch - 9 Cring	- 3 Cring	- 6 Cring		- 6 Cring		
New ductile iron	ID 2	- 6 CT WOL	- 3 CT WOL	- 3 FT CT - 5 SSRT with notch/ M10 - 3 smooth SSRT / M10 - 3 FCG CT	- 6 CT WOL - 8 FT CT - 5 smooth SSRT / M10	- 6 CT WOL - 5 FT CT - 5 smooth SSRT / M10		- 5 FT CT - 5 smooth SSRT / M10
New ductile iron Elbow FGL	ID 3	- 6 CT WOL						- 3 FCG CT
New grey cast iron	ID 4			- 3 Cring		- 3 Cring		
New grey cast iron	ID 5			- 3 CT WOL		- 3 CT WOL		
New grey cast iron- Weld	ID 6	- 9 CT WOL		- 8 FT CT				
New gray cast iron Tee FGL	ID 6	- 6 CT WOL		- 3 FCG CT				
New Ductile transition FGL	ID 7	- 6 CT WOL						- 3 FCG CT
Brass bar	ID 8	- 9 CT WOL						- 8 FT CT - 8 smooth SSRT / M10
Vintage ductile iron	spool 1	- 6 Cring	- 6 Cring with notch - 3 Cring	- 6 Cring with notch - 6 Cring		- 6 Cring with notch - 6 Cring		
Ductile iron pipe (DN200 WT7mm)	spool 10	- 6 Cring with notch						
Vintage gray cast iron (DN4'' WT10)	spool 11	- 6 Cring with notch - 9 Cring						- 8 SSRT with notch / M8 - 8 smooth SSRT / M8
Vintage ductile iron - bell	spool 2					- 3 CT WOL		
Vintage ductile iron - pipe	spool 2			- 3 Cring		- 3 Cring		
Vintage ductile iron	spool 3			- 5 SSRT with notch / M6 - 5 smooth SSRT / M6	- 3 SSRT with notch / M6	- 5 SSRT with notch / M6 - 5 smooth SSRT / M6	- 3 SSRT smooth / M6	- 5 SSRT with notch / M6 - 5 smooth SSRT / M6
Vintage ductile iron - Elbow 45°	spool 7					- 3 FCG CT		
Vintage ductile iron - Elbow 90°	spool 7					- 3 FCG CT		
Vintage ductile iron - Coupling	spool 7					- 3 FCG CT		

Figure 17: Summary table of tests to be performed by each lab and for each material. The color gradient indicates tests in RR tests and individual tests.

Material	Material ID	Fha	RINA	GRTgaz	Tecnalia
New ductile iron	ID 1	- 6 Cring with notch + 2 back-up - 3 Cring + 1 back-up	- 18 Cring + 3 back-up		
New ductile iron	ID 2	- 3 CT WOL + 1 back-up	- 18 CT WOL + 3 back-up - 18 FT CT + 3 back-up - 5 SSRT with notch + 1 back-up / M10 - 18 smooth SSRT + 3 back-up / M10 - 3 FCG CT + 1 back-up		
New ductile iron Elbow FGL	ID 3	- 6 CT WOL + 2 back-up			- 3 FCG CT + 1 back-up
New grey cast iron	ID 4		- 3 Cring + 1 back-up	- 3 Cring + 1 back-up*	
New grey cast iron	ID 5		- 3 CT WOL + 1 back-up - 8 FT CT + 2 back-up - 8 smooth SSRT + 2 back-up / M10 - 3 FCG CT + 1 back-up	- 3 CT WOL + 1 back-up*	
New grey cast iron- Weld	ID 6	- 9 CT WOL + 2 back-up	- 8 FT CT + 2 back-up - 8 smooth SSRT / M10 + 2 back-up - 3 FCG CT + 1 back-up		
New gray cast iron Tee FGL	ID 6	- 6 CT WOL + 2 back-up	- 3 FCG CT + 1 back-up		
New Ductile transition FGL	ID 7	- 6 CT WOL + 2 back-up			- 3 FCG CT + 1 back-up
Brass bar	ID 8	- 9 CT WOL + 2 back-up			- 8 FT CT + 2 back-up - 8 smooth SSRT / M10 + 2 back-up
Vintage ductile iron	spool 1	- 3 Cring + 1 back-up	- 18 Cring with notch + 3 back-up - 18 Cring + 3 back-up		
Ductile iron pipe (DN200 WT7mm)	spool 10	- 6 Cring with notch + 2 back-up - 9 Cring + 2 back-up			
Vintage gray cast iron (DN4'' WT10)	spool 11	- 6 Cring with notch + 2 back-up - 9 Cring + 2 back-up			- 8 SSRT with notch / M8 + 2 back-up - 8 smooth SSRT / M8 + 2 back-up
Vintage ductile iron - bell	spool 2		- 3 CT WOL + 1 back-up**	- 3 CT WOL + 1 back-up - 8 FT CT + 2 back-up - 3 FCG CT + 1 back-up	
Vintage ductile iron - pipe	spool 2		- 3 Cring + 1 back-up**	- 3 Cring + 1 back-up - 8 smooth SSRT + 1 back-up / M6	
Vintage ductile iron	spool 3		- 18 SSRT with notch + 3 back-up / M6 - 15 smooth SSRT + 3 back-up / M6	- 3 smooth SSRT + 1 back-up / M6	
Vintage ductile iron - Elbow 45°	spool 7			- 3 FCG CT + 1 back-up	
Vintage ductile iron - Elbow 90°	spool 7			- 3 FCG CT + 1 back-up	
Vintage ductile iron - Coupling	spool 7			- 3 FCG CT + 1 back-up	
			* RINA machine for GRTgaz	** GRTgaz machine for RINA	

