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FULL SCALE FATIGUE CRACK GROWTH TEST UNDER HYDROGEN ATMOSPHERE

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ABSTRACT

This paper describes the issues in the development and execution of a full scale hydrogen fatigue test. The test is intended to be performed this year a 28",2019 X70 material and subsequently a 1970'ies X60 is to be tested. The intention is to discuss the preparations and help our associated organizations who are looking at similar challenges with full scale testing in a hydrogen environment. The items discussed are material selection, hydrogen purity, girth welding, notch dimensioning and nothing approach as well as information on the process control, execution of the test and monitoring of the crack growth.

1. INTRODUCTION

EPRG is in the process of executing a full-scale fatigue crack growth test of transmission pipes for hydrogen transport. This paper is meant to share the process of drawing up the request for proposal and the subsequent ongoing discussions with the contractor in preparations of the full-scale fatigue crack growth test on a 28" OD pipe section with defects. Various topics under discussion until now will be presented and the solutions chosen by the project team together with the contractor will be described.

EPRG Project Team

Due to the importance and scale of the project a team of 5 project leaders (co-authors of this paper) is responsible on behalf of EPRG. Each team member brings his own knowledge and experience to this complex project.

2. BACKGROUND

Energy is an essential element for economic growth. An increasing awareness of the greenhouse effect and the resulting warming of the earth promotes an alteration of the energy system shifting from fossil fuels to renewable energy sources. Therefore, Europe has the ambition to increase both the energy efficiency as the fraction of sustainable energy sources by approximately 30% before 2030.
The existing gas infrastructure in Europe could be used to transport and store green energy. Currently it is foreseen that about 75% of the existing natural gas grid will be repurposed for transport of hydrogen or hydrogen/ natural gas blends by 2050. The existing grid will therefore play an essential role in the transition to a more sustainable energy-based economy. Incorporating the existing infrastructure into the renewed energy system would make the transition economically more viable.

Renewable energy can be used to produce hydrogen gas, following the power-to-gas (P2G) principle as an energy carrier, which is then transported to the consumers via pipelines. The gas systems can, as such, store surpluses of green electricity which would otherwise be lost. Using the existing system to transport mixtures of natural gas and hydrogen would offer the possibility to accommodate significant volumes of hydrogen and a unique opportunity to connect hydrogen producers and end users on the short term and at relatively limited cost. However, the physical and chemical properties of hydrogen differ significantly from those of natural gas.

Repurposing of existing gas infrastructure or building on new pipelines on basis of existing reference documentation such as the ASME B31.12 is therefore not straightforward, even though this is the unique, up to now, recognized worldwide standard for Hydrogen transportation by pipeline. On other hand, in EU, existing Standards valid for natural gas (NG) are going to be adapted for the future H2 or H2 NG blend transportation. For example, the base code EN1594 used for building natural gas infrastructure allows girth weld hardness to a maximum 350 HV10 while the ASME B31.12 requires a hardness of 235 HV10. For the time being, it is not clear whether and how hardness characterises the hydrogen performance of CMn-pipe material in the intended range of hydrogen partial pressures up to 100 bar and where limit states should be defined. From the literature review in a recent EPRG project , it follows that some of the more stringent requirements in the ASME B31.12 are not based on tests but have been taken over from other codes like those used for the transport of sour gas or from some companies conservative approach (low design factor & low material grade). Even though sour service and gaseous hydrogen environments can lead to the deleterious release of atomic hydrogen into the pipe wall, the amount of hydrogen introduced by two mechanisms is expected to be significantly different with sour service a magnitude order higher than gaseous hydrogen.
From discussions with regulators that use the ASME B31.12 code as a reference, due to a lack of availability of another code, some of the biggest hurdles to repurpose existing infrastructure or build new lines are as follows:

- The maximum hardness requirements for welds

- The minimum required fracture toughness under hydrogen atmosphere (55 MPa Öm)
- The requirement to take material for mechanical testing every 1,6 km(1mile)

A reduces toughness of the pipeline and an increased fatigue crack growth rate are also disadvantageous implications when gaseous hydrogen will be transported compared to natural gas. These can be mitigated by applying a fit for purpose welding acceptance criteria considering the minimum required toughness and expected fatigue crack growth rate for the specific pipeline and by control of the pressure fluctuations during operation. For the current approach the fatigue crack growth rate guidance of ASME B31.12 can be used and is expected to be conservative given these were based on measurements of clean (oxide free) CT specimens in a 210 bar gaseous hydrogen atmosphere.

There are also new developments in the understanding of the role of natural oxide layer on the metal surface in providing a barrier to hydrogen ingress in pipeline wall. This may particularly affect the bulk charging mechanisms away from girth welds and stress concentrations which influences other pipeline failure modes (dent / external corrosion driven burst / running fractures) which are not in scope of this paper.

Many small-scale tests are being performed at the moment in the industry, but the degree of conservatism in translating to full scale behaviour via fracture mechanics is not fully understood and hence the impetus for conducting the full-scale fatigue crack growth and fracture test in the presence of notches in the seam and girth welds.

3. OBJECTIVES OF FULL SCALE TEST

The aim of the EPRG full scale project is to determine through a combination of full scale and small scale testing in an H2 environment, cognizant of current standards/guideline requirements:

- Whether high hardness (HV10>235) girth welds have a deleterious effect on material performance (fracture/fatigue/ductility) in pure hydrogen for European linepipe materials
- The material performance difference between modern steels and automated girth welding techniques compared to vintage steels with manual girth welding techniques in a pure gaseous hydrogen
- How well fatigue behaviour from small scale tests via fracture mechanics translates to full scale behaviour for all the defects by comparison of the fatigue crack growth rates (Paris law curves) in pure hydrogen.
- An estimation of the fracture behaviour of the seam weld, after fatiguing to the point where the remaining ligament either breaks or pops through, compared to the prediction via fracture mechanics calculations using the small scale test inputs in pure hydrogen.

To achieve these aims a series of defects will be introduced in the pipe body and seam welds. For the girth welds, these will be scanned for any existing defects and when the desired defects are not present of the required dimensions, they will be introduced in the girth welds. The defects will consider workmanship requirements for seam weld and the EPRG Tier 2 criteria for the girth welds. Some seam weld defects will also be sized with the fracture mechanics calculations such that they grow to failure during the envisaged 4 month long fatigue cycling test.

4. PROJECT APPROACH AND SCOPE OF WORK

The overall test program is split across 2 projects and consists of:

1. Small scale testing to characterize the material properties (tensile, fracture toughness etc.) on the mother joint and girth welds used in the full scale programme
2. Full scale test setup
3. Full scale test under hydrogen atmosphere.

The programme will conduct two full scale fatigue crack growth tests with accompanying small scale studies, first for the modern linepipe and the second for the vintage linepipe.

5. TASK 1, SMALL SCALE TESTING

The small scale testing programme will establish the basis in-air mechanical characterisation followed by fatigue crack growth in pure H2 and fracture toughness in pure H2 using the same material, test parameters and environment from the full scale test. Specifically for H2 environment:

- stress-strain curve including yield,
- ultimate tensile strength
- da/dN fatigue curves
- fracture toughness estimates by several methods ; ASTM E1684 constant displacement , ASTM E1820 rising displacement and methods developed for sour service such as the constant K method.

The information from the small-scale test will provide inputs for definition of the test parameters and for post-mortem analysis of the full-scale test results. Secondly the small scale test programme will provide guidance on the test method to be used, in particular for determining the fracture toughness for the needs of

- linepipe manufacturing QA/QC
- Fitness for service calculations such as girth weld flaw sizing.

6. TASK 2, FULL SCALE TEST SETUP

The full scale test setup will define the parameters for executing the test and reporting the outcomes as follows as a minimum,

- the full scale test setup
- the specimen configuration including
    - pipe material test records
    - welding procedures
    - location and defect size/orientation and derivation of sizing where applicable such that the girth welds will fail first
- the loading spectrum including
    - fatigue spectrum and frequency (to be cycled down from maximum pressure)
    - loading rate
    - the number and procedure to introduce beachmarks on crack growth surface
- instrumentation to measure the following
    - loading spectrum
    - loading rate
    - the defect growth during testing
    - crack mouth opening
    - strains at the pipe OD opposite the internal notch
- post-test investigation requirements of through thickness fracture surfaces of all defects
    - hardness traverse of welds
    - starter defect size, beach marks, and final defect sizing before break/pop through
- test output
    - Logs of actual pressure cycles & number of cycles applied, associated crack growth, crack mouth opening displacement and strains at pipe OD,
    - sufficient electronic and physical measurements to allow a post fracture mechanics evaluation based on small scale testing to enable a comparison to full scale test results (post fracture mechanics evaluation not the subject of this proposal)
- any other test parameter/configuration or item that may affect the objective of the test and needs be defined and agreed with EPRG before the test

7. FULL SCALE TEST

Two full scale tests will be conducted in total. The remaining part of this paper describes the preparatory steps to prepare the test on the modern linepipe material. The preparation of the test on the vintage pipe material will be subject to a future paper.