Figure 18: Summary table of specimens to machine for each lab and each material.

Material	Material ID	Fha	RINA	GRTgaz	Tecnalia
New ductile iron	ID 1	Pipe : Length 350mm min.	Pipe : Length 550mm min.		
New ductile iron	ID 2	Pipe : Length 100mm min.	Pipe : Length 130mm min.		
New ductile iron Elbow FGL	ID 3	Pipe : Length 100mm min.	Pipe : Length 100mm min.		
New grey cast iron	ID 4		Pipe : Length 250mm min.		
New grey cast iron	ID 5		Pipe : Length 130mm min.		
New grey cast iron- Weld	ID 6	Pipe : Length 100mm min.	Pipe : Length 100mm min.		
New gray cast iron Tee FGL	ID 6	Weld: Length 365mm min.	Weld: Length 890mm min.		
New Ductile transition FGL	ID 7	Pipe : Length 100mm min.			Pipe : Length 100mm min.
Brass bar	ID 8	Bar: Length 60mm min.			Bar: Length 200mm min.
Vintage ductile iron	spool 1	Pipe : Length 150mm min.	Pipe : Length 1100mm min.		
Ductile iron pipe (DN200 WT7mm)	spool 10	Pipe : Length 500mm min.			
Vintage gray cast iron (DN4'' WT10)	spool 11	Pipe : Length 500mm min.			Pipe : Length 100mm min.
Vintage ductile iron - bell	spool 2			all the bell part	
Vintage ductile iron - pipe	spool 2			Pipe : Length 350mm min.	
Vintage ductile iron	spool 3		Pipe : Length 150mm min.	Pipe : Length 100mm min.	
Vintage ductile iron - Elbow 45°	spool 7			all the elbow 45° part	
Vintage ductile iron - Elbow 90°	spool 7			all the elbow 90° part	
Vintage ductile iron - Coupling	spool 7			Pipe : Length 100mm min.	

Figure 19: Summary table of material needed for each lab and each material.

7. CONCLUSION AND PERSPECTIVES

Based on the information gathered from WP2 and the characteristics (i.e. type, dimensions, etc.) of the materials available for use in CANDHy, a matrix of experiments has been defined within Task 3.2 of WP3 and it is explained in this report. The tests and the dimensions of the specimens have been selected according to the materials available and the limitations of the platforms.

In total, 14 materials will be tested, 6 vintage materials and 8 new ones. Specimens will be collected on pipe’s body but also on welds, and elbow. More than 360 tests will be realized, including SSRT, CT-WOL, FT, Fatigue and C-Ring.

The experimental campaign of CANDHy will start with a round robin test, which will allow to compare the results between the partners to have robustness on results and to propose a procedure for machining, performing tests and analyzing them. This procedure will be used for individual tests.

Moreover, some decisions could be adapted according to the results of WP2 as test parameters which could be adapted regarding possible standard or guideline updates during the project.