Modern pipe test description

An illustration of the test setup for the modern pipe is shown in Figure 1. The test vessel comprises of the 3 pup pieces each approximately 660 mm long. The pup pieces are welded together with a mechanised welding process by an EPRG member company Subsea 7 using a narrow gap weld bevel and are targeting a normal and a high hardness level. The end caps are welded with the construction welds and those welds are not in scope of the test.

In total 10 machined notches or natural flaws are planned to be placed in the test vessel. 8 notches will be machined by electro-discharge machining (EDM) as illustrated in Figure 1. Three will be longitudinal in the seam welds of the linepipe, three in the parent metal and two circumferential in the girth welds. In addition 2 lack of root penetration (LOP) flaws shall be intentionally introduced in the girth weld root to simulate the worst case flaw scenario and avoid concerns with incubation time from a blunt EDM notch in the girth weld.
The dimensioning of the notches is discussed further below. The longitudinal EDM notches shall be 0.3mm wide with a sharp tip. The circumferential notches shall be 1.1 mm wide with a sharp crack tip due to limitations of the EDM tool to create the necessary defect size and profile with a thinner blade.

The test vessel will be placed in the test chamber at a controlled test site. The vessel shall be connected to the pressuring plant by use of the flexible hoses such as shown in Figure 2. This shall facilitate periodic removal of the test vessel from the safety chamber for the purpose of NDE inspection to monitor the growth of the flaws.

The key objective of the proposed research is the validation of the fatigue crack growth in a full sized transmission pipe in order to compare with numerous small scale fatigue crack growth test data. Therefore a regular monitoring of the crack growth with high precision is of a paramount importance. Two approaches are going to be used for crack growth monitoring :

- the primary approach shall use of the TOFD ultrasonic measurement technique to monitor the growth of all 10 defects in periodic intervals
- the secondary approach shall use beach marking technique by temporarily adjusting the fatigue cycling parameters to introduce the marking on the fracture surface.

The TOFD test method can achieve a resolution of 0.2 ~ 0.3 mm on flaw height when performed in a consistent manner (same probe / operator/ position on pipe). The beachmarking approach shall be trialled on the modern pipe and on small scale test samples to indicate feasibility of this process for hydrogen environment. Other method such as the DCPD techniques using changes in electric resistivity due to growth of the flaws have been considered but is not adopted because of the uncertainties how such technique should be applied to a multitude of defects in different orientations in the test vessel.

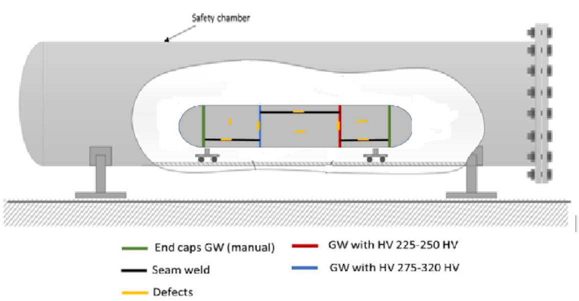

Figure 1-Schematic of the test sample in a safety chamber

Figure 2- Example photo of a test vessel inside the safety chamber

8. INFORMATION FROM PREVIOUS FULL SCALE TESTS

From literature review only limited information of full scale testing for FCGR of hydrogen pipes was available. The most recent full scale test was performed in Denmark on a small section of X70 L485 material. This test, Naturgasnettets anvendelighed til ren brintdistribution, fase II [1] in 2010 was performed on a X70 material, but were limited to sections of 20" pipe which were subjected to pressure cycles equivalent to 80 years of service life. No defects were present or induced in the material but the sections contained original girth welds form the 1980's. Although there are details on the number and frequency of cycles there was no information on material structure, mechanical characteristics and hardness of the material weld and heat affected zone.

The other report which was identified from 1982 by J.H. Holbrook and H.J. Clalone [2] is an extensive report, but most importantly, the result of the full scale testing is doubted to be representative since during the execution of the test oxygen entered into the test environment. This probably influenced the crack growth and therefore the results are presented as not viable. The material tested in the 1982 test are also low grade materials, X42 and A-106 grade B. Nevertheless both papers provided clues on how to go forward with the EPRG full scale project in particular the importance of controlling the oxygen levels during the test.

9. MATERIAL SELECTION FOR THE FULL SCALE TEST ITEMS

Within the EPRG H2 topic group a discussion was held to identify which modern materials were available and best suited for the full scale testing. From this meeting notable is the review of the influence of microstructure having a possible influence on the Hydrogen influence of the steel. Standard CMn-steels for linepipe for European NG pipelines are characterised by carbon contents in the range of 0.10 and ferritic-pearlitic microstructure to fulfil Y/T requirements from ISO 3183 Annex A. The theory is these pearlite areas are the concern for hydrogen – they are harder phases (effectively lamellar arrays of alternating Cementite (Fe_3C) and Ferrite; the lamellar nature means that surface energy is present and can act as gathering sites for hydrogen atoms to progress to diatomic hydrogen leading to HIC . Whether this happens at the partial pressures experienced at 100/120 Bar H2 is what we need to check. For the challenges of high atomic contents in sour service, lower carbon steels, significantly below 0,07% C are used. For this service, metallurgy reduces non-metallic inclusion and rolling and cooling parameters are set for achieving homogeneous bainitic microstructure, which minimises areas for recombination of atomic hydrogen. Whether these sour service features are needed for achieving an appropriate toughness in hydrogen will be objective of future investigation.

Although it would be of interest to see if there are differences in performance in these two types of microstructures, it was decided to first focus on the most used type of steels in the European Gas transportation network. This resulted in the selection of two types of steel based on a carbon percentage over 0,07% C. The Modern steel is a 28" X70 UOE line pipe produced . For the vintage material, a part of a 26"- X60 line was taken out of service recently where all mill test certificates and additional testing was available. See table 1 for more details on the selected materials.

Table 1: Overview of materials for the full and small scale tests

Parameter		Specimen #1 (Vintage)	Specimen #2 (Modern)
Pipe Material	Diameter	26"/DN650	28"/DN 700
	Wall thickness	11,13 mm	17,5 mm
	Grade	X60/L415	X70/L485M
	Seam weld	SAW	DSAW
	Production Date	1970's	2019
Girth weld	Welding Process	1. Existing vintage 2. Manual cellulosic	Mechanized; normal and high hardness

10. DESIGN OF GIRTH WELDS

In order to investigate if the current ASME B31.12 limitation on hardness can be raised the weld hardness needs to be varied.

In the modern pipe test vessel both girth welds will be specifically made for the test. The welds will be of a narrow gap design, see figure 3, with a mechanized GMAW welding system. Two welding procedures were developed, one aiming at a weld hardness of around 240 HV10 and the other procedure aiming at a 275 to 300 HV10. From various tests it became clear the pipe material would not harden above 240 to 250 HV10 in the HAZ due to a lean chemistry. Even with use of forced air and water mist cooling on the inside of the pipe. This leads to the choice of using a different welding consumable for each girth weld. For the normal hardness weld a Böhler K-nova Ni, ER 80 S wire was selected. The higher weld was made with a Böhler NiMo IG, ER 90 S. This also allows a more practical method to target the required hardness area with the artificial defects in terms of accuracy of positioning the EDM notching in a full scale test setup.