8. ACKNOWLEDGEMENTS

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Clean Hydrogen Partnership

Co-funded by the European Union

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ANNEX 1: ACCRONYMS

ASTM: American Society for Testing and Materials

BPVC: Boiler and Pressure Vessel Code

CT: Compact Tension

COD: Crack test Opening Displacement

EAB: External Advisory Board

FCG: Fatigue Crack Growth

FT: Fracture Toughness

ISO: International Organization for Standardization

KIC: Fracture Toughness of first opening mode

KIH: Stress intensity factor

NG: Natural Gas

OD: Outer Diameter

RR: Round Robin

SSRT: Slow Strain Rate Testing

WOL: Wedge-Opening-Load

WP: Work Package

WT: Weight

ANNEX 2: INITIAL MATRIX

Material		Condition	Static loaded								Dynamic loaded								Fatigue tests			
			C-Ring				CT-WOL				Fracture Toughness (FT)				SSRT				Fatigue Crack Growth (FCG)			
			Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec	Fha	RINA	GRT	Tec
RR tests on ductile iron (pipes)	Gr xxx for RR tests	<15% blend										3										
	Gr xxx for RR tests	20%blend	3	3	3		6	6	6			3		3		6				3		
	Gr xxx for RR tests	100%H2	3	3	3		6	6	6			3	3	3		6	6	6		3		
	Gr yyy for RR tests	<15% blend										3										
	Gr yyy for RR tests	20%blend	3	3	3		6	6	6			3		3		6				3		
	Gr yyy for RR tests	100%H2	3	3	3		6	6	6			3	3	3		6	6	6		3		
Individual tests (Cooper, Brass, Aluminium, Lead,...) (pipes)	Material type 1	<15% blend										3										
	Material type 1	20%blend	3				6					3				6						
	Material type 1	100%H3	3				6					3				6						
	Material type 2	<15% blend											3									
	Material type 2	20%blend	3				6						3				6					
	Material type 2	100%H3	3				6						3				6					
	Material type 3	<15% blend												3								
	Material type 3	20%blend	3				6							3				6				
	Material type 3	100%H4	3				6							3				6				
Fittings	Ductile iron Gr xxx - reduction	20%blend																			2	
	Ductile iron Gr xxx - reduction	100%H4																			2	
	Ductile iron Gr xxx - elbow	20%blend																			2	
	Ductile iron Gr xxx - elbow	100%H4																			2	
	Ductile iron Gr xxx - tee	20%blend																			2	
	Ductile iron Gr xxx - tee	100%H4																			2	
	Ductile iron Gr yyy - reduction	20%blend																				
	Ductile iron Gr yyy - reduction	100%H4																				2
	Ductile iron Gr yyy - elbow	20%blend																				
	Ductile iron Gr yyy - elbow	100%H4																				2
	Ductile iron Gr yyy - tee	20%blend																				
	Ductile iron Gr yyy - tee	100%H4																				2
	TOTAL		30	12	12	0	60	24	24	0	0	27	15	21	0	36	24	24	0	12	12	6

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ANNEX 3: FINAL MATRIX

	Material	Condition	Static loaded											Dynamic loaded									Fatigue tests		
			C-Ring				C-Ring with notch			CT-WOL				Fracture Toughness (FT)			SSRT with notch			SSRT			FCG		
			Fha	Fha (2nd load)	RINA	GRT	Fha	RINA	GRT	Fha	Fha (2nd load)	RINA	GRT	RINA	GRT	Tec	RINA	GRT	Tec	RINA	GRT	Tec	RINA	GRT	Tec
RR tests on ductile and grey cast iron (pipes)	Vintage ductile iron - spool 3	20%blend															3				3				
	Vintage ductile iron - spool 3	Air															2	2	2	2	2	2			
	Vintage ductile iron - spool 3	100%H2															3	3	3	3	3	3			
	Vintage ductile iron - spool 1	20%blend	3		3	3	3	3	3																
	Vintage ductile iron - spool 1	100%H2	3	3	3	3	3	3	3																
	New ductile iron - ID 2	20%blend								3		3	3	3						3					
	New ductile iron - ID 2	Air												2	2	2	2			2	2	2	1		
	New ductile iron - ID 2	100%H2								3	3	3	3	3	3	3	3			3	3	3	2		
	New ductile iron - ID 1	20%blend	3		3	3	3																		
	New ductile iron - ID 1	100%H2	3	3	3	3	3																		
Individual tests (Cooper, Brass, Aluminium, Lead,...) (pipes)	New grey cast iron - ID 5	20%blend											3	3						3					
	New grey cast iron - ID 5	Air												2						2			1		
	New grey cast iron - ID 5	100%H2										3		3						3			2		
	New grey cast iron - ID 4	20%blend				3																			
	New grey cast iron - ID 4	100%H2			3																				
	Vintage ductile iron - spool 2	20%blend				3							3		3						3				
	Vintage ductile iron - spool 2	Air													2						2			1	
	Vintage ductile iron - spool 2	100%H2			3							3			3						3			2	
	Vintage gray cast iron - spool 11	20%blend	3				3												3			3			
	Vintage gray cast iron - spool 11	Air																	2			2			
	Vintage gray cast iron - spool 11	100%H2	3	3			3												3			3			
	Ductile iron pipe - spool 10	20%blend	3				3																		
	Ductile iron pipe - spool 10	100%H2	3	3			3																		
	New grey cast iron - ID 6	20%blend								3				3						3					
	New grey cast iron - ID 6	Air												2						2			1		
	New grey cast iron - ID 6	100%H2								3	3			3						3			2		
	Brass bar - ID 8	20%blend								3						3						3			
	Brass bar - ID 8	Air														2						2			
	Brass bar - ID 8	100%H2								3	3					3						3			
Fittings	Vintage ductile iron - spool 7 - Elbow 45°	Air																						1	
	Vintage ductile iron - spool 7 - Elbow 45°	100%H2																						2	
	Vintage ductile iron - spool 7 - Elbow 90°	Air																						1	
	Vintage ductile iron - spool 7 - Elbow 90°	100%H2																						2	
	Vintage ductile iron - spool 7 - Coupling	Air																						1	
	Vintage ductile iron - spool 7 - Coupling	100%H2																						2	
	New ductile iron Elbow FGL - ID 3	20%blend								3															
	New ductile iron Elbow FGL - ID 3	Air																							1
	New ductile iron Elbow FGL - ID 3	100%H2								3															2
	New gray cast iron Tee FGL - ID 6	20%blend								3															
	New gray cast iron Tee FGL - ID 6	Air																					1		
	New gray cast iron Tee FGL - ID 6	100%H2								3													2		
	New Ductile transition FGL - ID 7	20%blend								3															
	New Ductile transition FGL - ID 7	Air																							1
	New Ductile transition FGL - ID 7	100%H2								3															2
	TOTAL		24	12	18	18	24	6	6	36	9	12	12	24	13	13	13	5	13	29	21	26	12	12	6

ANNEX 4: MATERIALS MACHINING MATRIX

Material		Spool/ID	Static load				Dynamic loaded							Fatigue tests
			C-Ring	C-Ring with notch	CT-WOL	CT-WOL with notch	Fracture Toughness (FT)	SSRT with notch			SSRT			FCG
								M10 x 6 mm	M8 x 5 mm	M6 x 4 mm	M10 x 6 mm	M8 x 5 mm	M6 x 4 mm	
RR tests on ductile and grey cast iron (pipes)	Vintage ductile iron	spool 3								18			18	
	Vintage ductile iron	spool 1	21	18										
	New ductile iron	ID 2			21		18	5			18			3
	New ductile iron	ID 1	21	6										
Individual tests (Cooper, Brass, Aluminium, Lead,…) (pipes)	New grey cast iron	ID 5			6		8				8			3
	New grey cast iron	ID 4	6											
	Vintage ductile iron - bell	spool 2			6		8							3
	Vintage ductile iron - pipe	spool 2	6										8	
	Vintage gray cast iron (DN4'' WT10)	spool 11	9	6					8		8			
	Ductile iron pipe (DN200 WT7mm)	spool 10	9	6										
	New grey cast iron- Weld	ID 6			9		8				8			3
	Brass bar	ID 8				9	8				8			
Fitting tests	Vintage ductile iron - Elbow 45°	spool 7												3
	Vintage ductile iron - Elbow 90°	spool 7												3
	Vintage ductile iron - Coupling	spool 7												3
	New ductile iron Elbow FGL	ID 3			6									3
	New gray cast iron Tee FGL	ID 6			6									3
	New Ductile transition FGL	ID 7			6									3
		Total	72	36	60	9	50	5	8	18	50	0	26	30

COMPATIBILITY ASSESSMENT OF NON-STEEL METALLIC DISTRIBUTION GAS GRID MATERIALS WITH HYDROGEN

Clean Hydrogen Partnership

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