- The normal hardness welds were produced with the average root hardness of 257 HV and weld metal of 262 HV.
- The high hardness welds were produced to the average root hardness of 293 HV and weld metal of 320 HV
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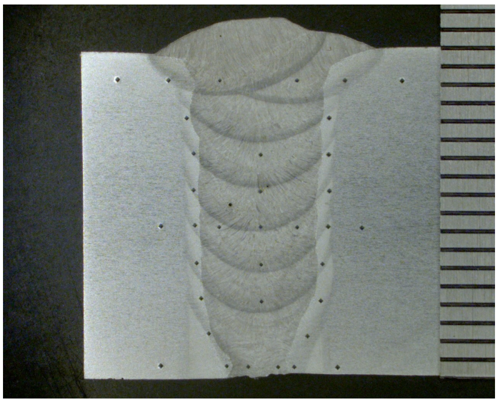

Figure 3: Narrow gap weld used for the modern pipe girth welds

11. FATIGUE TESTING PARAMETERS

The fatigue cycle shall be defined from the maximum design pressure for a design factor of 0.72 and cycling down in either 20% to 30% delta pressure steps. This is in part to simulate the expected operating pressure cycling in hydrogen pipelines and in part to create a sufficient long period of crack growth to be able to monitored by periodic NDE inspections. The load cycle shall be non-symmetric with a slow ramp up to max pressure and a faster release. The details of the loading procedure are still under discussions. The test plant will have a closed loop setup with hydrogen delivered in bottle banks, a high flow booster pump to achieve the target max test pressure of 170 bar(g) for the modern pipe and storage accumulators. The test plant is still under design.

12. DESIGN OF DEFECTS

10 defects in total shall be introduced into the test vessel for modern pipe test as summarised in the table 2 with reference to Figure 1. The defect shall be placed in the weld centreline for the girth welds while for the seam welds the plan is to:

- Position one defect near the toe of the seam weld (on the weld metal side) such that the crack growth direction is through the HAZ microstructures of a DSAW seam weld.
- Position a 2nd identical sized defect in the weld metal centreline such that it grows through the weld metal microstructures

The identical sized defects will also be placed into the parent metal.
In this way the effect of the seam weld microstructures and varying levels of residual stresses in the weld will be captured and compared with the identical sized defect in the parent metal and small scale test results. An example of the ECA calculation is shown in Figure 4 using the actual measured fatigue crack growth data on the linepipe material in small scale laboratory test to ASTM E647 in pure H_2 in a comparable pressure.

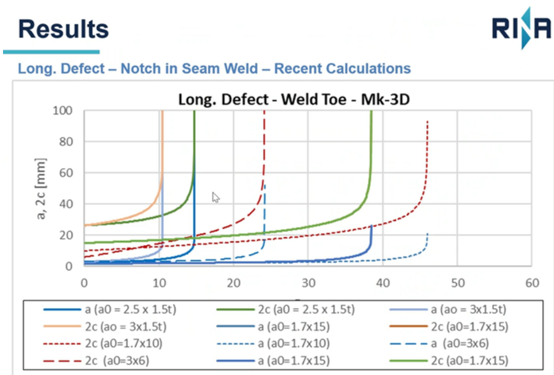

Figure 4: Example of the ECA calculation for notch sizing of the longitudinal notch in the seam weld

Further small scale fatigue crack growth testing will be conducted on the test vessel material post full scale tests

The selection of the notch dimensions needs to accommodate several constraints:

- The critical defect(s) need to be large enough to grow to failure within the approx. 100 days of net cycling time (excluding stoppages for the NDE inspections and nucleation time)
- The defects must not grow too rapid such that at least 4 measurement data points of crack growth can be taken.
- The minimum duration of the interval between the measurement of defect growth is 2 weeks in order to consider time needed for the blowdown and subsequent re-pressurisation / use of H_2 during such process / discernability of the NDE measurements
- The defects should grow in a linearly increasing fashion as much as possible, and avoid a sudden exponential acceleration in growth through the thickness. One option to avoid such behaviour is to reduce the cyclic delta pressure amplitude when the defects start to approach the "knee" region on the crack growth curve (see figure 4) and this shall be considered in devising the testing procedure.

Table 2: Summary of the defects in the modern pipe test vessel

Defect location	**Defect orientation**	**Type of defect**	**Size**	**Number of defects**
Girth weld	Circumferential	EDM machined	EPRG tier 2 criteria	1 per girth weld
Girth weld	Circumferential	Natural LOP flaw in weld root	3mm x 50 mm	1 per girth weld
Parent metal	Longitudinal	EDM machined	1st defect: Depth according to N10 notch, length 50 mm (workmanship) 2nd defect: same as for the seam weld	2 off in total
Parent metal	Circumferential	EDM machined	EPRG Tier 2 criteria	1 off
Seam weld	Longitudinal	EDM machined	1st defect: depth according to N10, length 50 mm , (workmanship) 2nd defect; ECA calculated to fail by fracture at the end of the test; placed in seam weld HAZ 3rd defect: same as 2nd defect, placed in Weld centerline	3 off in total

A notching trial is also being performed where a set of 3 longitudinal defects and 3 circumferential defects have been created in a section of the modern pipe. An example of nothing of the seam weld toe is shown in

Figure 5. Two of the three defects in each category will be destructively sectioned to confirm the notch tip geometry for use in the nucleation testing described below. The third notch shall be used for setup (calibration) of the TOFD inspection technique.

In order to understand the time required for nucleation of a growing fatigue crack from the EDM machined notch a small-scale round notched tensile specimens shall be fatigue tested in H_2 atmosphere under identical condition. The notch geometry shall be designed to replicate those created by the EDM tool in the test vessel. The small-scale test shall provide steer on the required initial delta pressure to be applied on the test vessel to nucleate the fatigue crack growth in a reasonable timeframe (within 1 month).

Figure 5: Notching of the seam weld at the weld toe during trials

13. WELD RESIDUAL STRESS

The role of the weld residual stress on fatigue crack growth can be significant and shall be examined in the test. Firstly, the weld residual stress shall be measured in the pipe body and in the seam weld on the OD and ID surfaces by small hole drilling technique to provide information about of the residual stresses in the pipe. For the seam weld this is particularly interesting since the failure is envisaged to occur in the defect placed in the seam weld and in this mother joint the pipe has undergone 2 heat treatment cycles for coating application and subsequent coating removal which could have further altered the residual stress state. A deep hole drilling through the seam weld metal is also envisaged to complement the small hole drilling method data.

In addition, the small hole drilling method shall also be applied on the extracted CT specimens used for measuring the crack growth in the laboratory setting. The measurement shall be performed firstly on the machined blanks and secondly on the notched and fatigue pre-cracked sample (ahead of the crack tip) to capture the level of relaxation of the residual stress.

14. PROCESS CONTROL

The two main impurities known to significantly affect the fatigue crack growth in hydrogen - oxygen and humidity levels - shall be carefully controlled, initially by purging the entire system with dry air followed by nitrogen and subsequently by hydrogen. The hydrogen shall be purchased at grade 5.0 with < 0.2 ppm O_2 and 5 ppm H_2O content in line with the standard for fuel cells in ISO 14687-2.

The system shall always remain closed. Care shall be taken to purge the lines connecting the interchangeable hydrogen bottles each time.

The oxygen levels shall be monitored periodically during the blowdown of the vessel for NDE inspections with an oxygen analyser which shall be connected on a vent line. A suitable analyser has been identified with the resolution of 0.1 ppm in the measurement range of 0 ~100 ppm.

15. CONCLUSIONS

With the evolving Hydrogen economy, the demand profile from the hydrogen pipelines will remain uncertain for some time. The pipelines may experience significant pressure fluctuations and with that significant fatigue crack growth in service can occur based on laboratory small scale data. EPRG is undertaking a full-scale fatigue crack growth testing program to investigate the realistic behaviour considering the system effects on a crack growth in a welded pipeline compared to an idealized small scale laboratory test setup. The outcomes of the works will inform the emerging European guidelines for repurposing and qualification of new build pipelines.

16. ACRONYMS

CT	Compact Tension
DCPD	Direct Current Potential Drop
DN	Diameter
DSAW	Double Submerged Arc Welding
ECA	Engineering Critical Assessment
EDM	Electro-Discharge Machining
FCGR	Fatigue Crack Growth Rate
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HV	Hardness Vickers
LOP	Lack Of Penetration
NIST	National Institute for Standardisation and Measurements
NDE	Non Destructive Evaluation
NG	Natural gas
OD	Outside Diameter
P2G	Power to Gas
QA/QC	Quality Assurance / Quality Control
SAW	Submerged Arc Welding
TOFD	Time Of Flight Diffraction
UOE	U-Ing, O-Ing and Expanding pipe

17. REFERENCES

[1] Naturgasnettets anvendelighed til ren brintdistribution, fase II, ISBN 978-87-7795-334, Denmark, 2010

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[3] Kalwa C, “EUROPIPE Pipes – ready for 100% Hydrogen”, October 2021